Rock Slope Design Criteria

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16. Abstract

Based on the stratigraphy and the type of slope stability problems, the flat lying, Paleozoic age, sedimentary rocks of Ohio were divided into three design units: 1) competent rock design unit consisting of sandstones, limestones, and siltstones that may exhibit discontinuity-related failures; 2) incompetent rock design unit consisting of shales, claystones, and mudstones that may exhibit raveling and gully erosion; and 3) inter-layered design unit consisting of both competent and incompetent rocks where differential weathering may result in undercutting-induced failures. Data regarding geological parameters (stratigraphy, joint orientation, joint spacing, bedding thickness, total thickness of rock unit), geotechnical parameters (point load strength index, slake durability index, plasticity index, geologic strength index, rock quality designation), and geometrical parameters (slope height, slope angle, catchment ditch width, catchment ditch depth) were collected for 26 cut slopes containing the three design units. Twenty three additional sites were later added to the study for a more detailed investigation of undercutting-induced failures within inter-layered rock sequences and the instability caused by raveling of incompetent rock. The data were used to perform slope stability analyses including kinematic analysis using discontinuity data, global stability analysis using the geological strength index (GSI) and the Franklin shale rating system, and an analysis for determining the stable slope angles using the approach described in the Ohio Department of Transportation Geotechnical Bulletin 3 (GB 3).

Results show that slopes cut at 0.5H:1V and 0.25H:1V are adequate in minimizing the potential for discontinuity related failures in competent rock design units and second-cycle slake durability index (Id_2) values can be used to select stable slope angles for incompetent rock and inter-layered rock design units. Based on Id_2 values, these angles range from < 2H:1V to 0.5H:1V. RocFall analysis indicates that either a 13 ft (3.9 m) wide by 1 ft (0.3 m) deep ditch with a 10 ft (3 m) wide flat bottom and a 3H:1V foreslope or 16 ft (4.8 m) wide by 1 ft (0.3 m) deep ditch with a 10 ft (3 m) wide flat bottom and a 6H:1V foreslope would adequately contain at least 95 % of the rockfalls, as long as the slope height does not exceed a certain limit. For higher slopes, either rockfall barriers or wider and deeper catchment ditches will be required. The choice between a rockfall barrier and a catchment ditch will depend on economic considerations and/or space limitations. Based on these results, detailed cut slope designs, including slope angle, catchment ditch and bench design, and stabilization techniques, are recommended for each of the three design units.

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ABSTRACT

Design of cut slopes along Ohio highways depends on geologic conditions and type of slope stability problems prevalent in the state. Based on the stratigraphy and the type of slope stability problems, the flat lying, Paleozoic age, sedimentary rocks of Ohio were divided into three design units: 1) competent rock design unit consisting of sandstones, limestones, and siltstones that may exhibit discontinuity-related failures; 2) incompetent rock design unit consisting of shales, claystones, and mudstones that may exhibit raveling and gully erosion; and 3) inter-layered design unit consisting of both competent and incompetent rocks where differential weathering may result in undercutting-induced failures.

Data regarding geological parameters (stratigraphy, joint orientation, joint spacing, bedding thickness, total thickness of rock unit), geotechnical parameters (point load strength index, slake durability index, plasticity index, geologic strength index, rock quality designation), and geometrical parameters (slope height, slope angle, catchment ditch width, catchment ditch depth) were collected for 26 cut slopes containing the three design units. Twenty three additional sites were later added to the study for a more detailed investigation of undercutting-induced failures within inter-layered rock sequences and the instability caused by raveling of incompetent rock. The data were used to perform slope stability analyses including kinematic analysis using discontinuity data, global stability analysis using the geological strength index (GSI) and the Franklin shale rating system, and an analysis for determining the stable slope angles using the approach described in the Ohio Department of Transportation Geotechnical Bulletin 3 (GB 3).

In addition, cartoon models were used to identify slope angles that help reduce undercutting-induced toppling in competent rock design units, talus angles were measured to determine if slopes cut at these angles would minimize the potential for raveling and gulley

erosion in incompetent rock design units, multiple regression analysis was conducted to identify factors contributing to undercutting in inter-layered design units, and RocFall (a rockfall simulation program) was used to evaluate the effectiveness of catchment ditches and benches.

Results show that slopes cut at 0.5H:1V and 0.25H:1V are adequate in minimizing the potential for discontinuity related failures in competent rock design units and second-cycle slake durability index (Id_2) values can be used to select stable slope angles for incompetent rock and inter-layered rock design units. Based on Id_2 values, these angles range from < 2H:1V to 0.5H:1V. RocFall analysis indicates that either a 13 ft (3.9 m) wide by 1 ft (0.3 m) deep ditch with a 10 ft (3 m) wide flat bottom and a 3H:1V foreslope or 16 ft (4.8 m) wide by 1 ft (0.3 m) deep ditch with a 10 ft (3 m) wide flat bottom and a 6H:1V foreslope would adequately contain at least 95 % of the rockfalls, as long as the slope height does not exceed a certain limit. For higher slopes, either rockfall barriers or wider and deeper catchment ditches will be required. The choice between a rockfall barrier and a catchment ditch will depend on economic considerations and/or space limitations. Regression analysis shows that amount of undercutting is greater for competent rock units that are closer to the slope crest and are closely jointed. Based on these results, detailed cut slope designs, including slope angle, catchment ditch and bench design, and stabilization techniques, are recommended for each of the three design units.

CHAPTER 1

INTRODUCTION

1.1 Objective

The main objective of the study presented herein was to develop a comprehensive, consistent methodology for designing cut slopes that takes into account the stratigraphic variations, engineering properties, and differential weathering of the flat-lying sedimentary rocks present in Ohio. The important aspects of design include selecting appropriate cut slope angles, bench locations, drainage methods, remedial measures, and catchment ditch dimensions.

1.2 Need for Research

Design of rock-cut slopes in Ohio is based on experience and judgment of the consultants hired by the Ohio Department of Transportation (ODOT), and does not always take into account the geological and geotechnical characteristics that are unique to the area. This practice leads to inconsistent and, occasionally, poor slope design that results in frequent slope failures, creating a potential hazard to traffic and causing damage to road structures. ODOT is interested in developing an easy-to-use, consistent methodology for cut slope design that is based on the geological and geotechnical characteristics of the rocks present in the state.

Most cut slopes in Ohio consist of inter-layered sequences of competent and incompetent rock units of varying thicknesses. These slopes are highly prone to differential weathering and result in undercutting-induced failures (Shakoor and Weber, 1988; Shakoor, 1995). Currently available methods of rock slope design can be used for designing slopes consisting of uniformly competent or uniformly incompetent rocks but they cannot be directly applied for designing slopes in inter-layered sequences of competent and incompetent rocks. Therefore, a rational

design approach, suitable for all types of geological scenarios, needs to be developed. The

research presented in this report was undertaken to address this need.

1.3 Geologic Setting of Ohio

The geologic setting of Ohio is mainly a result of Paleozoic sedimentation and

Pleistocene glaciation. The oldest rocks in Ohio are Ordovician age limestones deposited under a

shallow, warm sea (Camp, 2006). The Acadian mountains, resulting from the collision of the

Baltica plate with the North American plate (~375 Ma), supplied sediments for the Devonian-

Mississippian age shales and sandstones of Ohio. The latest orogeny, known as the Alleghenian

orogeny (~318 Ma), resulted in the rise of the Appalachian Mountains that provided the source

of Ohio's Pennsylvanian–Permian age sedimentary rocks. There is, however, little to no

sedimentary record from the late Paleozoic, Mesozoic, and most of Cenozoic time (between 290

million and 300,000 years) present in Ohio (Camp, 2006). Glacial deposits, resulting from

Pleistocene age continental glaciation, cover most of Ohio except the eastern-southeastern

region.

As a result of the tectonic history summarized above, the bedrock geology of Ohio

consists of nearly flat lying carbonate and siliciclastic sedimentary rocks from the Upper

Ordovician to the Lower Permian (Figure 1.1). Within southwestern Ohio, bedrock

predominantly consists of Upper Ordovician inter-layered limestones and shales. The Cincinnati

Arch defines the edges of the Ordovician bedrock in this area (Camp, 2006). The western and

west central parts are underlain by dolomites and shales of Silurian age. The northwestern and

central parts of Ohio are underlain by Devonian marine carbonate rocks (limestones and
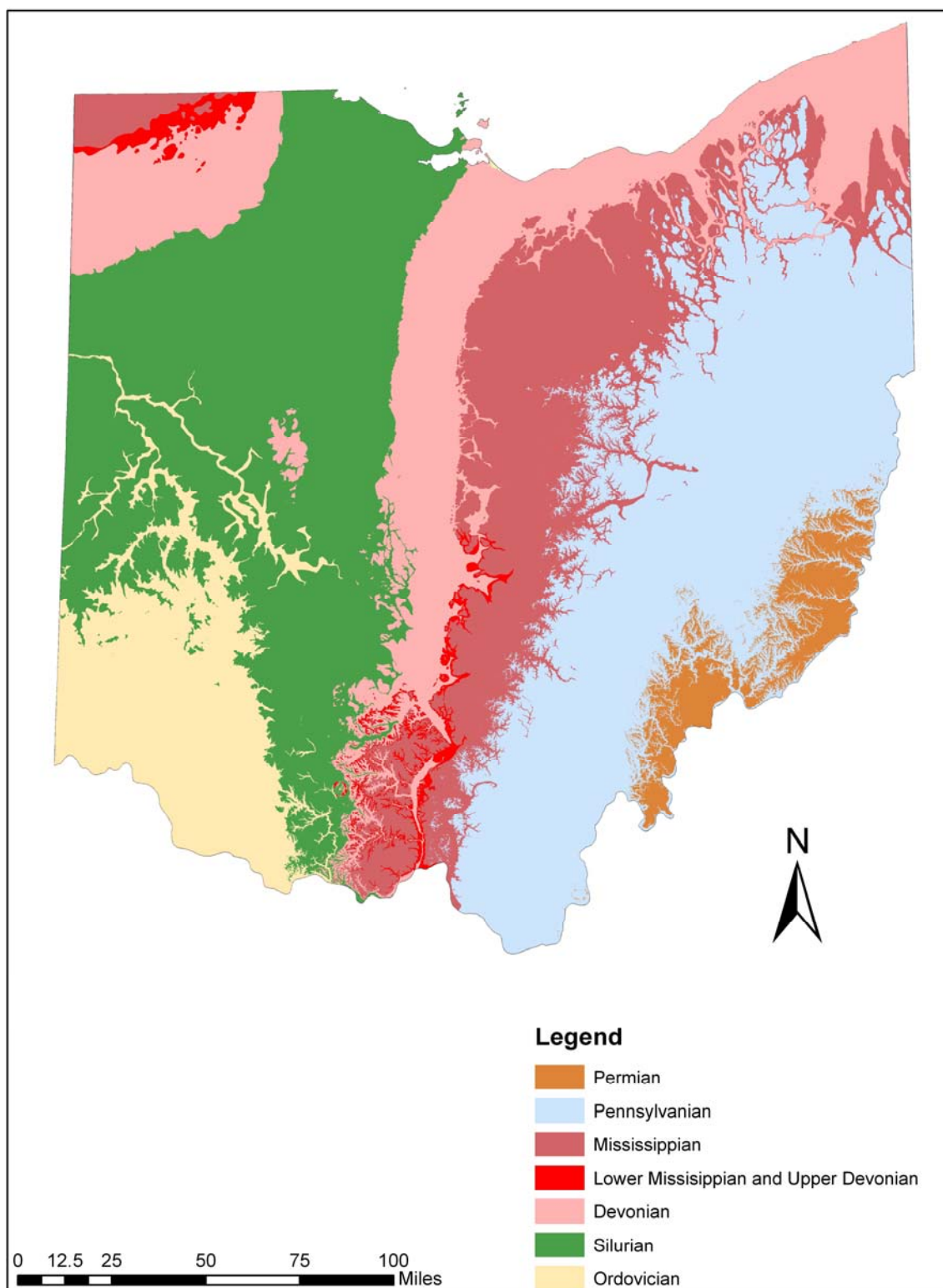
Figure 1.1: Bedrock map of Ohio (extracted from the GIS version of the geological map of Ohio prepared by the Ohio Department of Natural Resources, 2006).

dolomites inter-layered with shales) as well as siliciclastic rocks (shales, siltstones, and sandstones). The Devonian age Ohio shale wraps along Lake Eerie from northeastern Ohio to the Pennsylvania border in Ashtabula County. Mississippian age rocks, including sandstones, shales, siltstones, conglomerates, and minor proportions of limestone, cover the east-central portion, northeastern part, and the northwestern corner of the state. The largest part of eastern Ohio is covered by Pennsylvanian age rocks represented by sandstones, limestones, siltstones, shales, mudstones, and some coals. Southeastern Ohio is covered by Lower Permian/Upper Pennsylvanian age sandstones, siltstones, shales, mudstones, and minor amounts of coal.

Rock slopes are common mostly in non-glaciated portions of Ohio, typically found in southwestern, eastern, and southeastern parts of Ohio. Only a limited number of rock slopes are found in central Ohio underlain by Devonian and Mississippian aged rocks. In the southwest, Ordovician formations, such as the Kope and Grant Lake, are characterized by inter-layered fossiliferous limestone and shale (Camp, 2006). The eastern and southeastern parts, where cut slopes are most frequent, are characterized by inter-layered limestones, sandstones, shales, claystones, and mudstones belonging to the Pennsylvanian and Permian groups (Pottsville group, Allegheny group, Conemaugh group, Monongahela group, and Drunkard group). These rocks were deposited as cyclothems in non-marine, deltaic or estuarine environments (Chesnut, 1981, Bennington, 2002). Coal seams, known locally as No.1 through No.12, are associated with these groups of rocks. A brief description of these groups, taken from Camp (2006), is given below and a geologic column of the common Pennsylvanian and Permian rocks within these groups is shown in Table 1.1.

Pottsville Group: The Pottsville group mainly consists of shales and sandstones, with the Sharon sandstone at the bottom and Homewood sandstone on the top. Between these two end members

Table 1.1: Geologic column of the common Pennsylvanian and Permian rocks in Ohio (Camp, 2006).

Quaternary			
Permian	Dunkard	Greene Formation	
		Washington Formation	Upper Marietta Sandstone
			Creston Red Shale
			Lower Marietta Sandstone
			Washington Coal
			Mannington Sandstone
			Waynesburg Sandstone
			Waynesburg Sandstone
Pennsylvanian		Monongahela Group	Waynesburg Coal
			Uniontown Coal
			Benwood Limestone
			Upper Sewickley Sandstone
			Megis Creek Coal
			Fishport Limestone
			Pomeroy Coal
			Pittsburgh Coal
		Conemaugh Group	Summerfield Limestone
			Connellsville Limestone
			Morgantown Sandstone
			Skelley Limestone
			Ames Limestone
			Saltsburg Sandstone
			Cow Run Sandstone
			Portersville Shale
			Cambridge Limestone
			Buffalo Sandstone
			Brush Creek Limestone
			Mahoning Coal
			Mahoning Sandstone
		Allegheny Group	Upper Freeport Coal
			Upper Freeport Sandstone
			Lower Freeport Coal
			Washingtonville Shale
			Middle Kittanning Coal
			Columbiana Shale
			Lower Kittanning Coal
			Vanport Limestone
			Clarion Coal
			Putnam Hill Limestone
			Brookville Coal

Table 1.1: contd.

Pennsylvanian	Pottsville Group	Homewood sandstone
		Upper Mercer Limestone
		Lower Mercer Limestone
		Lower Mercer Coal
		Boggs Limestone
		Massillon Sandstone
		Quakertown Coal
		Lowellville Limestone
		Sharon Coal
		Sharon Sandstone/Conglomerate

are various limestones, discontinuous coal seams, clays, and iron-rich horizons. The Pottsville group is of variable thickness (100-350 ft/30-106 m) because of its unconformable contact with the underlying Mississippian Maxville limestone (Camp, 2006). It extends from Youngstown area to Geauga County, and southward to Scioto County.

Allegheny Group: With Brookville coal at the base and Upper Freeport coal on the top, the Allegheny group, varying in thickness from 175 to 280 ft (53-85 m), consists primarily of limestones, shales, clays, and minable coals. It forms a band along the western Allegheny Plateau from Mahoning to Scioto County (Camp, 2006).

Conemaugh Group: In the Conemaugh group, the lowermost and the uppermost units are the Lower Mahoning sandstone and the Summerfield limestone, respectively. Other units include sandstones, shales, clays, and a few thin coal seams. The Conemaugh group stretches from Columbiana County to Lawrence County in southern Ohio, and is 350 to 500 ft (106-156 m) thick (Camp, 2006).

Monongahela Group: This group represents the youngest Pennsylvanian age rocks and contains red and green claystones and shales, light colored limestones, minable coals, and a few massive sandstones (Camp, 2006). The Pittsburgh coal seam occurs at the base of the Monongahela group and the Waynesburg coal seam occurs at the top. The Monongahela group, with an average thickness of 250 ft (76 m), forms a broad band from Jefferson to Lawrence County (Camp, 2006).

Dunkard Group: Permian limestones, coals, sandstones, and red and buff shales, capping the uplands from Belmont County to Meigs County, comprise the Dunkard group (Camp, 2006).This group is subdivided into Washington and Greene formations. The Washington formation is composed of Permian sandstones, red colored shales, claystones, mudstones (redbeds), and

limestones. The formation is 270 ft (82 m) thick in Belmont County and thickens to 380 ft (115 m) near Marietta. The massive, cross-bedded, cliff-forming, Waynesburg sandstone forms the base of the Washington formation and redbeds dominate near the upper part (Camp, 2006). The Greene formation, a mixture of sandstone, coal, and limestone, represents the youngest bedrock in Ohio and forms the highest ridges from Belmont to Meigs County (Camp, 2006).

<u>1.4 Types of Rock Slopes in Ohio</u>

Based on lithologic conditions, cut slopes in rocks in Ohio can be divided into three broad types: i) those that are comprised mostly of competent rock units; ii) those that are comprised mostly of incompetent rock units; and iii) those that are comprised of inter-layered competent and incompetent rock units. For the purposes of this report, the term "rock slope" should be taken as referring to a cut slope in rock unless specified otherwise.

1.4.1 Rock Slopes Comprised Mostly of Competent Units

Rock slopes comprised mostly of competent units include those slopes where more than 90% of the cut slope (in both vertical and lateral directions) consists of competent rock units such as limestones, dolomites, sandstones, or hard and durable siltstones. Slopes consisting of sandstones and siltstones are present in various counties of ODOT Districts 3, 4, 5, 9, 10, and 11 whereas those consisting of limestones/dolomites (carbonate rocks) can be noticed in Districts 7, 9, and 10. These slopes are usually small in height (< 30 ft/9 m), and they may or may not be benched. Overall, such slopes make up approximately 20-25 % of all cut slopes. Figure 1.2 shows examples of rock slopes comprised mostly of competent rock units.

Figure 1.2-A: Example of a slope comprised mostly of sandstone (LIC-16-28).

Figure 1.2-B: Example of a slope comprised mostly of limestone (CLA-68-6.9).

1.4.2 Rock Slopes Comprised Mostly of Incompetent Rock Units

Rock slopes comprised mostly of incompetent units include those slopes where more than 90% of the cut slope (in both vertical and lateral directions) consists of incompetent rock units such as shales, claystones, and mudstones. Such slopes are significantly less common than the slopes comprised mostly of competent rock units, making up less than 10 % of all slopes. However, the actual percentage of these slopes may be slightly higher because some claystone/mudstone cut slopes may be covered with vegetation. ODOT Districts 4, 5, 6, 9, and 10 contain some slopes that consist mostly of incompetent rock units, with shale slopes being more common than the claystone/mudstone slopes. Figure 1.3 shows an example of a slope comprised entirely of incompetent rock units.

1.4.3 Rock Slopes Comprised of Inter-layered Competent and Incompetent Units

Rock slopes comprised of both competent and incompetent units include those slopes where stratigraphy throughout the entire slope consists of an inter-layered sequence of competent and incompetent rock units of varying thicknesses. For the purpose of this study, the number of competent and incompetent units can vary from one or more of each type. Majority of the slopes in Ohio belong to this category. Figure 1.4 shows examples of cut slopes comprised of both competent and incompetent rock units.

1.5 Types of Rock Slope Failure in Ohio

1.5.1 Classification of Slope Movements

In order to discuss the types of rock slope failure in Ohio, it is essential to first review the classification of slope movements. Table 1.2 shows the widely used classification of slope movements by Cruden and Varnes (1996) and brief descriptions of these movements. As can be

Figure 1.3-A: Example of a slope comprised mostly of shale (JAC-33-12).

Figure 1.3-B: Example of a slope comprised mostly of shale (FRA-270-23).

Figure 1.4-A: Example of a slope comprised of thick units of competent and incompetent rock (COL-7-3).

 Figure 1.4-B: Example of a slope comprised of thin units of competent and incompetent rock (ATH-50-22).

Table 1.2: Classification and descriptions of different types of slope movement (Cruden and Varnes, 1996).

Type of Slope Movement	Description
Fall	Detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material descends mainly through air by falling, bouncing, or rolling.
Topple	Forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass.
Slide	A down slope movement of soil or rock mass occurring along a curved surface, (rotational slide), planar surface (translational slide), or intersection of two planar surfaces (wedge slide).
Spread	An extension of cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material.
Flow	A spatially continuous movement of soil or rock material in which surfaces of shear are short lived, closely spaced, and usually not preserved. The displaced mass resembles like a viscous liquid.

seen from Table 1.2, slope movements or failures can be of five types: fall, topple, slide, spread, and flow. Slides can be either rotational or translational. Depending upon whether there is one plane of failure or two intersecting planes of failure, translational slides are categorized as plane failures or wedge failures. Two major factors can cause failures in rock slopes:

1) unfavorable orientation of discontinuities with respect to slope face, and

2) low rock mass strength.

Discontinuities are the pre-existing planes of weakness in a rock mass such as joints, faults, bedding planes, foliation, and shear zones. The types of slope movement associated with unfavorable orientation of discontinuities with respect to slope face are the plane failures, wedge failures, and toppling failures. A rotational slide, occurring in a rock mass, represents a slope failure that is independent of the orientation of discontinuities. This type of failure is attributed to low rock mass strength. Weathered rock masses with closely spaced (2 in-1ft/5 cm-30 cm) discontinuities tend to have low strength. Cut slopes in such rock masses can experience rotational slides along interconnected discontinuities. Multiple factors, including the nature of discontinuity surfaces (roughness, infilling material), intact rock strength, spacing between discontinuities, and ground water conditions affect rock mass strength (Bieniawski, 1976).

1.5.2 Types of Failure Affecting Rock Slopes in Ohio

Types of failure affecting slopes in Ohio depend on the geology of the slope. This section describes different types of failure associated with the three types of slopes described in Section 1.4, i.e., slopes consisting mostly of competent rock units, slopes consistently mostly of incompetent rock units, and slopes consisting of inter-layered competent and incompetent rock units.

1.5.2.1 Types of Failure Affecting Slopes Comprised Mostly of Competent Rock Units

As discussed above, the common types of slope failure in competent rocks include plane, wedge, and toppling failures. In Ohio, plane and wedge failures are rare in case of slopes consisting mostly of competent rock units. This is because of the steeply dipping nature of discontinuities that prevents them, or their lines of intersection, from daylighting on the slope face. However, where thick units of competent rock are inter-layered with incompetent rock units, undercutting of competent units by incompetent units due to differential weathering promotes all three types of failure (Shakoor and Weber, 1988; Shakoor, 1995). Figure 1.5 displays examples of plane and wedge failures in slopes consisting of competent rock. Slope failures due to low rock mass strength were not observed in Ohio during the course of this study. This may be attributed to the fact that discontinuities in Ohio are not very closely spaced to render the rock mass weak enough to cause rotational sliding.

1.5.2.2 Types of Failure Affecting Slopes Comprised Mostly of Incompetent Rock Units

Although plane, wedge, and toppling failures commonly occur in competent rocks, slopes consisting of incompetent rocks can also exhibit these failures (Krinitzsky and Kolb, 1969; Franklin, 1983; Young and Shakoor, 1987; Wu et al., 1987; Rauber and Shakoor, 2009). Figure 1.6 shows a wedge failure that occurred within a cut slope in a silty shale. Claystones and mudstones may fail as rotational slides along circular, or more commonly quasi-circular, surfaces which develop as a result of water pressure build up in sub-vertical valley stress relief joints that form due to river erosion (Bjerrum, 1967). In addition, a common problem with slopes consisting of incompetent rock units is degradation due to weathering. Weathering causes raveling (fragmentation) of incompetent rock units, with the raveled material accumulating at the base of the slope, often posing no hazard (Franklin, 1983). In Ohio, raveling, mudflows, and gully

Figure 1.5 A: Example of a plane failure within a slope consisting mostly of sandstone. Note that undercutting by shale promotes the failure (COL-7-5).

Figure 1.5-B: Example of a wedge failure within a slope consisting mostly of sandstone (RIC-30-12). Notice the steep line of intersection of the wedge.
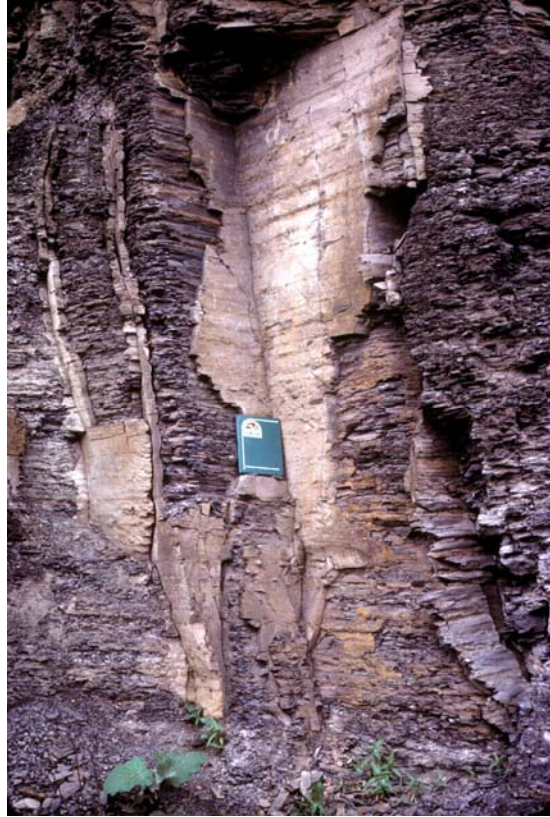
Figure 1.6: Example of a wedge failure in shale bedrock, State Route 2, West Virginia.

Figure 1.7: Raveling of a shale slope (FRA-270-23).

erosion are the main problems affecting slopes consisting of incompetent rocks. All three of these are surficial processes and do not represent deep-seated instability. They, however, create unsightly slope surfaces. Figures 1.7, 1.8, and 1.9 show examples of raveling, mudflows, and gully erosion, respectively, affecting incompetent rock slopes.

1.5.2.3 Types of Failure Affecting Slopes Comprised of Inter-Layered Competent and Incompetent Rock Units:

Slopes with Inter-layered stratigraphy experience failures that are typical of both competent rock units (plane, wedge, and toppling failures) and incompetent rock units (raveling, mudflows, erosion gullies). However, the most frequent and the most hazardous failures affecting these slopes are the undercutting-induced failures. Difference in the durability of inter-layered rock units causes differential weathering, resulting in undercutting of competent units by the incompetent units. Undercutting causes the competent rock units to fail along discontinuities that do not daylight on the original cut slope face (Shakoor and Weber, 1988; Shakoor, 1995). Undercutting-induced failures require at least three sets of intersecting discontinuities to be present so that a rock block can freely move when the depth of undercutting exceeds the spacing between the discontinuities. The three common types of discontinuities present in Ohio are the bedding, orthogonal joints, and valley stress relief joints. Orthogonal joints are sub-vertical joints that develop perpendicular to each other. Valley stress relief joints form due to horizontal expansion of valley walls as river erosion removes lateral support (Ferguson and Hamel, 1981). The released blocks can be bounded either by the bedding and two sets of orthogonal joints (Figure 1.10) or by the bedding, a set of orthogonal joints, and a set of stress relief joints (Figure1.11). When the undercut blocks are first released, the initial movement could be either in the form of a plane failure or a wedge failure (Shakoor and Weber, 1988). Toppling failures,

Figure 1.8: Mudflow on a shale slope caused by ground water seepage (CLE-275-5.2).

Figure 1.9: Gully development on a slope consisting of redbeds (ATH-33-23).

Figure 1.10: Undercutting-induced rockfalls resulting from the intersection of orthogonal joints, with bedding serving as a release surface (MUS-70-25).

Figure 1.11: Undercutting-induced rockfalls resulting from the intersection of orthogonal and stress relief joints, with bedding serving as a release surface (JEF-CR77-0.38).

associated with undercutting, occur when the depth of undercutting extends beyond the block's center of gravity. Regardless of the initial mode of failure, all undercutting-induced failures end up as rockfalls. The sizes of undercutting-induced rockfalls vary substantially Figures 1.12 and 1.13), ranging from less than $1 ft^3$ ($0.03 m^3$) to $144 ft^3$ ($4.1 m^3$). The shapes of rockfalls range from being cubical (Figure 1.12) to slab-shaped (Figures 1.14). Cubical rockfalls tend to roll down the slope whereas slab-shaped rockfalls tend to remain on the slope face.

1.6 Current Methodologies of Rock Slope Design in the Appalachian Basin

This section summarizes the slope design guidelines currently followed by the Ohio Department of Transportation and some of the neighboring states in the Appalachian basin, where geology is similar to that of Ohio.

1.6.1 Slope Design Guidelines by Ohio Department of Transportation (ODOT)

ODOT has prepared a Geotechnical Bulletin, designated as GB 3, for designing cut slopes (ODOT, 2006). According to GB 3, the rock mass comprising a cut slope is first classified into very poor, poor, fair, good, and very good categories based on rock quality designation (RQD) and second-cycle slake durability index (Id_2) values (Figure 1.15). Based on this categorization and unconfined compressive strength of the intact rock, slope angles are suggested as shown in Table 1.3. GB 3 suggests placing benches where a competent rock unit overlies an incompetent rock unit. For incompetent units of 10 ft (3 m) thickness or less, GB 3 recommends a 10 ft (3m) wide bench. For thicker incompetent units, wider benches are recommended based on design engineer's judgment. Where there is a known mineral or coal seam present, GB 3 recommends a 20 ft (6.1 m) wide bench on top of an unmined seam or under a suspected mined seam.

Figure 1.12: Small-size (< 1 ft^3/0.03 m^3) cubical rockfalls generated as a result of undercutting (BEL-7-10).

Figure 1.13: A large-size (> 100 ft^3/2.83 m^3) rockfall generated as a result of undercutting (WAS-7-18.2).

Figure 1.14: Slab-shaped rockfalls generated as a result of undercutting (JEF-22-8).
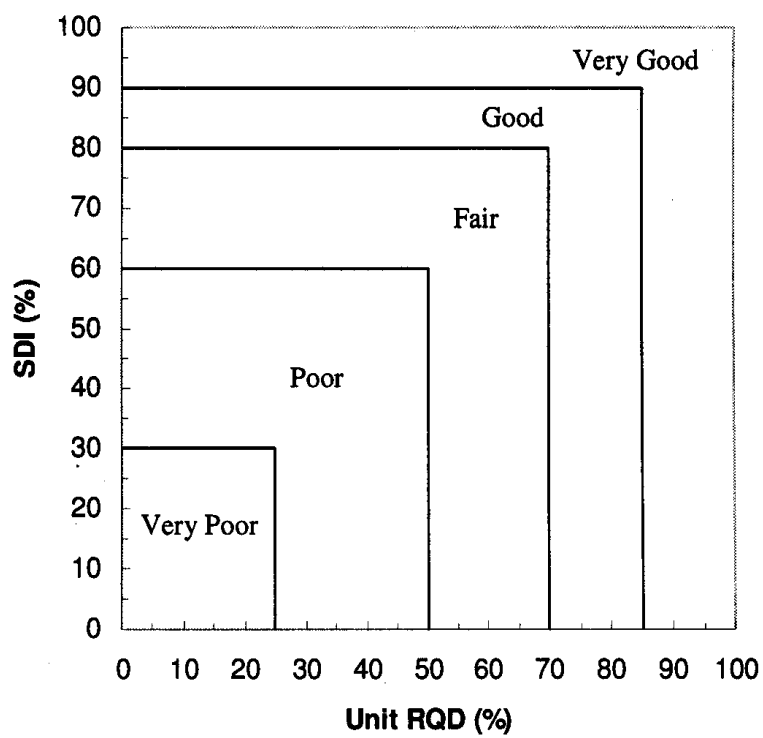
Figure 1.15: ODOT rock mass classification chart as included in GB 3 (ODOT, 2006).

Table 1.3: Cut slope angles recommended in GB 3 (ODOT, 2006).

Unconfined Compressive Strength (psi)*	ODOT Rock Index Property Classification	Cut-Slope (H:V)
>5000	Very Good	0.25:1 or 0.5:1
>5000	Good	0.25:1 or 0.5:1
>5000	Fair	0.5:1 or 1:1
>5000	Poor	1:1
>5000	Very Poor	1:1 or 1.5:1
3000-5000	Very Good	0.25:1 or 0.5:1
3000-5000	Good	0.5:1 or 1:1
3000-5000	Fair	0.5:1 or 1:1
3000-5000	Poor	1:1 or 1.5:1
3000-5000	Very Poor	1:5 or 2 :1
1500-3000	Very Good	1:1
1500-3000	Good	1:1
1500-3000	Fair	1:1 or 1.5:1
1500-3000	Poor	1.5:1 or 2:1
1500-3000	Very Poor	2:1
<1500	N/A	Special Design

* 1psi = 6.895 kPa

Table 1.4 summarizes GB 3 recommendations for catchment ditch design whereas Figure 1.16 explains the application of Table 1.4.

Although GB 3 is a good attempt at streamlining the methodology for rock slope design in Ohio, it has certain shortcomings that are outlined below:

1. RQD and slake durability index values are simultaneously used in classifying the rock mass. However, RQD is a more relevant property for competent rocks and slake durability index (Id_2) is more useful for characterizing the incompetent rocks. An apparent discrepancy in GB 3 is that a highly fractured rock having a low RQD value can have a high Id_2 value and, therefore, can be classified as a good rock mass.

2. Although both RQD and Id_2 are used to classify the rock mass, the higher value of either RQD or Id_2 governs the ultimate classification of a given rock mass. A rock mass with a low RQD and a high Id_2 would still be rated as a very good or good rock, which does not describe the actual rock quality. This is due to the way Figure 1.15 is constructed.

3. GB 3 does not consider slope failures that are primarily controlled by the unfavorable orientations of discontinuities.

4. GB 3 does not specifically provide a design method for inter-layered sequences where sandstone or limestone units are too thin and numerous to provide benches.

5. GB 3 does not consider any specific scenarios for using rock slope stabilization techniques, such as rock bolts and shotcrete.

1.6.2 Slope Design Guidelines by West Virginia Department of Transportation (WVDOT)

WVDOT geotechnical document on rock slope design (WVDOT, 2006) is based on lithology and unconfined compressive strength of rock units involved. Based on these two parameters, four classes of geologic units are identified for which the document suggests slope

Table 1.4: Catchment ditch design guidelines proposed in GB 3 (ODOT, 2006).

	3:1 Fore Slope					
	Cut-Slope Height (ft)*					
Cut-Slope Angle	16-40	50	60	70	80-100	>100
	Catchment ditch Width (ft)					
0.25:1	10	15	15	15	20	25 min.
0.5:1	10	15	20	20	20	25 min.
1:1	15	20	20	20/25**	25	30 min.

	4:1 Fore Slope					
	Cut-Slope Height (ft)					
Cut-Slope Angle	16-40	50	60	70	80-100	>100
	Catchment ditch Width (ft)					
0.25:1	10/15*	15	20	20	25	30 min.
0.5:1	15	15	20	20	25	30 min.
1:1	15/20*	20	20/25*	25/30*	30	30 min.

	6:1 Fore Slope					
	Cut-Slope Height (ft)					
Cut-Slope Angle	16-40	50	60	70	80-100	>100
	Catchment ditch Width (ft)					
0.25:1	15	20	25	30	35	40 min.
0.5:1	20	20	25	30	35	40 min.
1:1	25/30*	25/30*	30	35	40	40 min.

* 1 ft = 0.3048 m

** Option 1catchment ditch width/ Option 2 catchment ditch width. See Figure 1.15 for explanation.

Fore Slope 3:1, 4:1, 6:1

Catchment Ditch
Width

Option 1

Catchment Ditch
Width

Fore Slope 3:1, 4:1, 6:1

10 ft
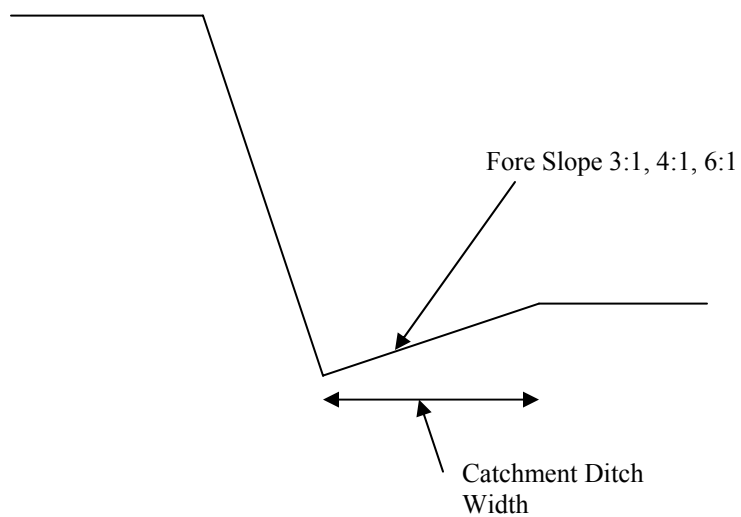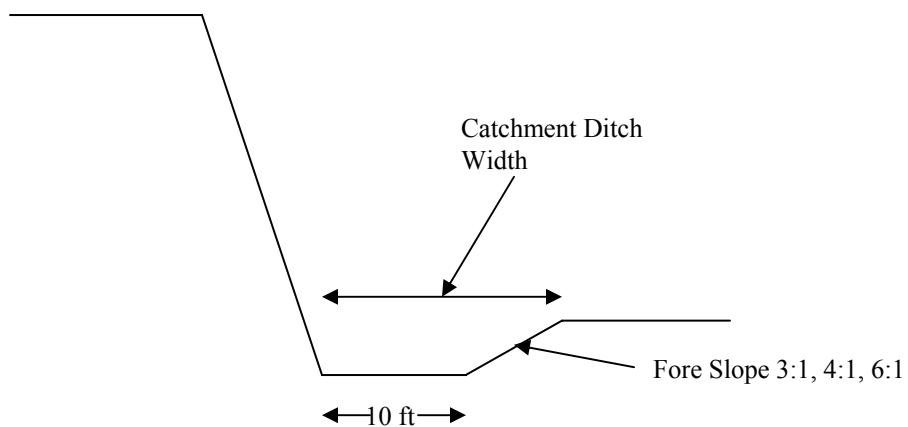
Option 2

Figure 1.16: Two options of catchment ditch design, as given in GB 3, to complement Table 1.4 (ODOT, 2006).

angles (in ratios), bench heights, and bench widths (Table 1.5). Figure 1.17 illustrates the notations used in Table 1.5.

1.6.3 Slope Design Guidelines by Kentucky Transport Cabinet (KYTC)

KYTC manual for cut slope design (KYTC, 1997) considers lithology and second-cycle slake durability index (Id_2) as important parameters for cut-slope design. Shales having Id_2 values of greater than 95% are classified as durable. Shales having Id_2 values less than 95% are classified as non-durable. Non-durable shales are further classified into Class I ($Id_2 = 80-94$ %), Class II ($Id_2 = 50-79$ %) and Class III ($Id_2 < 50$ %). Table 1.6 shows KYTC recommendations for slope design.

According to KYTC guidelines (KYTC, 1997), the location of benches depends on lithologic composition of the rock units involved. The guidelines recommend placing benches on top of highly nondurable shales. Bench width can reach 20-25 ft (6.1–7.6 m) if the bench height exceeds 30 ft (9.1 m). Benches are not recommended if the rock is homogeneous, a massive failure is unlikely to occur, or if too many rockfalls are anticipated to accumulate on the benches, making them ineffective. Benches are also not recommended when the rock consists of limestones of low RQD inter-bedded with shales of low Id_2, or when the rock contains joints that are discontinuous.

KYTC (1997) recommends that overburden benches (benches placed between the cut slope and the back slope) should be as wide as 15 ft (4.6 m). KYTC geotechnical manual considers cut slope design for situations where the entire slope consists of either shale, or limestone/sandstone units, or where thick limestone/sandstone units are underlain by thick shale units. It does not explain how rock slopes consisting of inter-layered rock sequences, involving numerous and thin units, should be designed.

Table 1.5: Guidelines for slope design by WVDOT (WVDOT, 2006).

Type	Height of Cut (ft)*	Height Between Benches (ft) (see Figure 1.16)		Width of Benches (ft) (see Figure 1.16)		Slope Angle Ratios Between Benches (H:V) (see Figure 1.16)	
		H_a (height of the first slope)	H_b,H_c (heights of the first slope $_{(b)}$ and the following slope$_{(c)}$)	Ws (width of last bench between the cut and the back slope)	Wb,Wc (widths of first bench$_{(b)}$ and the following bench$_{(c)}$)	S_a(angle of first slope)	S_b, S_c (angles of second and the following slopes)
Medium hard to hard sandstone, limestone and hard shale(>8000psi)**	>50	5-50	50	10	10-20	1/6:1	1/6:1
	<50					1/6:1	
Soft sandstone, medium hard shale, soft limestone, siltstone, or an inter-bedded combination (4000-8000psi)	>50	5-25	50	10	10-20	3/4:1	1/2:1
	25-50	5-25	20-45	10	10-20	3/4:1	1/2:1
	<25			10		1:1	3/4:11
Soft shale inter-bedded with siltstone, sandstone, or limestone (1000-4000psi)	>50	5	45	10	10-20	1:1	3/4:1
	25-50	5	20-45	10	10-20	1:1	3/4:1
	<25			10		1.5:1	
Soft shale (1000 psi)	>45	5	40	10		1.5:1	1:1
	25-45	5	20-40	10	10-20	1.5:1	1:1
	<25			10		2:1	

* 1 ft = 0.3048 m

** 1 psi = 6.985 kPa

Ha: Height of the first slope

Hb: Height of the second slope

Hc: Height of the back slope

Wb Width of the first bench

Ws: Width of the last bench between the cut and the back slope

Sa: Angle of the first slope

Sb: Angle of the second slope
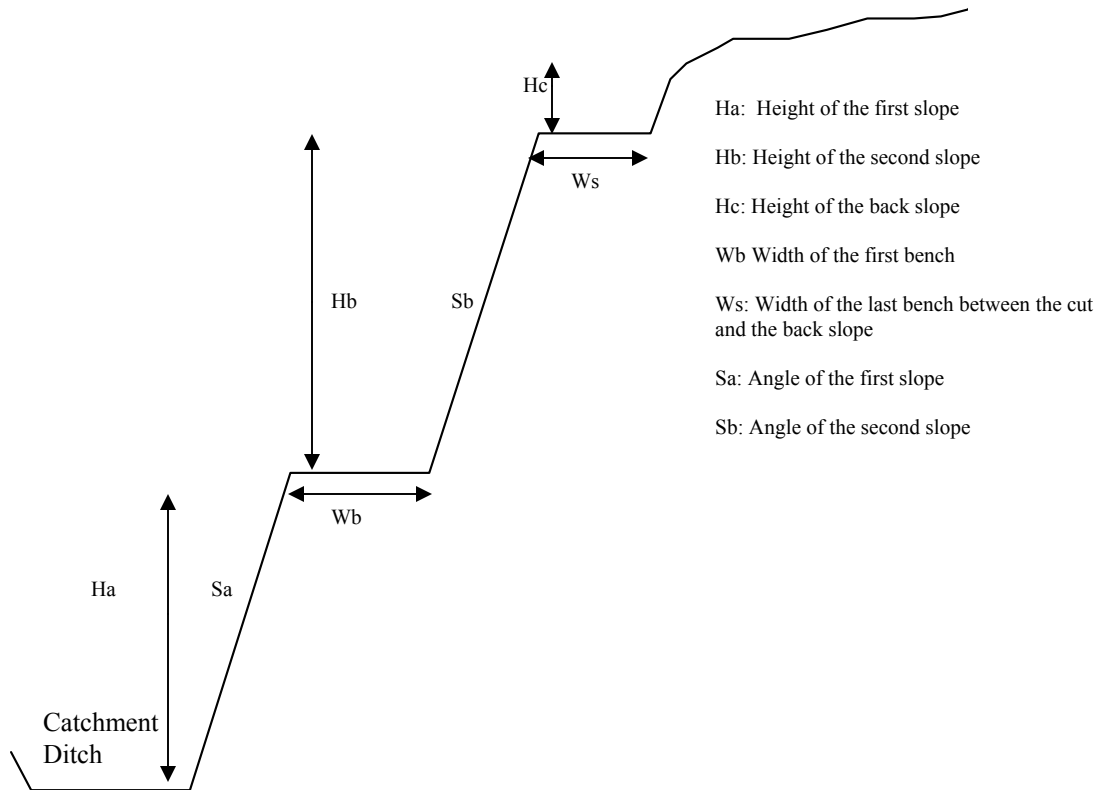
Figure 1.17: WVDOT sketch of a slope to illustrate notations used in Table 1.5.

Table 1.6: KYTC recommendations for cut slope design (KYTC, 1997).

Shale Type	Slope Angle (V:H)	Catchment Ditch	Intermediate Bench (lift height*/width) in ft**
Class III	1:2	No catchment ditch required	No intermediate bench required
Class II	1:1 to 2:1	Catchment ditch required	30 ft/12 ft
Class I	4:3 to 4:1	Catchment ditch required	30 ft/18 ft
Durable	2:1 to 4:1	Catchment ditch required	30-45 ft/18-20 ft
Limestone and sandstone	2:1 to 20:1	No information given	60 ft/18-20 ft
Argillaceous limestone and sandstone	1:1 to 2:1	No information given	

* Lift height is the slope height between benches
** 1 ft = 0.3048 m

CHAPTER 2

ROCK SLOPE ANALYSIS AND DESIGN METHODOLOGIES

This chapter provides a brief review of the currently available methodologies of rock

slope analysis and design that include kinematic analysis, limit equilibrium analysis, rock mass

analysis, durability based analysis, and rockfall analysis.

2.1 Kinematic Analysis

Kinematic analysis evaluates mechanical requirements for rock slope failures associated with

unfavorable orientations of discontinuities with respect to orientation of the slope face. Figure

2.1, taken from Hoek and Bray (1981), shows the kinematic requirements for such failures

which, as discussed in Chapter 1, include plane, wedge, and toppling failures. A plane failure is

likely to occur when a discontinuity dips in the same direction (within 20 degrees) as the slope

face, at an angle gentler than the slope angle (Hoek and Bray, 1981). A wedge failure is likely to

occur when the line of intersection of two discontinuities plunges in the same direction (within

20 degrees) as the slope face and the plunge angle is less than the slope angle (Hoek and Bray,

1981). A toppling failure is likely to result when steep discontinuities are parallel to the slope

face and dip into it (Hoek and Bray, 1981). According to Goodman (1989), a toppling failure

involves inter-layer slip movement. While describing requirements for the occurrence of a

toppling failure, Goodman (1989) stated: "If layers have an angle of friction Φ_j, slip will occur

only if the direction of the applied compression makes an angle greater than the friction angle

with the normal to the layers. Thus, as shown in Figure 2.2, a pre-condition for inter-layer slip is

that the normals be inclined less steeply than a line inclined Φ_j above the plane of the slope. If
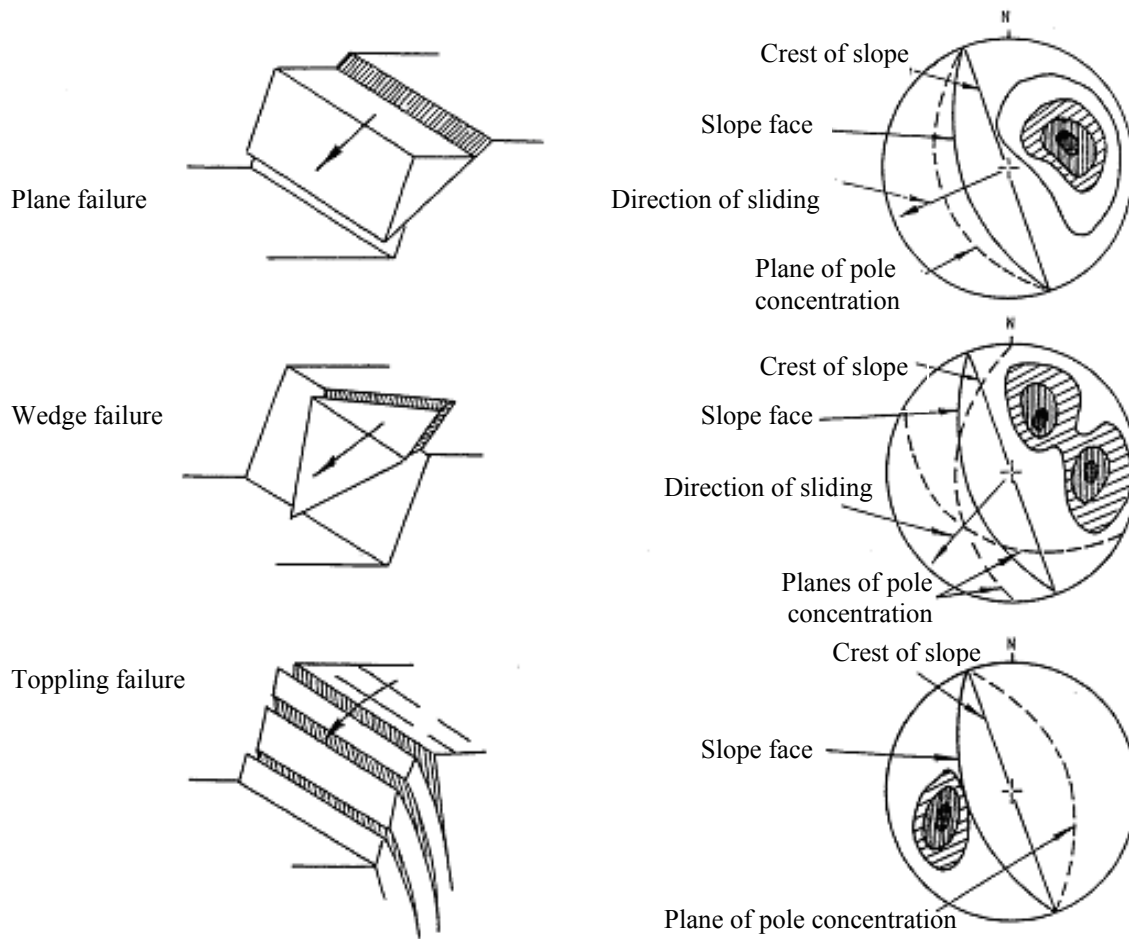
Figure 2.1: Stereographic projections of the requirements for kinematically possible plane, wedge, and toppling failures (from Hoek and Bray, 1981).
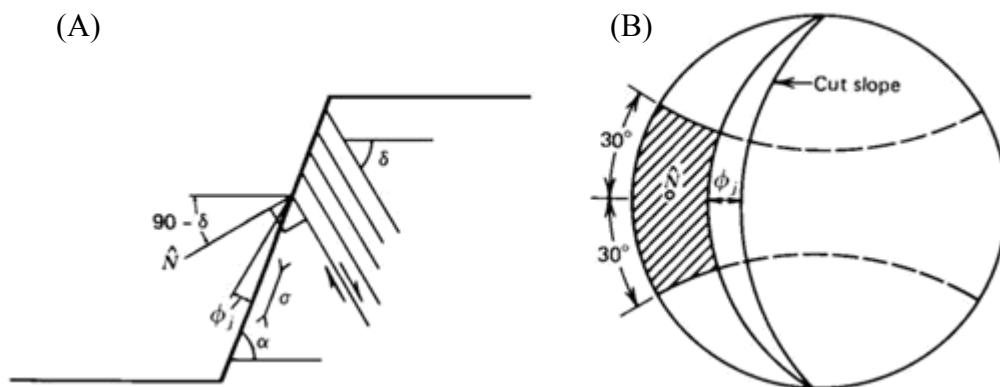
Figure 2.2: (A) Kinematics of toppling failure; (B) stereographic projection of the requirement for toppling failure, indicating that the normals (poles to discontinuities) should plot in the shaded zone (Goodman, 1989).

the dip of the layers is σ, then toppling failure with a slope inclined α degrees with the horizontal can occur if (90 - σ) + Φj < α".

Figures 2.1 and 2.2 show the kinematic requirements for rock slope failures due to unfavorable orientation of discontinuities. However, such failures will occur only if the shear strength along discontinuities, which is dependent mostly upon the friction angle, is exceeded. Stereographic projection techniques are frequently used in rock slope engineering to perform complete kinematic analysis with respect to failure potential, including consideration of frictional resistance. In this method, the potential for different types of slope failure is evaluated by plotting great circles corresponding to the discontinuity sets (cluster of discontinuities that can be represented by one plane) and the slope face, along with the friction circle, on the same stereonet. The potential for plane, wedge, and toppling failures, as described by Hoek and Bray (1981) and by Goodman (1989), is illustrated in Figures 2.3, 2.4, and 2.5, respectively. When designing cut slopes, slope orientations and angles can be chosen from the stereonet analysis so that the potential for plane, wedge, and toppling failures can be avoided.

2.2 Limit Equilibrium Analysis

Limit equilibrium analysis is used to calculate the factor of safety (F.S.) of a slope against failure once the kinematic analysis indicates the potential for failure. Factor of safety is the ratio of the resisting forces (shear strength) that tend to oppose the slope movement to the driving forces (shear stress) that tend to cause the movement. The equation for F.S. is:

F.S. = c + σ tan φ/τ

Where: F.S. = factor of safety

c = cohesion

φ = angle of internal friction
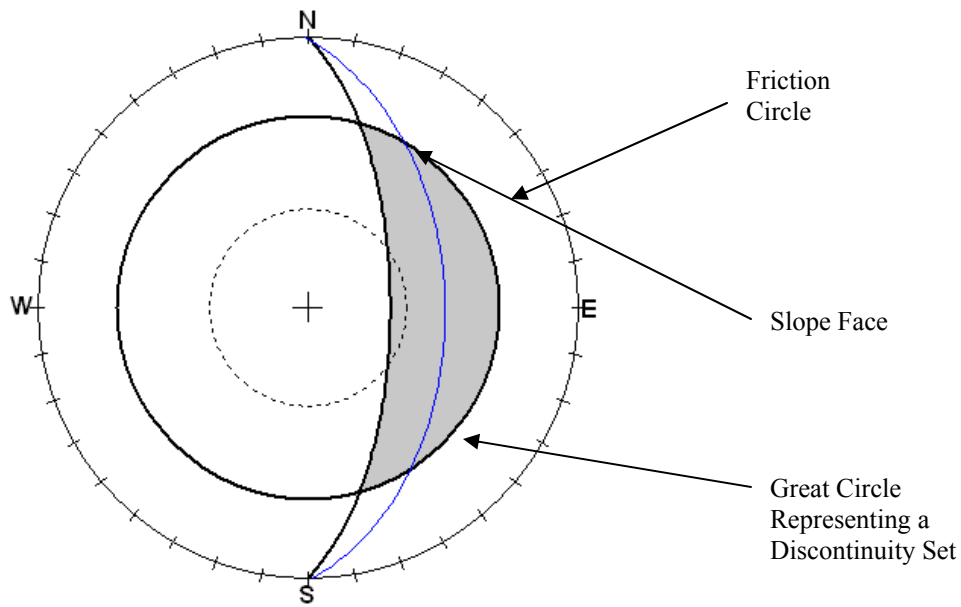
Figure 2.3: Stereographic plot showing requirements for a plane failure. If the great circle representing a discontinuity falls within the shaded area bounded by the slope face and the friction circle, the potential for a plane failure exists [figure created using RockPack software based on Hoek and Bray's (1981) criteria].
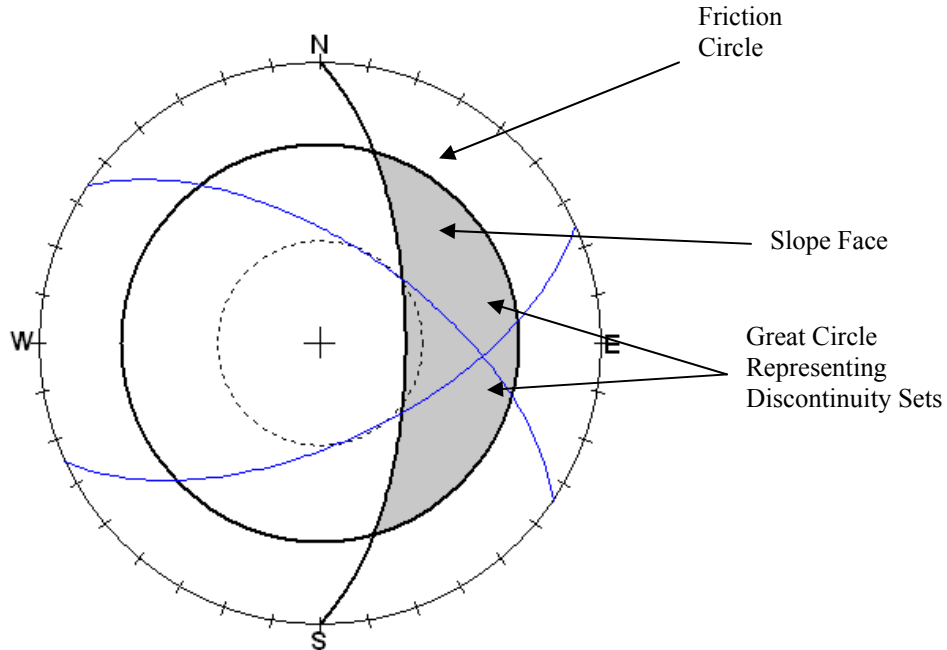
Figure 2.4: Stereographic plot showing requirements for a wedge failure. If the intersection of two great circles representing discontinuities falls within the shaded area bounded by the slope face and the friction circle, the potential for a wedge failure exists [figure created using RockPack software based on Hoek and Bray's (1981) criteria].
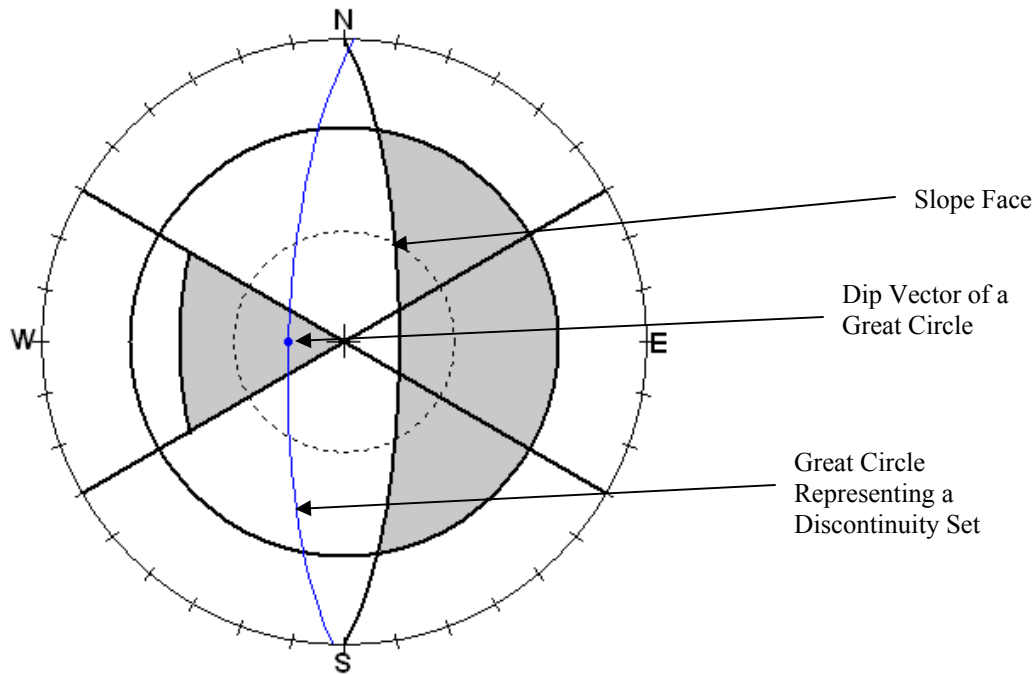
Figure 2.5: Stereographic plot showing requirement for a toppling failure. The potential for a toppling failure exists if the great circle representing a discontinuity is sub-parallel (within 30 degrees) to the great circle representing the slope face and its dip vector falls in the triangular shaded zone (figure created using RockPack software based on Goodman's, (1989) criteria).

σ = normal stress on slip surface

τ = shear stress

According to the limit equilibrium approach, a factor of safety value equal to 1 represents limiting condition, a value greater than 1 represents a stable slope, and a value less than 1 indicates an unstable slope. The desired value of factor of safety depends upon the importance of the slope and the consequences of failure. For heavily travelled roads, slopes are usually designed to have a factor of safety equal to or greater than 1.3 under saturated conditions, maximum loads, and worst expected geological conditions (Canadian Geotechnical Society, 1992; Wyllie and Mah, 2004). The methods of calculating the factor of safety for rotational and translational slides are discussed below.

2.2.1 Factor of Safety Determination for Rotational Slides

According to Wu (2006), factor of safety for rotational slides is calculated for the critical slip surface, circular in shape. The critical surface is the surface that results in the lowest factor of safety among all possible surfaces in two or three dimensions. For computing the factor of safety for a given surface, the mass of soil/rock bounded by the slip surface and the slope face is divided into a series of vertical slices, the resisting and driving forces are determined for each slice, and the ratio of the sums of resisting and driving forces is calculated. Commonly used methods of limit equilibrium analysis, representing variations of the method of slices, include: ordinary method of slices (Fellenius, 1927), Bishop's method (Bishop, 1955), force equilibrium method (Duncan,1996), Janbu's simplified method (Janbu, 1968), modified Swedish method (U.S. Army Corps of Engineers, 1970), Lowe and Karafiath's method (Lowe and Karafiath, 1960), Janbu's generalized procedure of slices (Janbu, 1968), Spencer's method (Spencer, 1967), Morgenstern and Price's method (Morgenstern and Price, 1965), Sarma's method (Sarma,

1973), and force equilibrium methods (Duncan, 1996). Differences between these methods lie primarily in the underlying assumptions and the shape of the slip surface. Details of these methods can be found in Duncan (1996).

2.2.2 Factor of Safety Determination for Translational Slides

The failure surface for translational slides is a pre-existing discontinuity or two intersecting discontinuities (Hoek and Bray, 1981). Detailed procedures and corresponding equations for determining the resisting and driving forces, including the effect of water pressure along discontinuities, and calculating the factor of safety values for plane, wedge, and toppling failures are given in Hoek and Bray (1981) and Wyllie and Mah (2004). Computer software packages like RockPack and Rocscience are available to facilitate such calculations.

2.3 Rock Mass Analysis

It was stated in Chapter 1 that slopes in weathered, closely jointed rock masses can fail because of low rock mass strength. The slope movement in this case is usually rotational in nature, with the curved failure surface developing along interconnected discontinuities. Multiple geological and geotechnical parameters are considered to evaluate rock mass quality for slope stability analysis and design purposes. Each parameter is assigned a numerical score based on its contribution toward rock mass quality, and the sum of the scores is used to determine the overall rock mass rating (RMR) (Bieniawski, 1976). The RMR is then used to estimate rock mass strength. The following parameters are used for RMR determination:

i)   Unconfined compressive strength (UCS)

ii)   Rock quality designation (RQD)

iii)   Discontinuity spacing

iv)   Condition of discontinuities

v)   Ground water condition

vi)   Discontinuity orientation favorability with respect to specific applications such as

tunnels, foundations, and slopes.

RMR can be used to determine rock mass strength using the following formula (Hoek

and Brown, 1980):

$\sigma_1 / \sigma_3 = \sigma_3/\sigma_c + \sqrt{(m (\sigma_3/\sigma_c) + s)}$

where: σ_1 = major principal stress at failure

σ_3 = minor principal stress at failure

σ_c = Intact rock strength

m and s for undisturbed (carefully blasted) rock are calculated as follows:

$m = m_i \exp ((RMR-100)/28)$

$s = \exp (RMR-100)/9$

m and s for disturbed (blast damaged) rock is calculated as follows:

$m = m_i \exp ((RMR-100)/14)$

$s = \exp (RMR-100)/6$

. m_i depends on the type of rock

Although RMR is widely used to estimate rock mass strength, Hack (2002) points out the

following problems in determining various parameters required for calculating RMR:

1.   The RQD depends on the orientation of the borehole axis. Vertical drilling would miss

sub-vertical joints, resulting in an unreasonably high RQD.

2.   Evaluating ground water conditions does not consider the size of the slope. Estimating

ground water conditions in terms of only the discharge neglects the effect of the size of

the slope on the amount of seepage.

3. The quantity of water seeping out of discontinuities does not necessarily show the uplift

     pressure due to water. Ground water seepage is high shortly after rain but in a few hours

     after the rain usually no seepage is observed.

     Hoek and Brown (1997) introduced another rock mass rating system known as the

geological strength index (GSI). GSI is a numerical rating of rock mass but, unlike the RMR, it is

determined by only a visual description of the stratigraphy and joint spacing of the rock slope

under consideration. Marinos and Hoek (2000) and Marinos and Hoek (2001) provide two

charts, one for competent rocks (Figure 2.6) and another for inter-layered rocks (Figure 2.7), that

relate different stratigraphic scenarios and joint spacing with the corresponding GSI values. The

GSI system does not require rating individual parameters as does the RMR.

     The potential for rock mass failure can be calculated using Hoek and Brown's (1997)

failure criterion given below:

$$\delta_1 = \delta_3 + \delta_{ci} \, (m_{b*} \, \delta_3/\delta_{ci} + s)^a$$

where: δ_1 and δ_3 are the maximum and minimum effective stresses at failure; δ_{ci} is the uniaxial

compressive strength of the intact rock; and m_b, s, and a are constants determined from GSI, mi,

and D values, using the following formula:

$$mb = mi^{\,(GSI-100/28-14D)}$$

$$s = \exp(GSI-100/9-3D)$$

$$a = 1/2+1/6(e^{-GSI/15}-e^{-20/3})$$

The mi constant is based on rock type. Granites have an mi value of 32 whereas shales have an

mi value of 6. D is a disturbance factor, which depends on the method of slope excavation.

Highly disturbed rock masses have a D value of 1 and undisturbed rock masses have a D value of

0.

GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

SURFACE CONDITIONS

VERY GOOD — Very rough, fresh unweathered surfaces

GOOD — Rough, slightly weathered, iron stained surfaces

FAIR — Smooth, moderately weathered and altered surfaces

POOR — Slickensided, highly weathered surfaces with compact coatings or fillings or angular fragments

VERY POOR — Slickensided, highly weathered surfaces with soft clay coatings or fillings

STRUCTURE

DECREASING SURFACE QUALITY ⟹

DECREASING INTERLOCKING OF ROCK PIECES

Structure	Description				
INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities	90, 80			N/A	N/A
BLOCKY - well interlocked un-disturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets		70, 60			
VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets			50		
BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity			40	30	
DISINTEGRATED - poorly inter-locked, heavily broken rock mass with mixture of angular and rounded rock pieces				20	
LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes	N/A	N/A			10

Figure 2.6: GSI chart for competent rocks (from Marinos and Hoek, 2000).

GSI FOR HETEROGENEOUS ROCK MASSES SUCH AS FLYSCH
(Marinos.P and Hoek. E, 2000)

From a description of the lithology, structure and surface conditions (particularly of the bedding planes), choose a box in the chart. Locate the position in the box that corresponds to the condition of the discontinuities and estimate the average value of GSI from the contours. Do not attempt to be too precise. Quoting a range from 33 to 37 is more realistic than giving GSI = 35. Note that the Hoek-Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behaviour of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

COMPOSITION AND STRUCTURE

SURFACE CONDITIONS OF DISCONTINUITIES
(Predominantly bedding planes)

VERY GOOD - Very rough, fresh unweathered surfaces

GOOD - Rough, slightly weathered surfaces

FAIR - Smooth, moderately weathered and altered surfaces

POOR - Very smooth, occasionally slickensided surfaces with compact coatings or fillings with angular fragments

VERY POOR - Very smooth slicken-sided or highly weathered surfaces with soft clay coatings or fillings

Contour values: 70, 60, 50, 40, 30, 20, 10

Box labels: A, B, C, D, E, F, G, H

A. Thick bedded, very blocky sandstone
The effect of pelitic coatings on the bedding planes is minimized by the confinement of the rock mass. In shallow tunnels or slopes these bedding planes may cause structurally controlled instability.

B. Sand-stone with thin inter-layers of siltstone

C. Sand-stone and siltstone in similar amounts

D. Siltstone or silty shale with sand-stone layers

E. Weak siltstone or clayey shale with sandstone layers

C,D, E and G - may be more or less folded than illustrated but this does not change the strength. Tectonic deformation, faulting and loss of continuity moves these categories to F and H.

F. Tectonically deformed, intensively folded/faulted, sheared clayey shale or siltstone with broken and deformed sandstone layers forming an almost chaotic structure

G. Undisturbed silty or clayey shale with or without a few very thin sandstone layers

H. Tectonically deformed silty or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces.

↑ : Means deformation after tectonic disturbance

Figure 2.7: GSI chart for inter-layered rocks (from Marinos and Hoek, 2001).

After determining mb, s, and a values, strength parameters (cohesion and friction) for a given rock mass are calculated using the following equations (Hoek and Brown, 1997):

Friction Angle $=\mathrm{Sin}^{-1}$ [(6amb $(s+mb\sigma_{3n})^{a-1})/(2(1+a)(2+a)+6amb(s+mb\sigma_{3n})^{a-1})$]

Cohesion $= \sigma_{ci}$ [(1+2a) s+ (1-a) mbσ_{3n})] $(s+mb\sigma_{3n})^{a-1}$ /

$$(1+a)(2+a) \sqrt{[1+ (6amb(s+mb\sigma_{3n})^{a-1})/ ((1+a) (2+a))]}$$

Where: $\sigma_{3n} = \sigma_{3max}/\sigma_{ci};$ σ_{3max} is the upper limit of confining stress that has to be determined for each individual case (Hoek and Brown, 1997).

The strength parameters for the rock mass, determined from the above stated equations, are used to perform stability analysis with respect to rotational slides. A computer software program, such as SLIDE, can be used to calculate the factor of safety values for a user-specified number of failure circles. In order to use the SLIDE program, a slope profile is drawn and the input parameters described above, such as GSI value, intact rock strength, disturbance factor, and mi values are entered. The SLIDE software computes the factor safety values for the specified number of failure circles, based on Bishop's (Bishop,1955) and Janbu's (Janbu, 1968) methods. The end product of analysis shows the location of the failure circle with the smallest factor of safety value.

2.4 Probabilistic Analysis

The above described methods of slope stability analysis for the two types of slope failure, one associated with unfavorable discontinuities and the other with low rock mass strength, are based on average values of relevant parameters (discontinuity orientation, shear strength, intact rock strength, etc.) which are determined from field or lab investigations. A different approach

known as the probabilistic analysis or approach can also be used to perform both the kinematic

and factor of safety analyses. The probabilistic analysis considers the uncertainty in input

parameters and factor of safety values. The uncertainty in geological and geotechnical

parameters is handled by considering each input parameter as a random variable and assigning it

a probability distribution function (PDF), instead of a single design value. The PDF basically

defines the range of all the variables used in the analysis. The Monte Carlo simulation is usually

used to generate random numbers for assigning variable values (Wyllie, 1996). The random

input values, based on PDF, are used in the calculation of a set of factor of safety values. From

the distribution of the calculated factor of safety values, the probability for the existence of factor

safety values lower than the acceptable value can be calculated (Priest and Brown, 1983; Park et

al., 2005). Based on the results of such an analysis, the design engineer can state the percent

probability of failure which can then be evaluated in light of the consequences of failure.

Applications of this method of analysis to highways have been described by Wyllie et al. (1979)

and Roberds (1990, 1991).

2.5 Durability-Based Analysis

Slopes consisting of incompetent rocks such as shales, claystones, and mudstones can fail

in the form of deep-seated rotational slides occurring along circular or quasi-circular surfaces

(Franklin, 1983). Stability analysis and design of such slopes need to consider durability

characteristics of the weak rocks in addition to strength properties. Franklin (1983) introduced a

rating system, known as the Franklin Shale Rating System, which numerically rates incompetent

rocks based on slake durability index, point load strength index, and plasticity index (Figure 2.8).

The rating value is then used to select cut angles for unsupported shale slopes (Figure 2.9). The

upper curve in Figure 2.9 represents probable maximum stable slope angles where jointing is
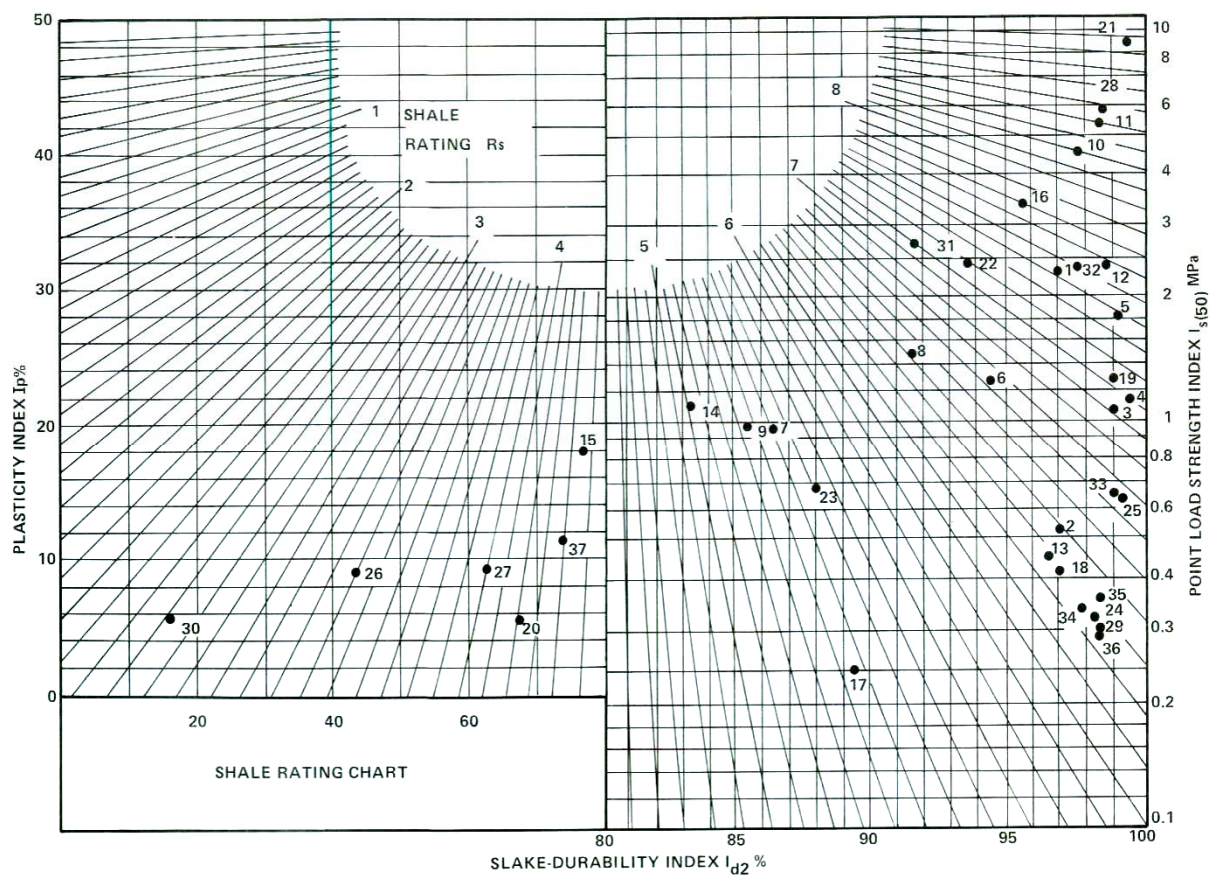
Figure 2.8: Franklin shale rating system (Franklin, 1983).
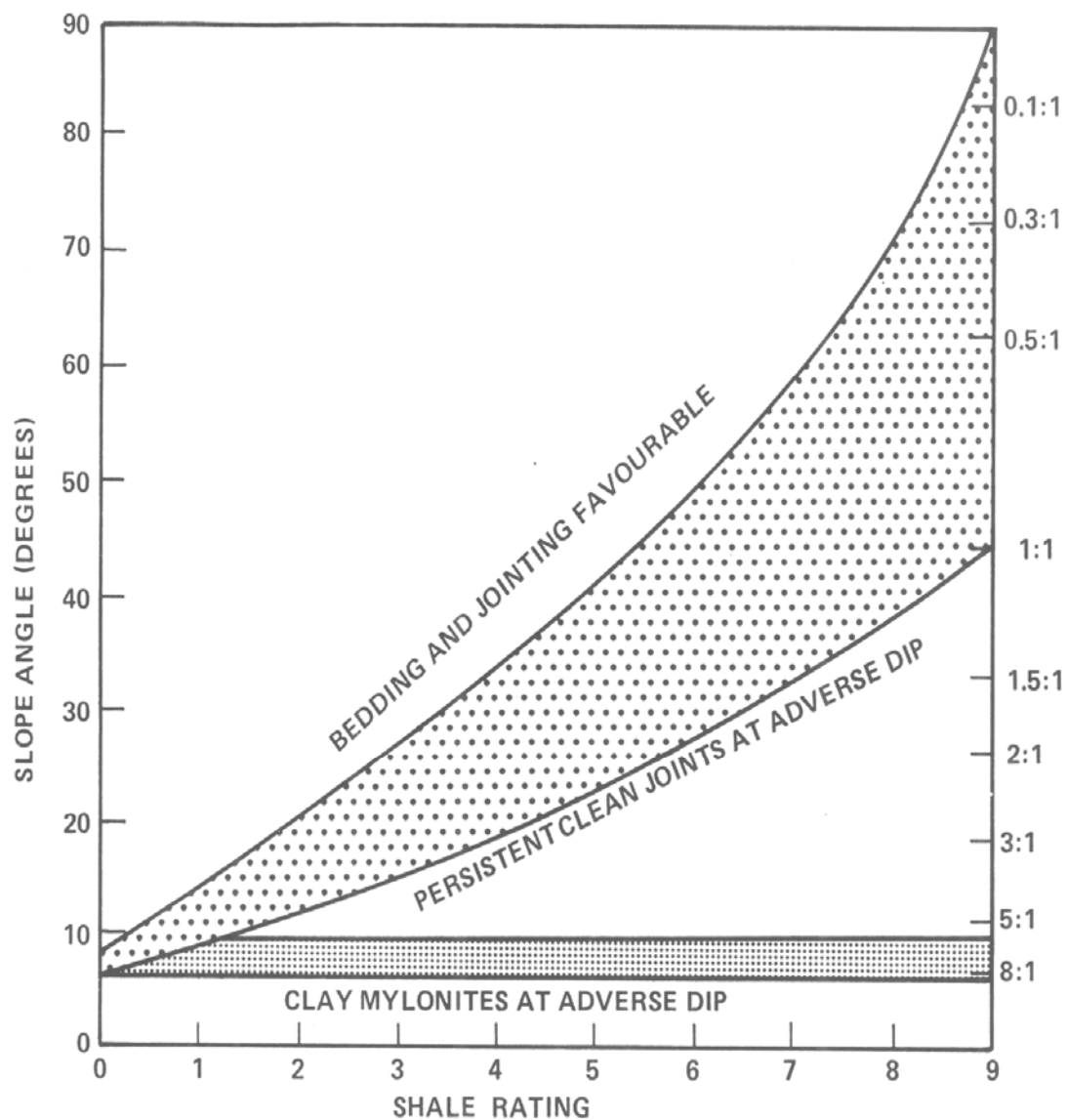
Figure 2.9: Trends in shale cut slope angles as a function of shale rating (Franklin, 1983).

either absent or at favorable orientations so that failure, if it occurs, would be through intact shale material. The lower curve represents stable slope angles where stability is controlled by unfavorably oriented discontinuities, daylighting on the slope face, and not by the intact strength of the shale (Franklin, 1983). Franklin (1983) states that the trends shown in Figure 2.9 are only approximate and that slopes in weak shales, or those with adverse jointing, should be checked using the limiting equilibrium analysis and laboratory determined strength values.

2.6 Rockfall Analysis

Rockfall analysis is used for selection and design of effective protection measures (ditches, fences, barriers) which, in turn, requires the ability to predict rockfall behavior. An early study of rockfall behavior was conducted by Ritchie (1963) who observed and photographed the behavior of boulders rolled from slope crest. Based on his observations, Ritchie (1963) developed empirical ditch design charts for slopes of varying heights and angles. In the 1980s, a series of computer programs were developed to simulate rockfall behavior with respect to landing site, bounce height, travel velocity, and impact energy (Piteau, 1980; Wu, 1984; Descoeudres and Zimmerman, 1987; Spang, 1987; Hungr and Evans, 1988; Pfeiffer and Bowen, 1989; Peiffer et al., 1990; Jones et al., 2000). Among these, the Colorado Rockfall Simulation Program (CRSP) (Jones et al., 2000) and Rocfall (Rocscience software, University of Toronto) are widely used. The inputs for these software programs include slope profile, slope surface roughness, normal coefficient of restitution (elasticity of rock colliding normal to the slope), tangential coefficient (frictional resistance parallel to the slope), weight of rockfall, and number of rockfalls. The normal and tangential coefficients depend on the type of rock on the slope surface. The software programs provide the histograms of rockfalls landing site on the slope face, bounce height, and energy of rockfalls. This output can be used to design catchment

ditches that are wide enough to contain all the rockfalls and barrier structures that are high and strong enough to contain bouncing rockfalls.

2.7 Design of Cut Slopes

Design considerations for cut slopes include: i) cutting slopes at angles that avoid slope failures identified by the above described methods of stability analysis, ii) placing benches within the slope height to facilitate construction and minimize the potential for undercutting of a competent rock unit by an incompetent rock unit iii) providing drainage, iv) providing catchment ditches to collect the failed material, and v) providing protection measures to minimize hazard. The optimum design is based on a balance between the cost of slope design and the cost of future maintenance (Baker, 1999).

CHAPTER 3

RESEARCH METHODS

3.1 Site Selection

One hundred and thirteen preliminary sites (Figure 3.1) were selected throughout the state of Ohio with the help of personnel from ODOT district offices. Information about the nature and extent of slope stability problems affecting each site was gathered through site visits, ODOT archives, and interviews with ODOT personnel. From the 113 sites initially evaluated, 26 sites (Figure 3.2) were selected for detailed study and are referred to as the "project sites" in this report. Twenty three additional sites (Figure 3.3) were added for a more intensive investigation of various aspects of undercutting-induced failures within inter-layered sequences of competent and incompetent rock and the instability caused by raveling of incompetent rock. Site designation for this study follows the ODOT standard notation which uses the three letter county code, the numerical name of the road, and the mile marker measured from the county line (also referred to as the section), separated by hyphens. For example, WAS-77-15 refers to a site in Washington County, along Interstate 77, at mile marker 15. The sites were selected to ensure that:

a) They were representative of different geological configurations in Ohio. Slopes consisting of mostly competent rock units, mostly incompetent rock units, and inter-layered competent and incompetent rock units were included to account for stratigraphic variations (Tables 3.1 and 3.2). The selected sites have a greater representation of slopes consisting of inter-layered competent and incompetent units, because they constitute the most common and problematic slopes in terms of performance and hazard potential.
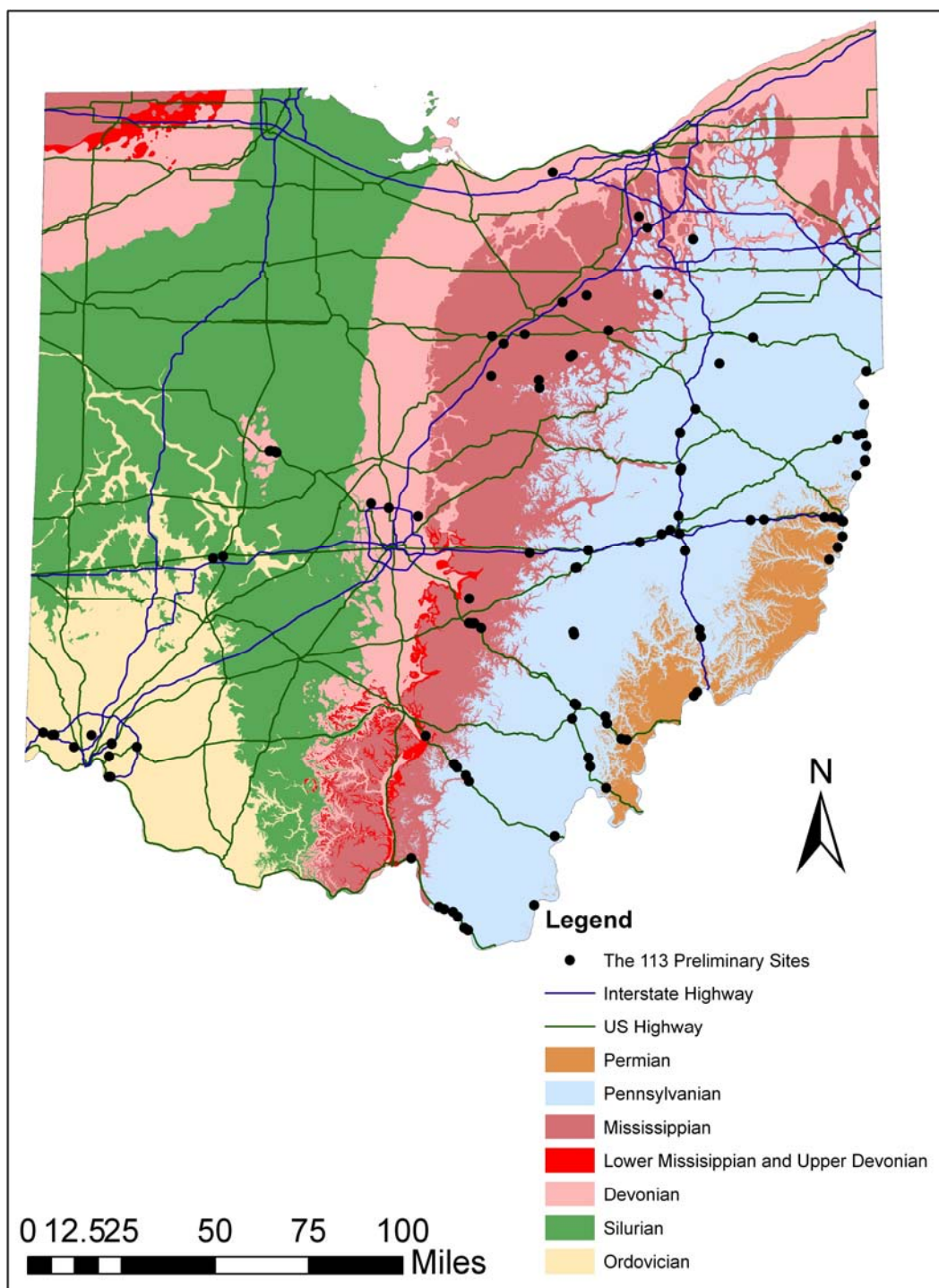
Figure 3.1: Location map of the 113 preliminary sites.
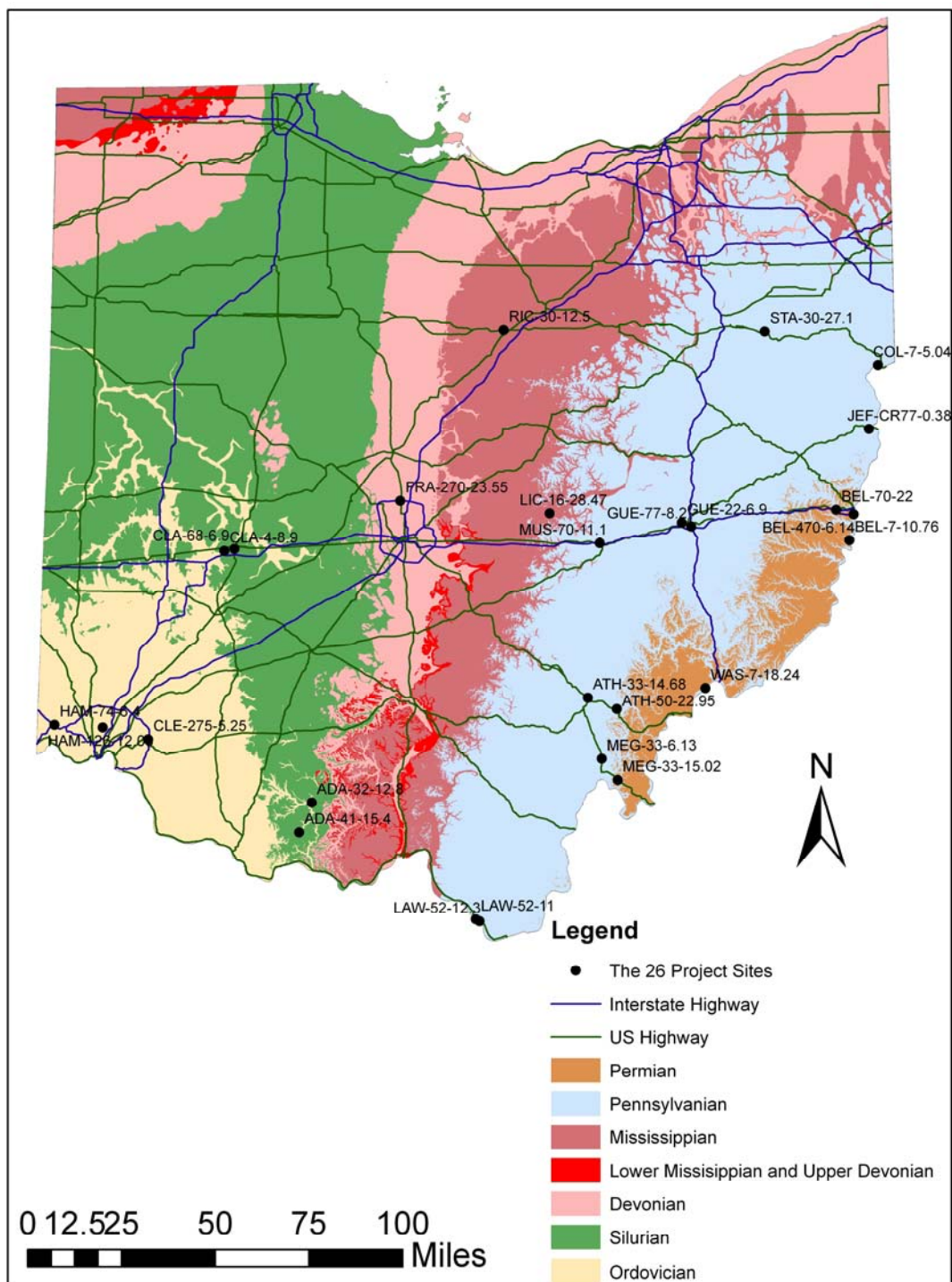
Figure 3.2: Location map of the 26 project sites.
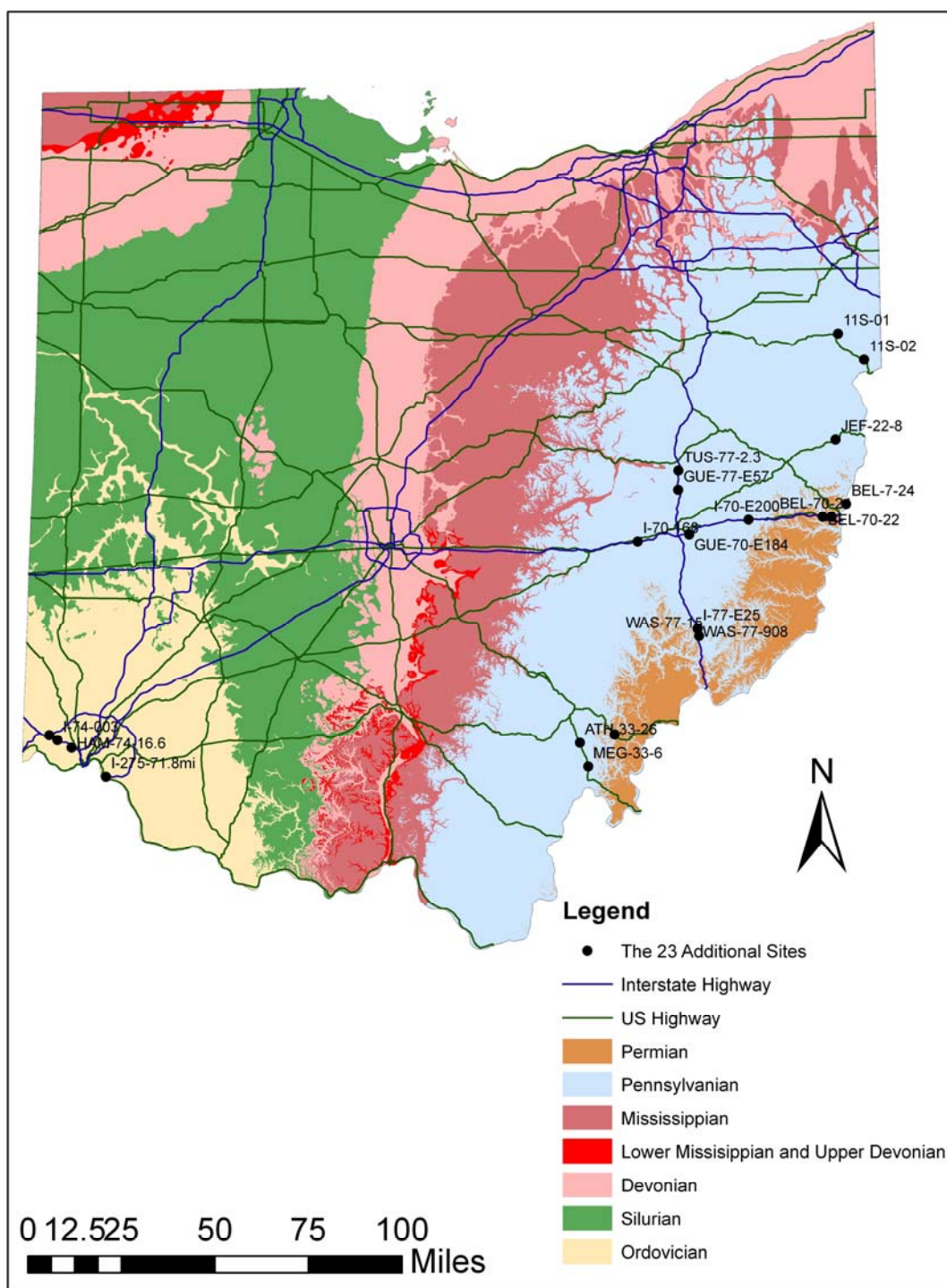
Figure 3.3: Location map of the 23 additional study sites.

Table 3.1: Geologic summary of the 26 project sites.

Site	Lithology	Slope Type			Geologic Age	Formation or Group Name
		Mostly Competent Rock	Mostly Incompetent Rock	Inter-layered Competent/ Incompetent Rock*		
ADA-32-12	Limestone underlain by claystone/ mudstone			√	Upper and Lower Silurian	Peebles Dolomite
ADA-41-15	Limestone inter-layered with claystone/ mudstone			√	Lower Silurian	Drowning Creek Formation
ATH-33-14	Sandstone	√			Upper Pennsylvanian	Conemaugh Group
ATH-50-22	Red claystone/ mudstone (redbeds) inter-layered with limestone			√	Upper Pennsylvanian	Conemaugh Group
BEL-470-6	Limestone and sandstone inter-layered with green shale			√	Upper Pennsylvanian	Monongahela Group
BEL-70-22	Sandstone inter-layered with shale			√	Lower Permian/ Upper Pennsylvanian	Dunkard Group
BEL-7-10	Limestone and sandstone inter-layered with green shale			√	Upper Pennsylvanian	Monongahela Group
CLA-4-8	Limestone	√			Upper and Lower Silurian	Cedarville, Springfield Formation
CLA-68-6.9	Limestone	√			Upper and Lower Silurian	Cedarville, Springfield Formation
CLE-275-5.2	Limestone inter-layered with claystone/ mudstone			√	Upper Ordovician	Kope Formation

Table 3.1: (contd.)

Site	Lithology	Slope Type			Geologic Age	Formation or Group Name
		Mostly Competent Rock	Mostly Incompetent Rock	Inter-layered Competent/ Incompetent Rock*		
COL-7-5	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
FRA-270-23	Shale		√		Upper Devonian	Ohio Shale
GUE-22-6.9	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
GUE-77-8.2	Sandstone underlain by coal with minor inter-layers with siltstone/shale	√			Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
HAM-74-6.4	Claystone/ mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation
HAM-126-12	Claystone/mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation
JEF-CR77-0.38	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
LAW 52-11	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
LAW-52-12	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
LIC-16-28	Sandstone	√			Lower Mississippian	Black Hand Member of the Cuyahoga Formation

Table 3.1: (contd.)

Site	Lithology	Slope Type			Geologic Age	Formation or Group Name
		Mostly Competent Rock	Mostly Incompetent Rock	Inter-layered Competent/ Incompetent Rock*		
MEG-33-6	Red claystone/ mudstone inter-layered with sandstone			√	Upper Pennsylvanian	Monongahela Group
MEG-33-15	Red claystone/ mudstone inter-layered with sandstone			√	Lower Permian/ Upper Pennsylvanian	Dunkard Group
MUS-70-11	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
RIC-30-12.5	Sandstone	√			Upper and Lower Mississippian	Logan and Cuyahoga Formations
STA-30-27	Shale with minor siltstone		√		Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
WAS-7-18	Red claystone/ mudstone inter-layered with sandstone			√	Lower Permian/ Upper Pennsylvanian	Dunkard Group

* Slopes consisting of Inter-layered competent/incompetent rocks also include those slopes containing just a few thick units of the two rock types.

Table 3.2: Geologic summary of the 23 additional sites.

Site	Lithology	Slope Type			Geologic Age	Formation or Group Name
		Mostly Competent Rock	Mostly Incompetent Rock	Inter-layered Competent/ Incompetent Rock*		
ATH-33-26	Red claystone/mudstone (redbeds)		√			
ATH-50-28	Red claystone/mudstone (redbeds)		√		Lower Permian/ Upper Pennsylvanian	Dunkard Group
BEL-70-1.58	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Monongahela Group
BEL-7-24	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
COL-30-30	Shale		√		Upper Pennsylvanian	Conemaugh Group
COL-11-16	Shale		√		Middle/Lower Permian	Allegheny and Pottsville Groups
COL-7-3	Sandstone inter-layered with shale			√	Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
GUE-70-12.9	Shale		√		Upper Pennsylvanian	Conemaugh Group
GUE-77-21	Shale		√		Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
HAM-74-12.4	Claystone/mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation
HAM-74-16.6	Claystone/mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation
HAM-74-8.9	Claystone/mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation

Table 3.2: (contd.)

Site	Lithology	Slope Type			Geologic Age	Formation or Group Name
		Mostly Competent Rock	Mostly Incompetent Rock	Inter-layered Competent/ Incompetent Rock*		
HAM-275-1.4	Claystone/mudstone inter-layered with minor limestone			√	Upper Ordovician	Grant lake Formation, Miamitown Formation, Fairview Formation
JEF-22-8N	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
JEF-22-8S	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
JEF-7-23	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
JEF-7-6	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
MUS-70-25	Red claystone/mudstone inter-layered with minor limestone		√		Middle/Lower Pennsylvanian	Allegheny and Pottsville Groups
TUS-77-3	Sandstone inter-layered with shale			√	Upper Pennsylvanian	Conemaugh Group
WAS-77-15 (799*)	Red claystone/			√	Upper Pennsylvanian	Monongahela Group
WAS-77-15 (801*)	Red claystone/mudstone inter-layered with limestone			√	Upper Pennsylvanian	Monongahela Group
WAS-77-15 (810*)	Red claystone/mudstone inter-layered with limestone			√	Upper Pennsylvanian	Monongahela Group
WAS-77-15 (908*)	Red claystone/mudstone inter-layered with limestone			√	Upper Pennsylvanian	Monongahela Group

* Slopes consisting of Inter-layered competent/incompetent rocks also include those slopes containing just a few thick units of the two rock types.

b) They were representative of different geological ages. Most of the cut slopes are located within the eastern and southeastern parts of Ohio, covered Pennsylvanian and Permian age rocks belonging to Pottsville, Allegheny, Conemaugh, Monongahela, and Dunkard groups (Tables 3.1 and 3.2). Rock slopes are also present in southwestern Ohio, covered by Ordovician age formations (Kope and Grant Lake formations). Therefore, the geology of the majority of the selected sites represents the Pennsylvanian-Permian groups of eastern and southeastern Ohio and the Ordovician formations of southwestern Ohio. Appendix 1 provides photographs of the 26 project sites used for developing design criteria as well as of the 23 additional sites used to complement undercutting related studies.

3.2 Field Investigations

Field investigations consisted of collecting data regarding slope geometry, slope stratigraphy, discontinuity characteristics, hydrologic conditions, and ditch dimensions, drilling of selected sites, and sampling of various lithologic units. Field data were recorded on a data collection forms included in Appendix 2.

3.2.1 Slope Geometry

Slope-geometry data included information about slope angle, slope height, slope aspect, and bench width. Slope angle, slope height, and bench width data were obtained from slope-profile sections drawn for the selected sites. A laser range finder was used to establish the slope profiles. The laser range finder calculates x and y coordinates of the slope toe, slope crest, and slope breaks. The reference plane for the x and y coordinates of the slope profiles was the location of the laser range finder for which x and y coordinates were taken as 0, 0. The x and y coordinates were later exported into ArcGIS, in which polygons were created by joining all

points to create slope profiles. Slope aspect was recorded using a transit compass. Appendix 3 includes all data related to slope geometry.

3.2.2 Slope Stratigraphy

A stratigraphic cross-section was prepared for each site incorporating the stratigraphic details into previously prepared slope profile. This was accomplished by creating polygons joining x and y coordinates of the lithologic contacts, determined by the laser range finder, using ArcGIS. Borehole logs from 15 of the drilled sites were used to cross check the stratigraphy established by using the laser range finder. Appendix 4 includes stratigraphic cross-sections for the individual sites and Appendix 5 contains borehole logs for the 15 drilled sites.

3.2.3 Data Collection on Existing Slope Face

3.2.3.1 Hardness and Rock Quality Designation (RQD) Data

Data regarding hardness values of rock units were collected and rock quality designation (RQD) estimates were made in the field for the 26 sites. Hardness was qualitatively determined using the hardness scale given in Table 3.3. RQD is defined as the sums of the lengths of core pieces greater than 4 inches (10 cm) divided by the total length of the core examined, expressed as a percentage. This definition of RQD applies for determining RQD values for core samples. RQD for various rock units outcropping on the slope face was estimated using the Palmstrom's method (Palmstrom, 1982), which estimates RQD from the number of joints within a cubic meter of outcrop rock. The formula used is:

Table 3.3: Hardness scale and identification techniques (Piteau, 1977)

Hardness Code	Field Identification
S1	Easily penetrated several inches by fist.
S2	Easily penetrated several inches by thumb.
S3	Can be penetrated several inches by thumb with moderate effort.
S4	Readily indented by thumb but penetrated with great effort.
S5	Readily indented by thumbnail.
S6	Indented with difficulty by thumbnail.
R0	Indented by thumbnail.
R1	Crumbles under firm blows with the point of a geological pick; can be peeled with a pocket knife.
R2	Can be peeled with a pocket knife with difficulty; shallow indentation made by a firm blow of a geological pick.
R3	Cannot be scratched or peeled with pocket knife; specimen can be fractured with single firm blow of the hammer end of a geological pick.
R4	Specimen requires more than one blow with the hammer end of a geological pick to fracture it.
R5	Specimen requires many blows with the hammer end of a geological pick to fracture it.
R6	Specimen can only be chipped with a geological pick.

$$RQD = 115\text{-}3.3\ J_v,$$

where J_v is the total number of joints in three mutually perpendicular directions within a cubic meter of rock mass. Appendix 6 summarizes the hardness and RQD data for rock outcrops.

3.2.3.2 Discontinuity Data

Discontinuity data for the 26 sites were collected using the detailed line survey method (Piteau and Martin, 1977), the window mapping method, and random measurements. A detailed line survey consists of stretching a measuring tape horizontally on the slope face and recording the desired information about each discontinuity crossed by the tape. In this study, the survey was performed on one accessible competent rock unit and, in some cases, on one accessible incompetent rock unit from each site. Based on visual observations, a representative portion of the rock layer was chosen and, in most cases, discontinuities were measured along an approximately 100 ft (30 m) long line, crossing 40-100 discontinuities. Where the line survey was difficult to perform due to safety considerations, window mapping of discontinuities was done. Window mapping involves measuring all discontinuities within a representative area or "window", rectangular or square, of fixed size (30 ft/10 m), spaced at regular intervals along the exposure (Wyllie and Mah, 2004). Random measurements were also made to include discontinuities not recorded by the detailed line survey or window mapping methods.

Discontinuity orientation (strike and dip) measurements were made using a transit compass. Discontinuity spacing was calculated by dividing the length of the survey line by the number of discontinuities intercepted by the line. Discontinuity aperture was measured using a ruler. The continuity of discontinuities was determined using a ruler and was recorded as: (i) very low continuity (< 3.3 ft/1m), (ii) low continuity (3.3-10 ft/1-3 m), (iii) medium continuity

(10-33 ft/ 3 m-10 m), (iv) high continuity (33-66 ft/10 m-20 m), and (v) very high continuity (> 66 ft/20 m). Appendix 7-A includes discontinuity orientation, spacing, aperture, continuity, and ground water flow conditions data, Appendix 7-B contains stereographic plots of discontinuity orientation data, and Appendix 7-C contains discontinuity spacing and bedding thickness data.

3.2.3.3 Undercutting Data

Total amount of undercutting was measured using a measuring tape for accessible layers and a laser range finder for inaccessible layers. The presence of pre-split blast hole markings on the undercut unit was used as reference to ensure that the undercut unit had remained intact since the time of construction. For sites where pre-split blast hole markings were absent, original design plans of the cut slopes, obtained from ODOT, were used in conjunction with the current slope profiles to estimate the amount of undercutting since construction. The total amount of undercutting for each site was divided by the age of the cut to determine the rate of undercutting. The total amount of undercutting and the rate of undercutting data for the 26 project sites and 23 additional sites are presented in Appendices 8-A and 8-B, respectively, and data pertaining to thicknesses of the undercut rock units are included in Appendix 8-C.

3.2.3.4 Hydrologic Data

Ground water flow conditions for each of the 26 sites were evaluated qualitatively and recorded as part of the discontinuity data. The following categories of water flow were identified: (i) dry with no possibility for water flow, (ii) dry with no evidence of water flow, (iii) dry with evidence of water flow, (iv) damp with no free water present, (v) seepage observed with occasional drop of water, and (vi) continuous flow of water observed. The ground water flow data are presented in Appendix 7-A along with other data on discontinuity aspects.

3.2.4 Catchment Ditch Data

The width and depth of catchment ditches were measured for each of the 26 sites. A measuring tape was stretched from the edge of pavement to the toe of a given slope. The distances from the edge of pavement to the beginning of the catchment ditch, to the deepest part of the ditch, and to the toe of the slope were designated as X1, X2, and X3, respectively. The difference between X3 and X1 was taken as the width of the catchment ditch. The depth of the ditch was measured at X2. These measurements were taken at 4 to 5 locations along the ditch length, and average values of width and depth were obtained. Catchment ditch data are presented in Appendix 9.

3.2.5 Data collection from Core Drilling

As stated previously, 15 of the 26 sites were drilled to obtain additional information about stratigraphy and rock mass characteristics. The drilled sites included ADA-32-12, ADA-41-15, ATH-33-14, BEL-7-10, BEL-70-22, BEL-470-6, CLA-68-6, CLE-275-5, GUE-77-8, HAM-126-12, LAW-52-11, LIC-16-28, MEG-33-6, RIC-30-12, and STA-30-27. The drilling locations had to be chosen at various distances from the edges of the cut slopes due to property-rights considerations and drilling-equipment accessibility problems. Therefore, in some cases, lithologic units crossed by the boreholes are not of the same thickness as the corresponding units outcropping on the slope face.

3.2.5.1 Borehole Logs

Detailed borehole logs were prepared for all 15 sites that were drilled. The logs include brief descriptions of the lithologic units encountered in the boreholes, depths of various lithologic units from the ground surface, location of ground water table, if present, and

information about RQD and percent recovery. Appendix 5 includes the borehole logs for the 15

sites.

3.2.5.2 Percent Recovery and RQD Data

Percent recovery and RQD were determined for the entire core from all 15 sites. Percent

recovery is defined as the ratio of the length of core recovered to the length drilled, expressed as

a percentage. Percent recovery depends upon soundness of rock and quality of drilling. Based on

percent recovery, rock quality is categorized as: (i) sound, homogeneous rock: – recovery > 90

%, (ii) rock with seams of weak material – recovery: 50-90 %, and (iii) decomposed rock -

recovery: 0-50 % (Deere et al., 1967). RQD indicates rock quality in terms of joint spacing.

Based on RQD values, rock quality is categorized as: (i) excellent - RQD = 90-100 %, (ii) good -

RQD = 75-90 %, (iii) fair – RQD = 50-75 %, (iv) poor – RQD = 25-50 %, and (v) very poor –

RQD = 0-25 % (Deere et al., 1967). Percent recovery and RQD data are included in the borehole

logs provided in Appendix 5.

3.2.6 Sampling of Various Lithologic Units

Three samples, each weighing approximately 30 pounds (13.6 kg), were collected from

the accessible layers of competent and incompetent rocks at the 26 sites. A sledge hammer was

used to break samples from competent units. Samples from the incompetent units were dug out

from 1-2 ft (0.3-0.6 m) depth to ensure that they were obtained from fresh bedrock. Core samples

were taken from the zones that corresponded to the lithologic units sampled on the cut-slope

face. One hundred and three outcrop samples of competent rock and 69 outcrop samples of

incompetent rock were collected during the field investigation stage. In addition, 56 core samples

of competent rock and 86 core samples of incompetent rock were collected. Outcrop and core

samples of incompetent rock were wrapped in plastic bags to preserve natural water content and prevent disintegration. A total of 314 samples were tested for unconfined compressive strength and slake durability index as discussed in the following sections.

3.3 Evaluation of Site Performance

Site performance was evaluated in terms of various types of failures (rockfalls, plane failures, wedge failures, toppling failures, mudflows) affecting the cut slopes, raveling problems, and gully erosion. Photographs of various types of failure affecting the sites are shown in Appendix 2. The performance was also evaluated in light of the age of the cut and whether the catchment ditch and any retaining structures were effective in preventing the failed material from reaching the road. Based on visual observations site performance was categorized as: good performance (limited rockfall activity; no evidence of erosion; catchment ditch generally clean); fair performance (moderate rockfall activity or gully erosion; catchment ditch contains many rock blocks of varying sizes); poor performance (extensive rockfall activity; slope severely degraded or exhibits extensive gully erosion; catchment ditch contains numerous rock blocks of varying sizes). Lastly, site performance was evaluated in terms of the effectiveness of existing slope design. Information about site performance is provided in Chapter 4.

3.4 Laboratory Investigations

3.4.1 Unconfined Compressive Strength

Unconfined compressive strength of both competent and incompetent rock units was determined using the point load test. The test was performed in accordance with the specifications of the International Society for Rock Mechanics (ISRM) (ISRM, 1985). Approximately 10 to 20 pieces of rock from each sample were failed by the point load tester to determine the point load index (I_s). For some core samples, however, fewer than 10 pieces were

tested because of the insufficient amount of sample available, especially of incompetent rock. All block samples of competent rock, taken from the slope face, were drilled in the laboratory to prepare NX-size core samples for the point load test. The uncorrected point load strength index (I_s) for all core samples was calculated as follows:

$$I_s = P/D_e^2$$

where: $D_e^2 = 4A/\pi$

$A = WD$ = minimum cross-sectional area of a plane through the platen contact points

(W = sample width or diameter; D = platen separation)

The I_s values were then corrected to correspond to a 50-mm diameter core sample by multiplying with a size correction factor, F, as follows:

$$I_{s50} = F \times I_s$$

Where: $F = (D_e/50)^{0.45}$

For outcrop samples of incompetent rock that could not be drilled in the laboratory because of their weak nature, I_s values were computed by dividing the failure load by the square of platen separation and converted to I_{s50} using the correction chart by Broch and Franklin (1972).

The point load test was performed on 314 samples of which 159 were of competent rock (103 outcrop samples, 56 core samples) and 155 of incompetent rock (69 outcrop samples, 86 core samples). The unconfined compressive strength (UCS) for competent rock units was determined by multiplying I_{s50} with a conversion factor of 24 (ISRM, 1985). In order to verify the use of 24 as the conversion factor for competent rocks from Ohio, selected core samples of sandstone and limestone rock from the study area were tested by using both the point load test (ISRM, 1985) and the American Society for Testing and Materials (ASTM) method D 2938 for

unconfined compressive strength (ASTM, 1996). A correlation between the results of the two

tests (Figure 3.4) indicated a conversion factor of 25.8. Therefore, it was decided to use a

conversion factor of 24 for all competent rock samples, as suggested by ISRM (1985). However,

the use of 24 as a conversion factor for incompetent rock samples consistently overestimated the

UCS. Thus, selected core samples of the incompetent rock units were also failed using both the

point load test and the standard ASTM methods. However, a plot of the results from the two tests

(Figure 3.5) did not indicate any correlation that could be used to determine a reliable value of

conversion factor. Greene (2001) conducted extensive research on the relationship between UCS

and I_{s50} and found a conversion factor of 9.5 for all clay bearing rocks, 8.5 for mudshales and

16.6 for siltstones. Based on these results and consultation with the consultants involved in this

project, a conversion factor 10 was chosen for incompetent rocks tested in this study.

3.4.1.1 Determination of Unconfined Compressive strength for Outcrop Samples

Unconfined compressive strength was determined by point load test for 166 outcrop

samples (samples from the existing slope face) from the 26 project sites, including 108 samples

of competent rock and 58 samples of incompetent rock. The Unconfined compressive strength

data for outcrop samples are given in Appendix 10-A.

3.4.1.2 Determination of Unconfined Compressive Strength for Core Samples

Unconfined compressive strength was determined for 134 core samples, using the point

load test, including 59 samples of competent rock and 75 samples of incompetent rock.

Additionally, 7 core samples (2 of limestone, 5 of sandstone) of competent rock and 17 core

samples of incompetent rock (7 of shale, 9 of claystone/mudstone, 1 of siltstone) were tested by
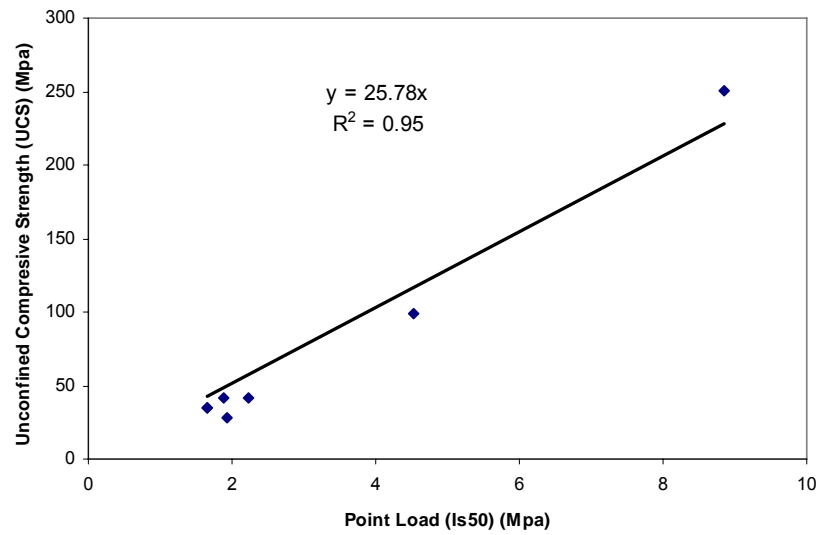
Figure 3.4: Relationship between Is_{50} and UCS for selected samples from competent rock units.
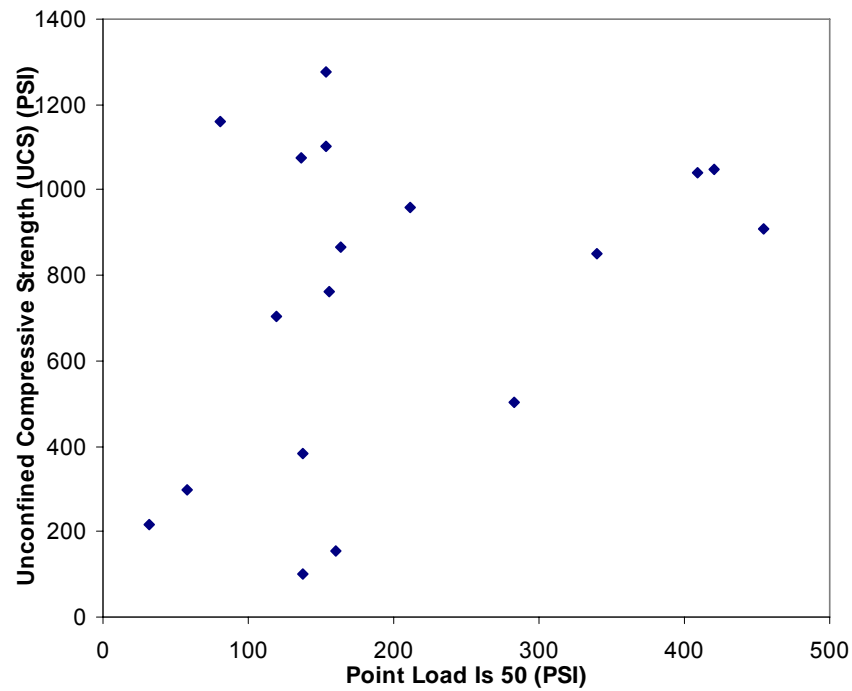
Figure 3.5: Relationship between Is_{50} and UCS for selected samples from incompetent rock units.

the ASTM method. As stated previously, data from these samples were used to determine conversion factors needed to convert point load index to compressive strength. Unconfined compressive strength data for core samples are provided in Appendix 10-B.

3.4.2 Slake Durability Index

Slake durability index, which represents the resistance of a rock to weathering and disintegration upon exposure to moisture, was determined for outcrop and core samples by performing the slake durability index test in accordance with ASTM method D 4644 (ASTM, 1996). The sample for slake durability test consisted of 10 pieces, each weighing between 40-60 g, with a total weight of 450-550 g. The sample was oven dried for 24 hours at 105° C, cooled to room temperature, placed in a 2-mm wire mesh drum, and rotated in a tank of water for 10 minutes at 20 rpm. The material retained in the drum was oven dried for 24 hours at 105° C. The slake durability index was computed by dividing the dry weight of the material retained in the drum by the original dry weight of the sample, expressing the ratio as a percentage. Two cycles of the test were run for each sample to determine the second-cycle slake durability index (Id_2).

3.4.2.1 Determination of slake Durability Index for Outcrop Samples

Second-cycle slake durability index was determined for 207 outcrop samples, including 115 samples of competent rock and 92 samples of incompetent rock. These samples were obtained from the 26 project sites and the 23 additional sites. Slake durability test data for outcrop samples is shown in Appendix 10-A.

3.4.2.1 Determination of Slake Durability for Core Samples

Slake durability test was performed on 142 core samples of which 56 consisted of competent rock and 86 of incompetent rock. The test results for core samples are provided in Appendix 10-B.

3.4.3 Friction Angle

The basic friction angle, used for kinematic analysis for competent rock units, was determined using the tilt test proposed by Stimpson (1981). The test consisted of placing two unprepared cores of the rock on a horizontal base in contact with each other. A third core of the same rock was placed on top of the two, forming a pyramid. The two base cores were restricted from sliding but the top core was free to slide. The base on which the cores were placed was slowly tilted until the top core slid. The angle of tilt (α) was recorded and the basic friction angle calculated using the following equation:

Tan ϕ = 1.115 x tan (α)

The tilt test was performed on sandstone and limestone cores. The test was repeated several times on each set of cores and the average tilt angle was used to determine the friction angle. The basic friction angle values are reported in the next chapter on data presentation.

3.4.4 Index Properties

Index property testing included determination of density for selected core samples and Atterberg limits for incompetent rock samples that had Id_2 values less than 80 %.

3.4.4.1 Determination of Density for Core Samples

Density was determined for 11 core samples of competent rock (4 limestone, 7 sandstone) and 21 core samples of incompetent rock (13 shale, 8 claystone/mudstone). Five measurements each of core diameter and length were taken to determine average core volume in cubic centimeters. The weight of each core sample, oven-dried for 24 hours at 105° C for 24 hours, was measured to the nearest tenth of a gram. These measurements were used to calculate density values in g/cm^3 that were then converted to lb/ft^3. Density values are reported in Appendix 11-A.

3.4.4.2 Determination of Atterberg Limits for Incompetent Rocks

Determining slope angle for incompetent rocks using the Franklin's shale rating system, as described in the Chapter 1, required the plasticity index values for the incompetent rock units with Id_2 values less than 80 %. Plasticity index is the difference between liquid limit and plastic limit of a fine-grained soil. Liquid limit and plastic limit are referred to as the Atterberg limits. Plastic limit is the minimum water content at which a soil changes from a solid state to a plastic state and liquid limit is the minimum water content at which a soil-water mixture changes from a plastic to a viscous liquid state (Holtz and Kovacs, 1981). The Atterberg limits test was performed on all samples of incompetent rock that had Id_2 values less than 80 %. Samples for Atterberg limits test were prepared by subjecting them to multiple wetting and drying cycles until 125g of material passing the No. 40 sieve was obtained. The material passing the sieve was used to determine the liquid limit, plastic limit, and plasticity index values in accordance with ASTM method D 4318 (ASTM, 1996). Appendix 11-B summarizes the Atterberg limits test data.

<u>3.5 Data Analysis</u>

3.5.1 Statistical and Stereonet Analyses

Microsoft Excel was used to draw histograms and determine descriptive statistics (range, mean, mode, standard deviation, confidence interval) of quantitative data (slope angle, slope height, total thickness of the undercut unit, bedding thickness within the undercut unit, discontinuity orientation, discontinuity spacing, RQD, total amount of undercutting, rate of undercutting, unconfined compressive strength, slake durability index, plasticity index). Descriptive statistics of data are provided in Appendix 12. Discontinuity orientation data were plotted and major discontinuity sets were identified using the stereonet software, DIPS (Appendix 7-B). The DIPS software was also used to determine the mean orientation values of discontinuity sets.

3.5.2 Stability Analysis

In order to perform slope stability analysis and develop design criteria, it was necessary to define the design units. For this research, a design unit is defined as a portion of a slope, or the entire slope, that can be cut at a unique stable angle. A design unit can be selected on the basis of its characteristic lithology and the anticipated slope failures. Based on these considerations, the following three design units were identified for Ohio:

1. Competent Rock Design Unit: consists of > 90 % of competent rocks including limestones, sandstones, and siltstones with the incompetent material (< 10 %) occurring evenly as thin layers. If the incompetent material occurs in layers thicker than 3 ft (1 m), the unit should be treated as an inter-layered design unit. The failures anticipated to occur in this design unit are those controlled by unfavorable orientation of discontinuities (plane, wedge, or toppling failures) or by low rock mass strength (rotational slides).

2. Incompetent Rock Design Unit: consists of > 90 % of incompetent rocks including shales, claystones, and mudstones with the competent material (< 10 %) occurring evenly as thin layers. If the competent material occurs in layers thicker than 3 feet (1 m), the unit should be treated as an inter-layered design unit. The anticipated slope stability problems in this design unit include raveling and mudflows.

3. Inter-layered Rock Design Unit: consists of inter-layered competent and incompetent rock units, each ranging in proportion from more than 10 % to 90 %. Undercutting-induced failures (rockfalls) are the anticipated failures in this design unit.

For the sake of brevity, the word "rock" will not be used while referring to a design unit in the remainder of this report. For example, "competent rock design unit" will be referred to simply as "competent design unit".

3.5.2.1 Stability Analysis of Slopes Consisting of Competent Design Units

Kinematic analysis, based on Hoek and Bray (1981) and Goodman (1989), was conducted for all slopes consisting of competent design units to evaluate the potential for discontinuity-controlled failures. Two types of software, RockPack III and DIPS, were used for this purpose. In addition, a quantitative approach for kinematic analysis, using Microsoft Excel, was also developed for this study.

SLIDE software was used to determine the factor of safety against a rotational slope failure due to low rock mass strength. In SLIDE, a slope profile was drawn and the parameters described in Chapter 1, such as GSI value, intact rock strength, disturbance factor, and mi values, were entered to determine the factor of safety for a selected number of failure circles. The result of the analysis was the location of the failure circle with the smallest factor of safety value.

3.5.2.2 Stability Analysis of Slopes Consisting of Incompetent Design Units

Slopes consisting of incompetent design units were analyzed using the Franklin shale rating system (Franklin, 1983), and the talus material angle and natural slope angle methods. Application of Franklin shale rating system involved using the point load index (Is_{50}), slake durability index (Id_2), and plasticity index (PI) to rate the incompetent units and determine stable slope angles against rotational failures from the graphs provided by Franklin (1983).

The angles of talus material accumulating at the bases of slopes consisting of incompetent units and the slope angles of adjacent natural slopes were measured. The natural angles are considered to be the final stable angles that slopes consisting of incompetent units are likely to attain after undergoing weathering and erosion. The angle of talus material was measured using a transit compass during the field investigation stage. The natural slope angles adjacent to slopes consisting of incompetent units were determined using raster GIS techniques. Digital elevation models (DEMs), 10 m x 10 m, were downloaded from http://seamless.usgs.gov/index.php and ARCGIS was used to calculate the natural slope angles. Histograms of natural slope angles were plotted and univariate statistics were calculated using Microsoft Excel. Talus angles and natural slope angles were used to compliment the angles derived from Franklin's shale rating system. Additionally, The SLIDE program, as described in the previous section, was used to calculate the factor of safety against rotational failures due to low rock mass strength of incompetent rocks.

3.5.2.3 Stability Analysis of Slopes Consisting of Inter-layered Design Units

The most common type of slope failure in Ohio is the undercutting-induced rockfalls that result from differential weathering of inter-layered competent and incompetent units. A rational method for analysis and design of cut slopes subject to differential weathering cannot be found in

literature. Therefore, an important objective of this research was to investigate the factors affecting the undercutting of competent rock units by weathering of the underlying incompetent rock units and suggest an appropriate method for slope analysis and design.

The main aspects of undercutting-induced rockfalls include the total amount of undercutting, the amount of rockfalls, and the fate of generated rockfalls. Bivariate and multivariate statistical methods were used to identify the geological and geotechnical parameters that influence these three aspects. SPSS (statistical package for the social sciences) and Microsoft Excel software were used for statistical analysis of these aspects. The fate of rockfalls with respect to the effect of slope height, slope angle, and catchment ditch dimensions was evaluated using the rockfall simulation software, RocFall (Rocscience, 2003). RocFall determines the trajectory and the landing place of a rockfall generated from any point on the slope face. RocFall is similar to the widely used Colorado Rockfall Simulation Program (CRSP).

The above described statistical methods identified the factors that have the most significant influence over the expected amount of undercutting, expected amount of rockfalls, and the fate of rockfalls. This information was then used to suggest an appropriate slope design (slope angle, bench width and location, stabilization techniques) for inter-layered strata that would minimize the effect of factors which were shown, statistically, to have the most impact on the stability of slopes subject to differential weathering.

The Franklin shale rating system was used to determine slope angles that reduce the chance of a rotational failure. Weighted average values of Is_{50}, Id_2, and PI were used when applying the shale rating system for inter-layered design units. In addition, the SLIDE software was used to determine the factor of safety against a possible rotational failure due to low rock mass strength for slopes consisting of inter-layered competent and incompetent rock units.

CHAPTER 4

DATA PRESENTATION

This chapter presents the data collected during field and laboratory investigations. Microsoft Excel was used to draw histograms and obtain descriptive statistics (range, mean, median, mode, standard deviation, skewness, and kurtosis) for all data suitable for such analysis. The class sizes in the histograms are chosen so that they clearly show the distribution of data. The upper bound of each class in the histogram is labeled in the middle of each bar. For each histogram, the range, average, and population count, as computed by descriptive statistics, are given below the histogram. Outliers were excluded from descriptive statistics as they would have resulted in unrepresentative values. Stereonet software program DIPS was used to plot discontinuity orientations, identify discontinuity sets, and determine their descriptive statistics. Descriptive statistics of all data are included in Appendix 12.

4.1 Field Data

4.1.1 Geometrical Data

Geometrical data include slope angle, slope height, and slope aspect for the 26 study sites. Field data about slope geometry are presented in Appendix 3 and descriptive statistics for these data are provided in Appendix 12-A.

4.1.1.1 Slope Angle

Slope-angle data for competent, incompetent, and inter-layered rock units were analyzed separately. For competent rock units, the slope angle ranges from 45–80 degrees with an average of 68 degrees (Appendix 12-A). The frequency distribution of slope angle for competent units is

right-skewed (Figure 4.1a), indicating that most slopes in competent rock have angles greater than 70 degrees. Slope angle for incompetent rock units ranges from 27–80 degrees with an average of 45 degrees (Appendix 12-A). The frequency distribution of slope angle for incompetent rocks is left-skewed (Figure 4.1b), indicating characteristically lower slope angles for incompetent rock units. Slope angle for inter-layered rock units ranges from 33–71 degrees with an average value of 49 degrees (Appendix 12-A). The frequency distribution of slope angle for inter-layered rock units is left-skewed (Figure 4.1c), indicating that angles between 40 and 50 degrees are more frequent. From the average values of slope angle, it is apparent that the slopes were cut considering the weathering characteristics of rocks comprising the slopes, using steeper angles for competent rock units, gentler angles for incompetent rock units, and intermediate angles for inter-layered rock units.

4.1.1.2 Slope Height

Slope height for the study sites ranges from 21-169 ft (6-52 m), with an average of 75 ft (23 m), except one site that has a height of 350 ft (107m) (Appendix 12-A). The frequency distribution of slope height is left-skewed (Figure 4.2), indicating that most sites have heights less than 100 ft (30 m).

4.1.1.3 Slope Aspect

Slope aspect was plotted on a rose diagram (Figure 4.3) to investigate if there was a predominant trend with respect to slope aspect. Figure 4.3 shows that SSW-facing slopes and NNE-facing slopes are the most frequent but W-facing, NW-facing, E-facing, and SE-facing slopes are also present at the study sites.
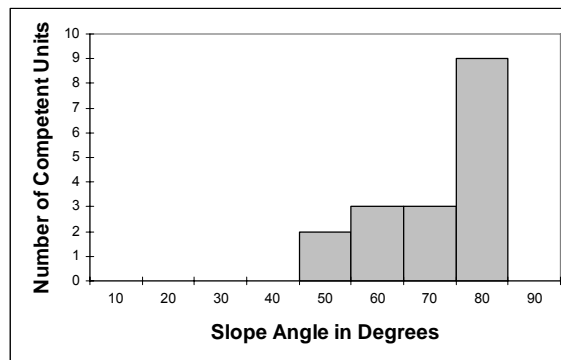
Range   Average   Count
45-80   68   17

(a)
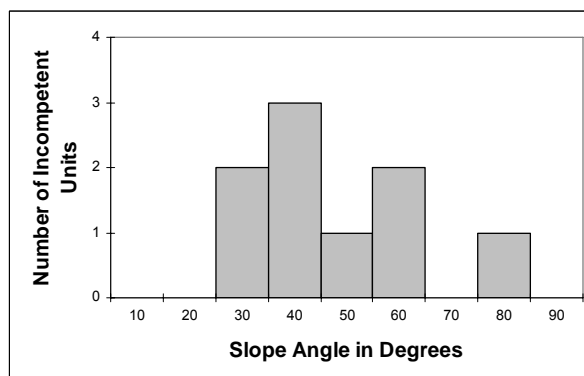
Range   Average   Count
27-80   45   9

(b)
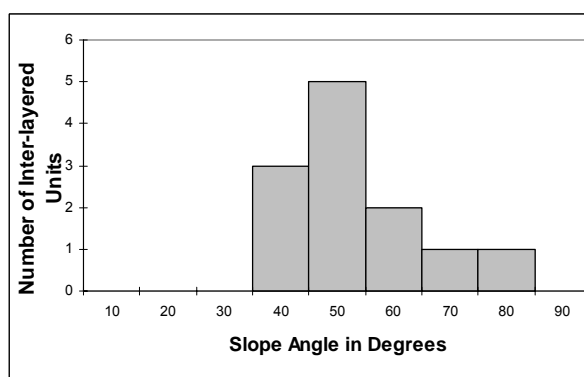
Range   Average   Count
33-71   49   12

(c)

Figure 4.1: Frequency distribution of slope angle for: (a) competent rock units, (b) incompetent rock units, and (c) inter-layered rock units.
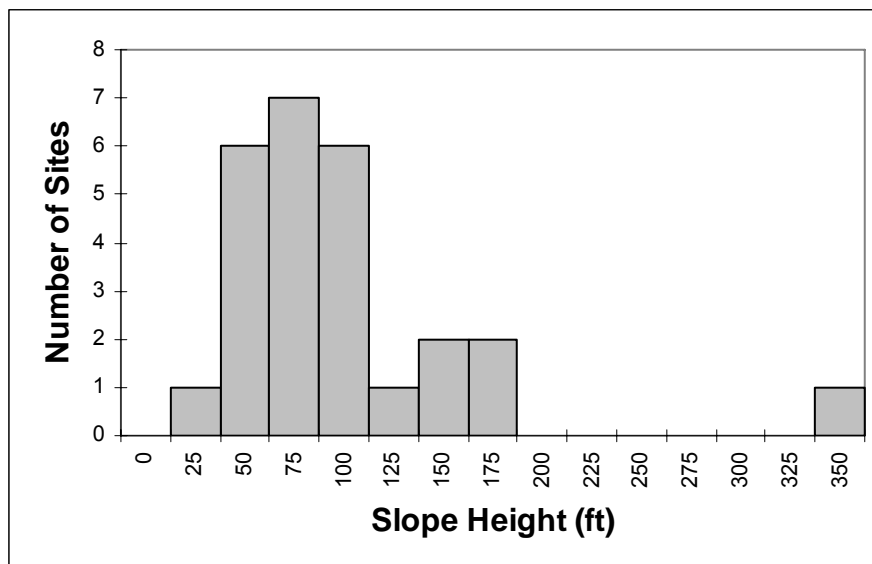
Range	Average	Count
21-169	75	25

Figure 4.2: Frequency distribution of slope height.
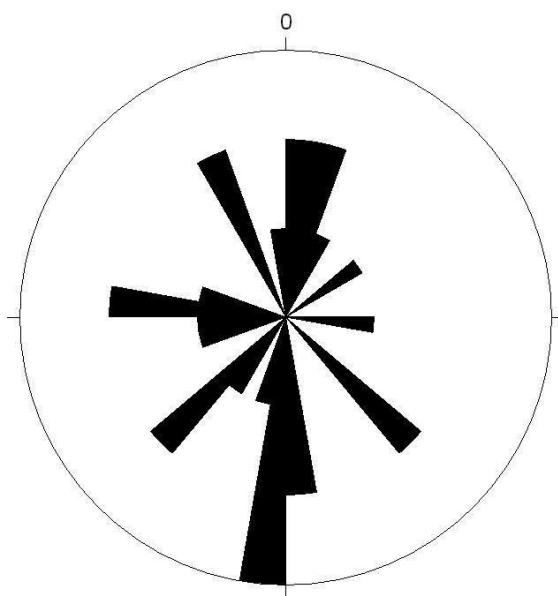
Figure 4.3: Rose diagram showing slope aspect.

4.1.2 Stratigraphic Cross-Sections

Stratigraphic cross-sections of the study sites are presented in Appendix 4 and examples of typical cross-sections for slopes comprised of competent, incompetent, and inter-layered competent and incompetent rock units are shown in Figures 4.4, 4.5, and 4.6, respectively. Appendix 1 contains photographs of all study sites which provide pictorial views of the stratigraphy. Competent rock units in the study area include limestones, dolomites, and sandstones. While preparing stratigraphic cross-sections, a distinction between limestones and dolomites was not made since both rock types exhibit very similar engineering behavior and slope stability problems. Therefore, only the term "limestone" is used in the stratigraphic cross-sections. The limestones at the study sites are further divided into fossiliferous and non-fossilifreous limestones as these two groups have notable differences with respect to their bedding thickness, fossiliferous limestones being thinly bedded. Fossiliferous limestone units belong to upper Ordovician formations and the non-fossiliferous limestones to upper and lower Silurian formations, Conemaugh group (upper Pennsylvanian), and Monongahela group (upper Pennsylvanian). One site, MUS-70-25, contains limestone belonging to the Allegheny and Pottsville groups (middle to lower Pennsylvanian). Ten of the 26 project sites and 9 of the 23 additional sites chosen for the study contain limestone units.

Sandstones, despite their differences in grain sizes and types of cement, are grouped together due to their similar behavior with respect to slope stability. Friable sandstones were observed to be significantly more weathered. Sandstones range in age from lower Mississippian to lower Permian. Most sandstone units at the study sites belong to the Allegheny, Pottsville, Conemaugh, and Monongahela groups. Fourteen of the 26 project sites and 7 of the 23 additional sites used contain sandstone units.

Inaccessible thinly bedded sandstone

Competent Design Unit
Sandstone: yellowish grey, slightly strong,
thickly bedded, moderately to slightly jointed
around the edges with the middle part being massive
Average unconfined compressive strength = 2925 psi
(core sample nos. 1-4)

Average slake durability index = 71 %
(core sample nos. 1-4)

RQD = 50 % (core depth 11-53 ft)

Representative core depth = 11- 53ft*

Black Hand Member of the Cuyhoga Formation (Lower Mississippian)

Elevation = 820 ft

1 in : 20 ft

0   5   10   20 Feet

Figure 4.4: Example of a stratigraphic cross-section for a slope comprised of entirely competent rock unit (LIC-16-28 site).

Incompetent Design Unit
Shale: yellowish grey, slightly strong,
moderately jointed
Average unconfined
compressive strength = 3854 psi
(outcrop sample no. 1)

Average slake durability index = 99 %
(outcrop sample no. 1)

RQD = 0 % (outcrop estimate)

Ohio Shale (Upper Devonian)

1 in : 10 ft

0   5   10   20 Feet

Figure 4.5: Example of a stratigraphic cross-section for a slope comprised of entirely incompetent rock unit (FRA-270-23 site).

Inter-layered Design Unit (15 % competent, 85 % incompetent)
Shale and claystone/mudstone inter-layered with sandstone
Sandstone: grey, strong, medium bedded, slightly jointed
to intact
Shale and claystone/mudstone: grey, weak
Sandstone average unconfined compressive strength = 12122 psi
(core sample nos. 5, 7, 12, 15)
Shale and claystone/mudstone average unconfined c
ompressive strength = 1565 psi
(core sample nos. 2, 3, 4, 6, 8, 9, 10, 11, 13, 14)
Weighted unconfined compressive strength = 3149 psi

Sandstone average slake durability index = 96 %,
(core sample nos. 5, 7, 12, 15)
Shale and claystone/mudstone average slake durability index = 83 %
(core sample nos. 2, 3, 4, 6, 8, 9, 10, 11, 13, 14)
Weighted slake durability index = 85 %

RQD = 85 % (core depth 26-118 ft)

Competent Design Unit
Sandstone: light brownish grey,
thickly bedded, not jointed
Average unconfined compressive strength = 3764 psi
(outcrop sample nos. 6, 9)

Average slake durability index = 90 %
(outcrop sample nos. 6, 9)

RQD = 100 % (core depth 118-159 ft)

Inter-layered Design Unit (57 % competent, 43 % incompetent)
Sandstone with minor limestone inter-layered with shale and claystone/mudstone
Sandstone: grey, strong, medium bedded, slightly jointed
to intact
Limesone: grey, strong, intact
Shale and claystone/mudstone: grey, weak
Sandstone average unconfined compressive strength = 7367 psi
(outcrop sample nos. 2, 3, 4, 7)
Limestone average unconfined compressive strength = 20745 psi
(outcrop sample nos. 8)
Shale and claystone/mudstone average unconfined compressive strength = 955 psi
(outcrop sample nos. 1, 5, 10)
Weighted unconfined compressive strength = 6135 psi

Sandstone average slake durability index = 97 %,
(outcrop sample nos. 2, 3, 4, 7)
Limesone average slake durability index = 99%
(outcrop sample nos. 8)
Shale and claystone/mudstone average slake durability index = 42%
(outcrop sample nos. 1, 5, 10)
Weighted slake durability index = 74 %

RQD = 85 % (core depth 26-118 ft)

*Thicknesses of various lithologic units
on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Representative core depth = 26 - 174 ft*

Allgheny and Pottsville Groups (Middle and Lower Pennsylvanian)

1 in : 30 ft   Elevation = 577 ft

0   10   20   40 Feet

.

Figure 4.6: Example of a stratigraphic cross-section for a slope comprised of inter-layered competent and incompetent rock units (LAW-52-11 site).

Incompetent units in the stratigraphic cross-sections are described as shales, claystones, and mudstones. These rocks were differentiated on the basis of presence or absence of fissility, with shales being fissile and claystones and mudstones being non-fissile. According to Potter et al. (1981), the distinction between claystones and mudstones depends on clay content. Since clay content cannot be determined without conducting a hydrometer analysis in the laboratory, claystones and mudstones are treated as one rock type in stratigraphic descriptions, referred to as claystones/mudstones. Most shales in the study area are silty in nature, and grey to dark grey in color. Upon weathering, shales produce sheet- like fragments whereas claystones and mudstones tend to turn into soil-like material. Shale outcrops belonging to the Ohio Shale formation (upper Devonian) are common. Shales are also associated with the sandstones belonging to the Allegheny, Pottsville, Conemaugh, Monongahela, and Dunkard groups (Lower Permian-Upper Pennsylvanian). Twelve of the 26 project sites and 10 of the 23 additional sites contain shales.

The claystone/mudstone units include the red, green, and gray varieties. The grey claystones/mudstones are mostly associated with the upper Ordovician age fossiliferous limestones. The green claystones/mudstones are commonly found with limestone units belonging to the Monongahela group. Red claystones/mudstones, often termed as redbeds, are associated with limestones and sandstones belonging to the Allegheny, Pottsville, Conemaugh, Monongahela, and Dunkard groups. Nine of the 26 project sites and 11 of the 23 additional sites contain claystones/mudstones.

4.1.3 Borehole Data

Borehole logs for the 15 drilled sites are presented in Appendix 5. The logs include a brief description of various rock units and information about RQD, percent recovery, and groundwater (if present) conditions. Borehole logs, and information available from historical

borings, were used to correct stratigraphic cross-sections for the 15 sites. Among the data collected during drilling, RQD was analyzed statistically and the results are presented in section 4.1.5 in conjunction with discontinuity data.

4.1.4 Hardness Data

Hardness of various rock units was rated in the field using the hardness scale given in Table 2.3 and the data are provided in Appendix 6. The hardness classes for limestone are R3 and R4 whereas sandstone falls in classes R2, R3, and R4. Shale units classify as S2 to S5, with some classifying as R1 and R2. The hardness classification for claystone/mudstone units ranges from S1 to S5.

4.1.5 Discontinuity Data

4.1.5.1 Discontinuity Orientation Data

Discontinuity orientation data (Appendix 7-A) for the competent rock units of the study sites were plotted on stereonets and contoured to determine principal joint sets (clusters of poles of discontinuities on the stereonets), using the DIPS software (Appendix 7-B). An exception to this is the CLA-68-9 and LAW-52-12 sites. This is because discontinuities are not well exposed at CLA-68-9 site and they were not measured at LAW-52-12 site due to its proximity to LAW-52-11 site. An example of a stereonet plot of contoured poles, showing various discontinuity sets and their corresponding great circles, is given in Figure 4.7.

Descriptive statistics for each discontinuity set (Fisher's k value, mean dip amount, mean dip direction, variability of each discontinuity set, and confidence interval around the mean), as provided by the DIPS software, are given in Appendix 12-B. Table 4.1 shows an example of the descriptive statistics for the stereoplot shown in Figure 4.7. The Fisher's k value is a measure of the tightness of the cluster of discontinuity poles (Borradaile, 2003). Large k values indicate a
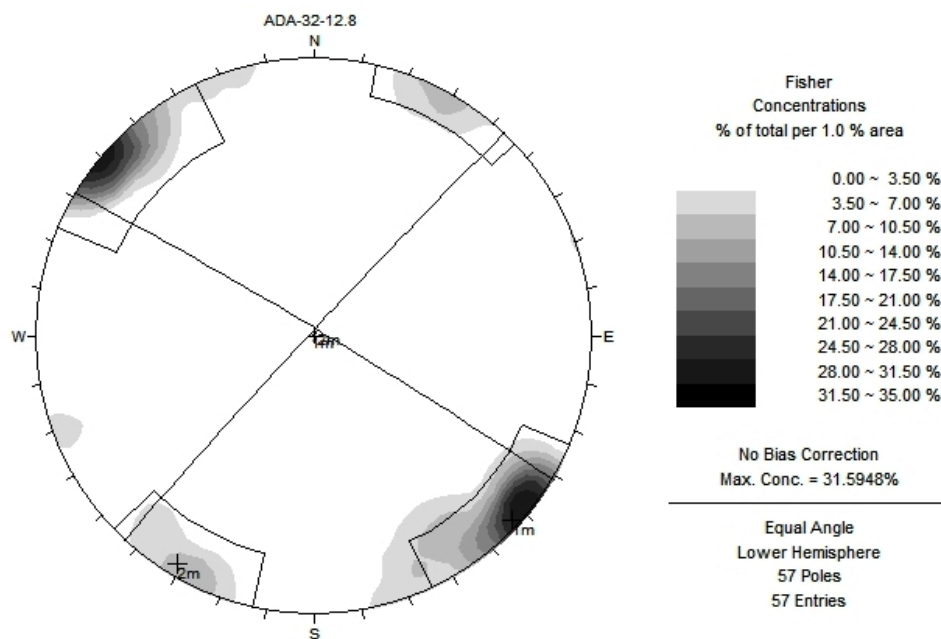
Figure 4.7: An example of contoured poles of discontinuities, with corresponding great circles representing discontinuity sets, drawn using the DIPS software program.

Table 4.1 Example of descriptive statistics obtained from the DIPS software program.

Site		ADA-32-12	
Set		1	2
Fisher's K		64.5	79.8
Dip		88.5	86.9
Dip Direction		313.2	31.19
Variability Interval	68.26%	10.8	9.73
	95.44%	17.79	15.99
Confidence Interval	68.26%	1.89	3.25
	95.44%	3.1	5.34
Count		33	9
Intersecting Sets		2/1	
Intersection Azimuth		16	
Intersection Plunge		87	

dense cluster, i.e. well developed discontinuity sets. The DIPS software program calculated the

mean dip amount and dip direction for each discontinuity set along with a circular confidence

interval (given in degrees) around the mean orientation of a set, based on the assumption that

discontinuity sets have circular distributions. The software program also calculated the

variability (in degrees) of orientation data within a discontinuity set. Figure 4.8 shows the means

of all discontinuity sets for all sites, along with their corresponding confidence circles, plotted on

one stereonet. It can be seen from Figure 4.8 that there is no preferred dip direction between the

sites. However, the average dip amount of all discontinuity sets is 79 degrees, indicating the sub-

vertical inclination of discontinuities across the sites.

In order to further explore the presence of any regional trends in discontinuity

orientations, rose diagrams showing discontinuity dip and azimuth trends were plotted using the

DIPS software (Appendix 7-B). Figure 4.9 shows rose diagrams for rocks belonging to different

age groups including the upper Ordovician, lower to upper Silurian, lower to upper

Mississippian, lower to upper Pennsylvanian, and upper Pennsylvanian to lower Permian. The

petals on the rose diagrams represent the frequency of dip directions. Lines representing strike

direction are manually drawn perpendicular to the most prominent dip directions. Table 4.2

summarizes the prevalent trends for different age groups. The NE-SW and NW-SE striking

discontinuities appear to be the most common for most age groups. However, the lower to upper

Pennsylvanian rocks do not exhibit any major trends.

Plunge and azimuth of the lines of intersection of discontinuity sets for each site are

plotted as poles in Figure 4.10. The azimuths of the intersection lines do not show any preferred

orientation (Figure 4.10).The average plunge of the lines of intersection of is 70 degrees. A plot
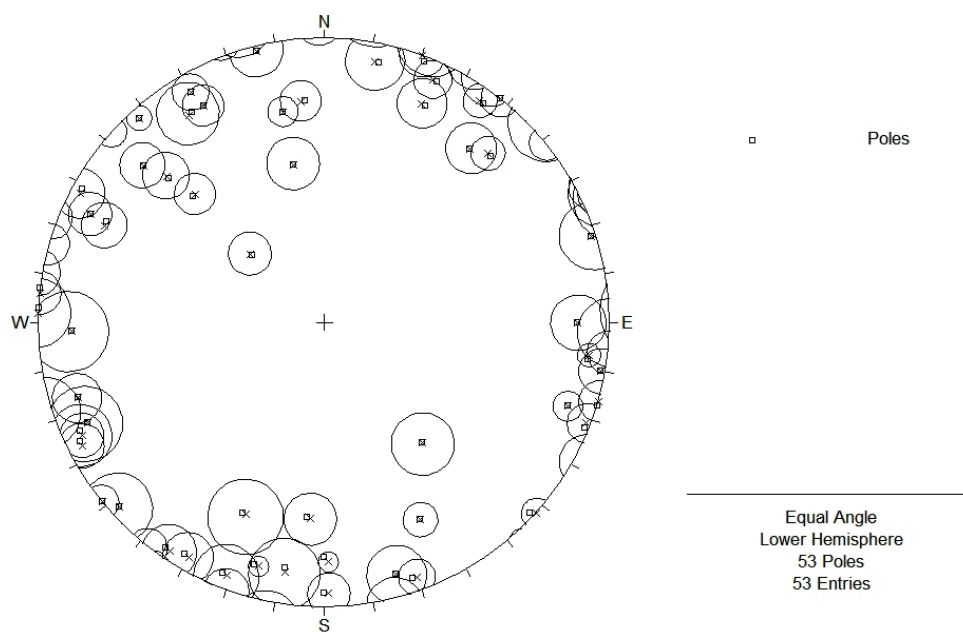
Figure 4.8: Stereoplot of mean orientation of poles for all discontinuity sets with their corresponding circles of confidence.

Upper Ordovician

Lower to Upper Silurian

n = 124

Lower to Upper Mississippian

n = 860

Lower to Upper Pennsylvanian

n = 204

Upper Pennsylvanian to Lower Permian
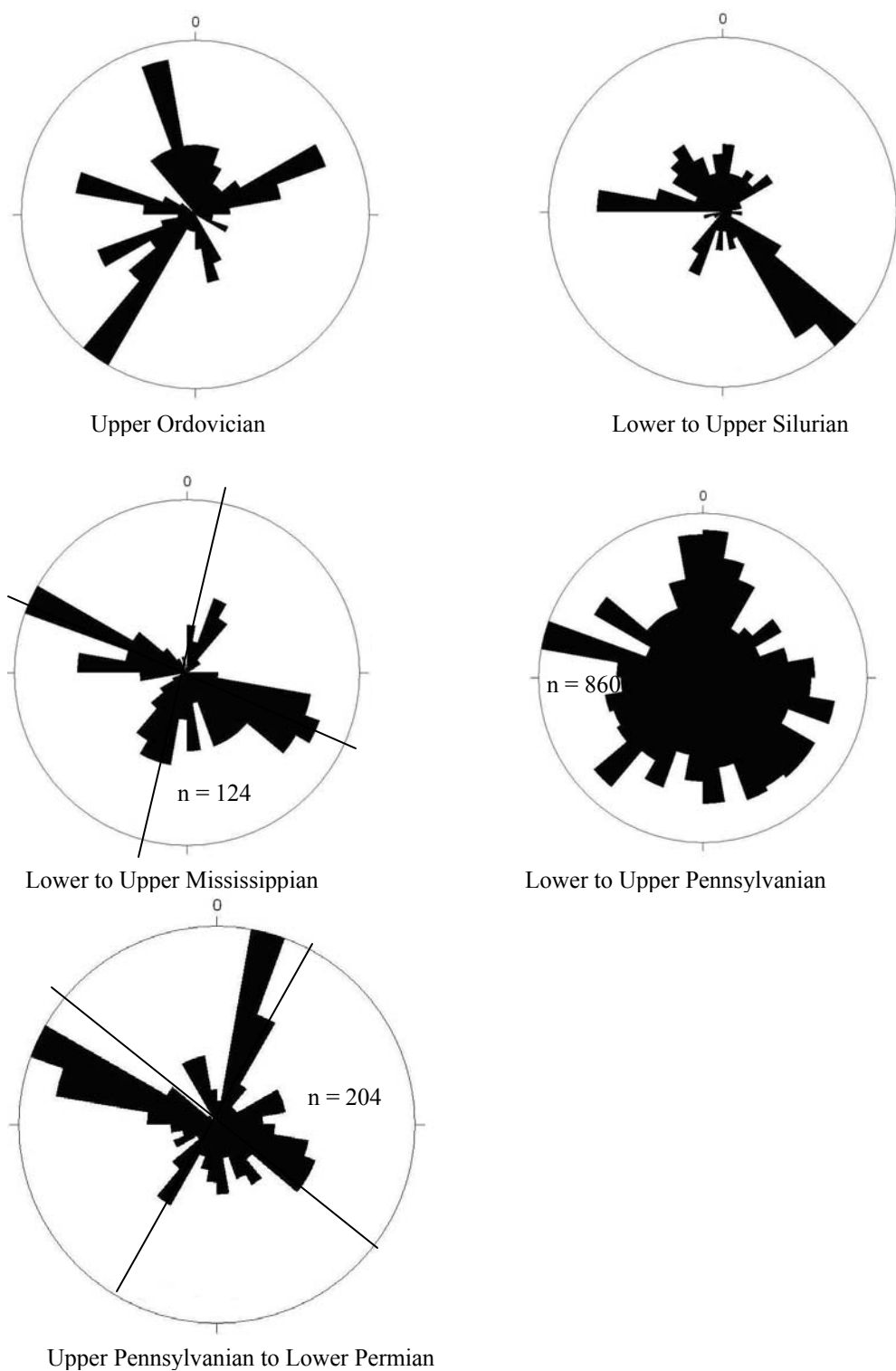
Figure 4.9: Rose diagrams of discontinuity azimuths for rock units belonging to different geological ages. Rose petals represent dip directions and lines represent prominent strike directions.

Table 4.2: Discontinuity-orientation trends for rocks of different ages.

Age	Prevalent Discontinuity Trend
Upper Ordovician	NE-SW, NW-SE
Lower to upper Silurian	N-S, NE-SW
Lower to upper Mississippian	NE-SW, WNW-ESE
Lower to upper Pennsylvanian	No preferential trend
Upper Pennsylvanian to lower Permian	NE-SW, NW-SE
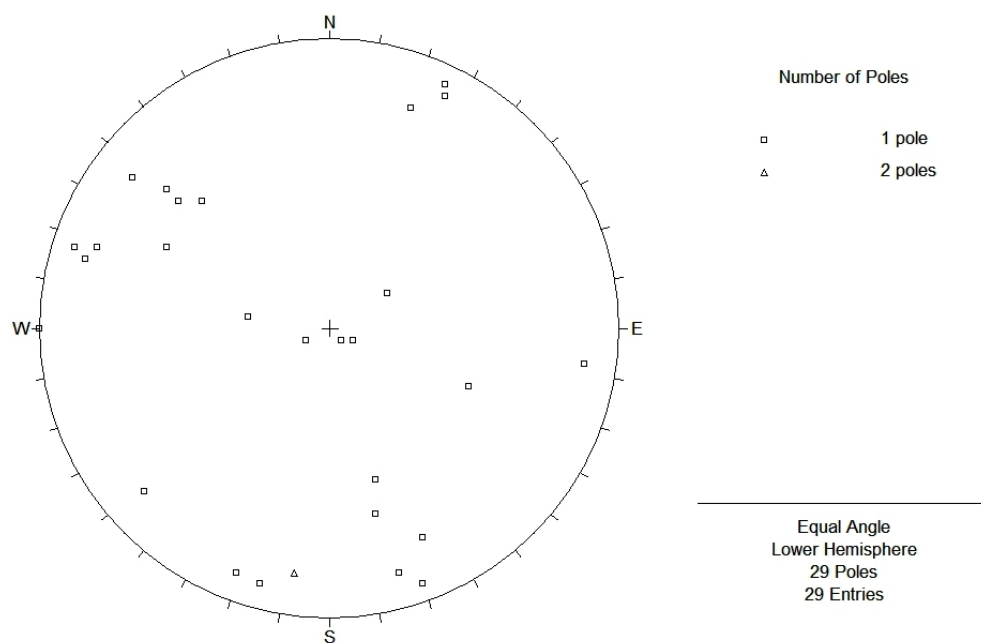
Figure 4.10: Plot of the poles of the lines of intersection of discontinuity sets.

of plunge values against percentage frequency shows that 70 % of the lines of intersection plunge at angles greater than 70 degrees (Figure 4.11).

4.1.5.2 Discontinuity Spacing Data

Discontinuity spacing data for orthogonal and stress relief joints, present in sandstone and limestone units, are presented in Appendix 7-C. The descriptive statistics for the spacing data are provided in Appendix 12-C. The spacing data for stress relief joints are limited because of their parallel orientation to the slope face. Therefore, only the spacing data for orthogonal joints is used for analysis.

Spacing for orthogonal joints from limestone units ranges from 3–42 inches (8–107 cm) with an average value of 16 inches (41 cm) (Appendix 12-C). Outliers having up to 30 ft (9 m) spacing exist. The distribution of spacing for limestone units is left-skewed (Figure 4.12), indicating that spacing between orthogonal joints is mostly less than 20 inches (50 cm).

Sandstone units have a more normally distributed population of joint spacing (Figure 4.13) with values ranging from 8-82 inches (20 cm-205 cm), having an average value of 34 inches (87 cm) and outliers measuring greater than 50 ft (15 m) (Appendix 1-C).

4.1.5.3 Discontinuity Aperture, Continuity, and Groundwater Flow Data

Aperture, continuity, and groundwater flow data, collected for orthogonal and valley stress relief joints, are presented in Appendix 7-A. The data were categorized qualitatively and quantitatively, assigning numerical codes that were averaged for each site.

Discontinuity aperture ranges from narrow (0.004-0.01in/0.1-0.25 mm) to wide (> 0.4 in/> 1 cm). The aperture of discontinuities at the study sites appears to be influenced by the type
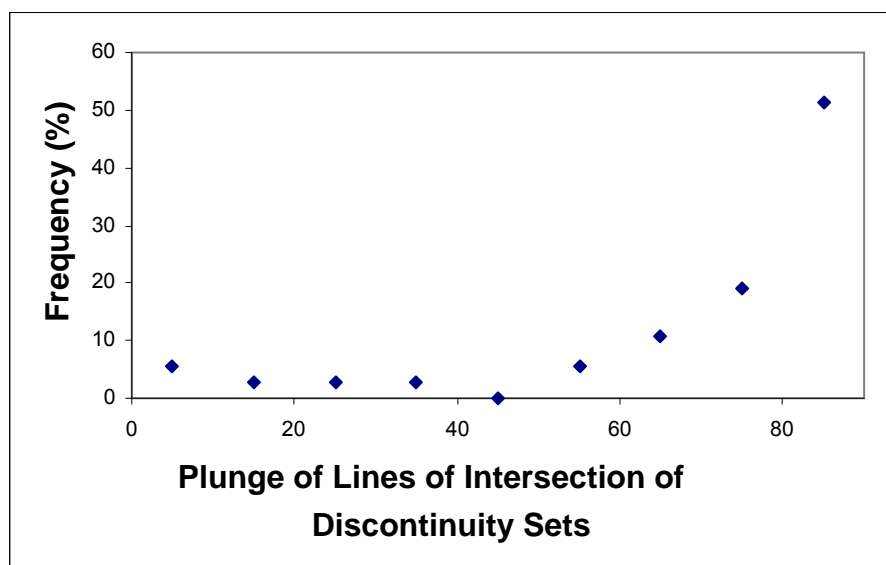
Figure 4.11: Frequency distribution of the mean plunge of the lines of intersection of discontinuity sets.
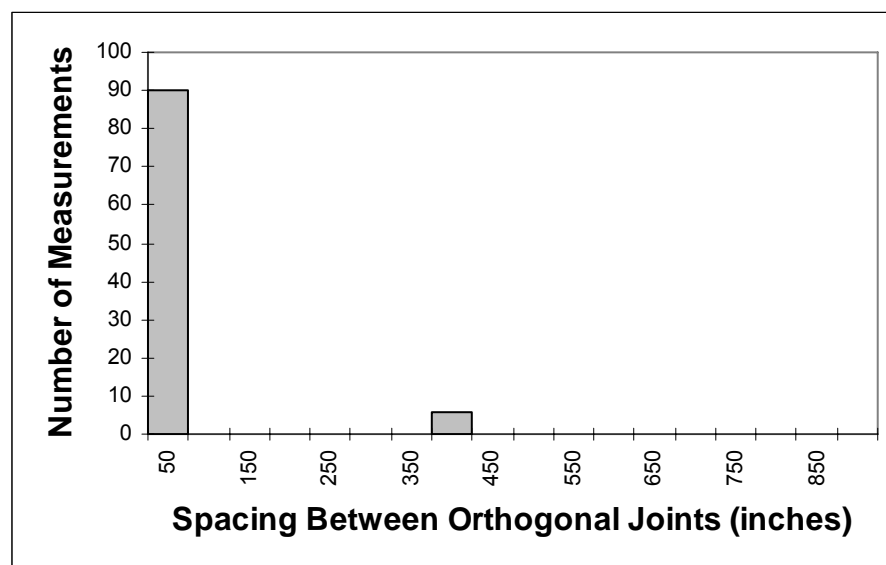
Range	Average	Count
3-42	16	90

Figure 4.12: Frequency distribution of spacing between orthogonal joints for limestone units.

Range	Average	Count
8-82	34	103
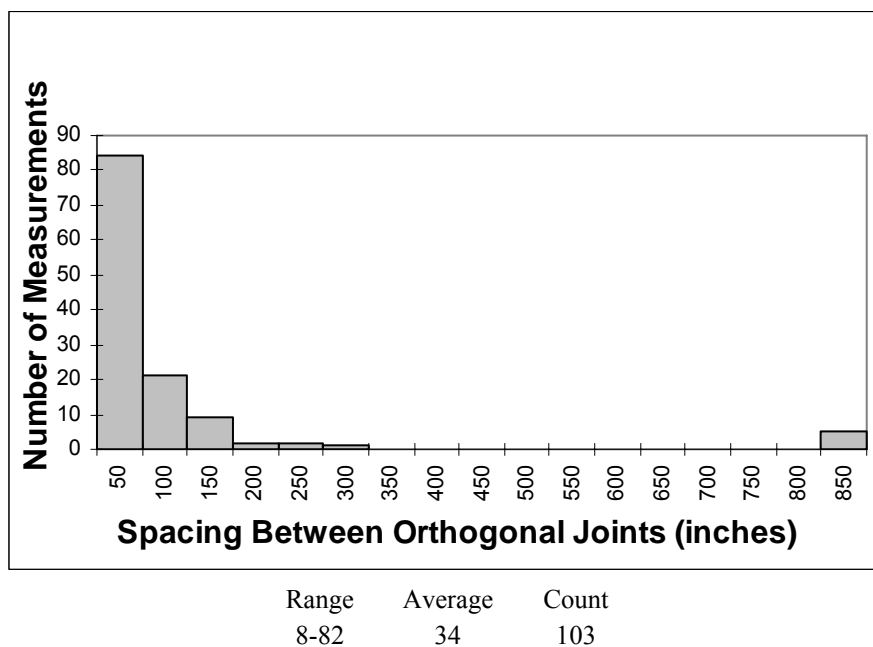
Figure 4.13: Frequency distribution of spacing between orthogonal joints for sandstone units.

of method used in constructing the slope (blasting versus excavation) and by the extent of slope

weathering. This makes aperture non-representative of the original rock mass behind the slope.

Continuity of discontinuities ranges from very low (< 3.3 ft/< 1 m) to low (3.3-10 ft/1-3

m). These values tend to suggest that discontinuities at the study sites are not continuous, but it

should be noticed that the competent rocks on which these measurements were taken are, in most

cases, less than 10 ft (3 m) thick. Therefore, most discontinuities are actually continuous within a

competent unit. Continuity data are presented in Appendix 7-A.

In terms of groundwater flow, most discontinuities were categorized as dry with evidence

of water seepage. Some discontinuities were rated as dry with no evidence of water flow and

some as damp. Groundwater flow estimation method used in this study is highly dependent on

the timing of observations with respect to rainfall periods. Groundwater flow data are included

in Appendix 7-A.

4.1.5.4 Rock Quality Designation (RQD)

Since RQD is a measure of discontinuity spacing, it is appropriate to discuss it alongside

other discontinuity data. RQD was measured both on rock outcrops and drilled core, as described

in Chapter 3. Appendix 6 contains RQD data for outcrops and Appendix 5 includes RQD data

for core samples. Descriptive statistics for RQD are provided in Appendix 12-C.

<u>RQD Data for Competent Rock Units</u>

Outcrop Data

RQD data distribution for limestone outcrops shows two populations (Figure 4.14).

Descriptive Statistics (Appendix 12-C) indicate that the first population has all values equal to

0% and the second population has values ranging from 77-100 % with an average of 91 %. The

Limestone (outcrop)

Range	Average	Count
77-100	91	8
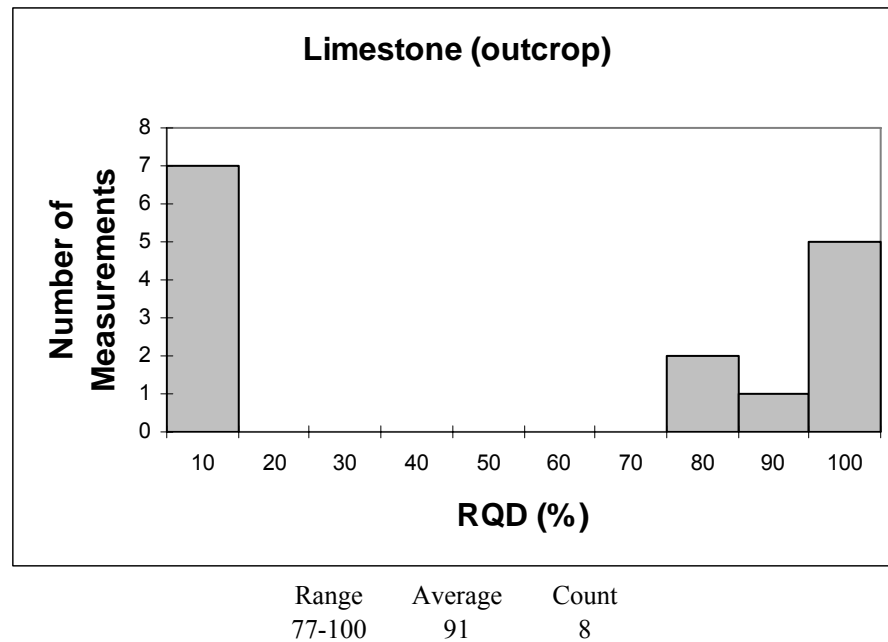
Figure 4.14: Frequency distribution of RQD for limestone outcrops.

limestones with 0% RQD are typically those which have desiccation cracks. RQD distribution for sandstone outcrops is right-skewed (Figure 4.15) with values ranging from 40-100 % and having an average of 79 % (Appendix 12-C). Some outliers have RQD values as low as 0 % (Appendix 12-C). RQD values for sandstone outcrops tend to vary from low near the edges of a cut to nearly 100% near the center of the cut. Overall, the right-skewed distributions of RQD for limestone and sandstone outcrops indicate the prevalence of greater than 90 % RQD values. Furthermore, limestone outcrops have higher values of RQD than sandstone outcrops.

Core Data

RQD values for limestone core range from 40–100 % with an average of 85 % (Appendix 12-C). The frequency distribution of RQD for limestone core is shown in Figure 4.16. Sandstone core shows two populations (Figure 4.17). The first population ranges from 0–50 % with an average value of 29 % and the second from 82 -100 % with an average value of 98 %. The two populations represent differences in sandstone types and depth of sampling. Lower values of RQD in most cases are typical of micaceous sandstones in which micaceous minerals are preferentially oriented parallel to bedding, facilitating core breakage along bedding. Overall, RQD populations for limestones and sandstones are right-skewed (Figures 4.16 and 4.17), indicating the prevalence of RQD values greater than 90 %. Limestone core has higher RQD values than sandstone core. Limestones bearing desiccation cracks, with 0% RQD values on outcrops, show higher RQD values for core samples as the cracks are sealed on fresh core samples. It should be noticed that RQD values are obtained from vertical drilling which misses the prominent sub-vertical joints and, therefore, RQD data do not indicate the actual extent of jointing in a given rock mass.

Sandstone (outcrop)

Number of Measuremnets vs RQD (%)

Range	Average	Count
40-100	79	14
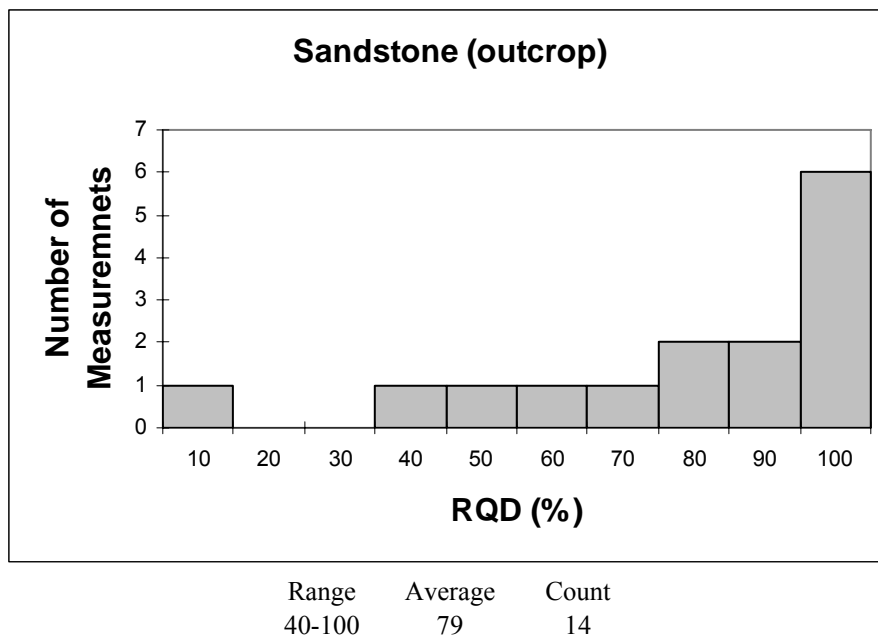
Figure 4.15: Frequency distribution of RQD for sandstone outcrops.

Limestone (core)

Number of Measurements vs RQD (%)

Range	Average	Count
40-100	85	19
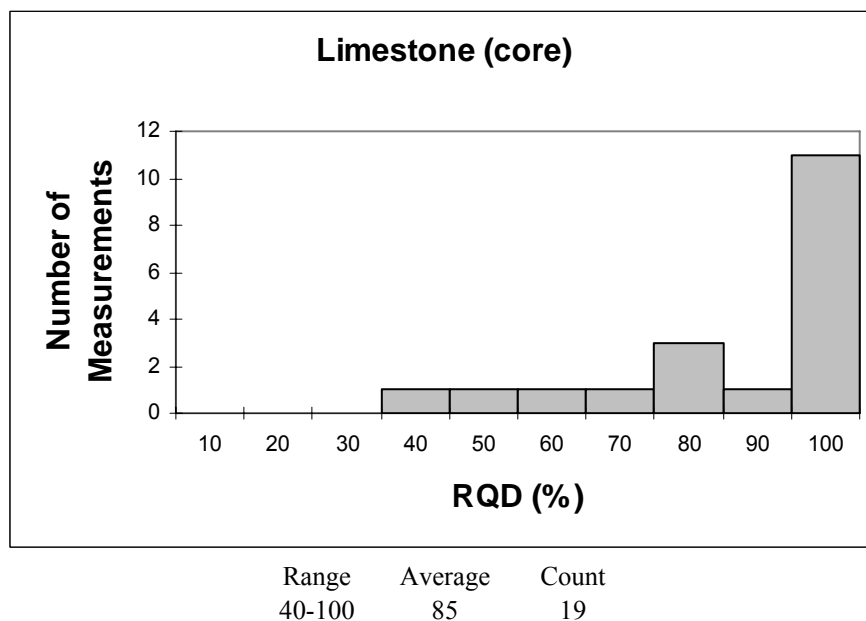
Figure 4.16: Frequency distribution of RQD for limestone core.
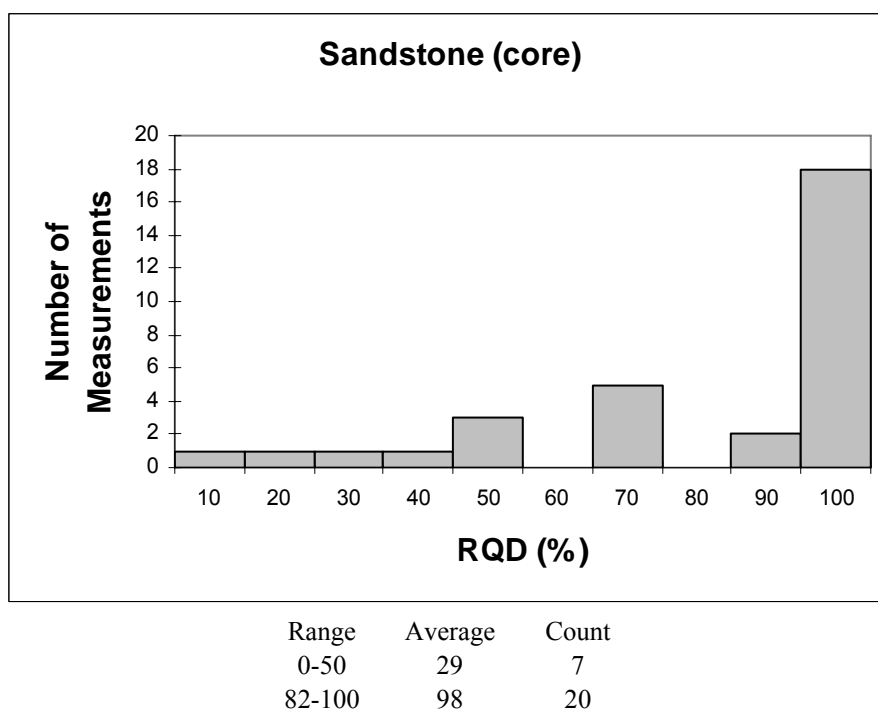
Figure 4.17: Frequency distribution of RQD for sandstone core.

RQD Data for Incompetent Rock Units

Outcrop Data

All RQD values for incompetent rock outcrops were recorded to be 0 %.

Core Data

Descriptive statistics indicate that RQD values for shale range from 65–100 % with an average value of 91 % (Appendix 12-C). Some outliers have values as low as 0 %. RQD values for claystone/mudstone core range from 54–100 % with an average value of 82 %. Some outliers have values as low as 31 % (Appendix 12-C). Both shale and claystone/mudstone units have right-skewed distributions (Figures 4.18 and 4.19), indicating the prevalence of greater than 80-90 % RQD values. However, there is a large difference in RQD values between outcrop rock and core samples. RQD values for outcrops are measured on weathered rock whereas RQD measurements for core represent fresh rock. Therefore, high RQD values for core samples of incompetent rock do not necessarily reflect the long-term performance of such rocks.

4.1.6 Undercutting Data

4.1.6.1 Total Amount of Undercutting

The total amount or depth of undercutting is the extent of undercutting a competent unit has experienced since the slope was constructed. Appendix 8 contains the total amount of undercutting data. Descriptive statistics for the undercutting related data are provided in Appendix 12-B. The total amount of undercutting ranges from 0–154 inches (0-392 cm) with an average of 54 inches (137cm) (Appendix 12-B).The frequency histogram for the total amount of undercutting (Figure 4.20) shows a slightly left-skewed distribution, indicating that undercutting depths of 30–40 inches (76–102 cm) are more frequent.

Range	Average	Count
65-100	91	35
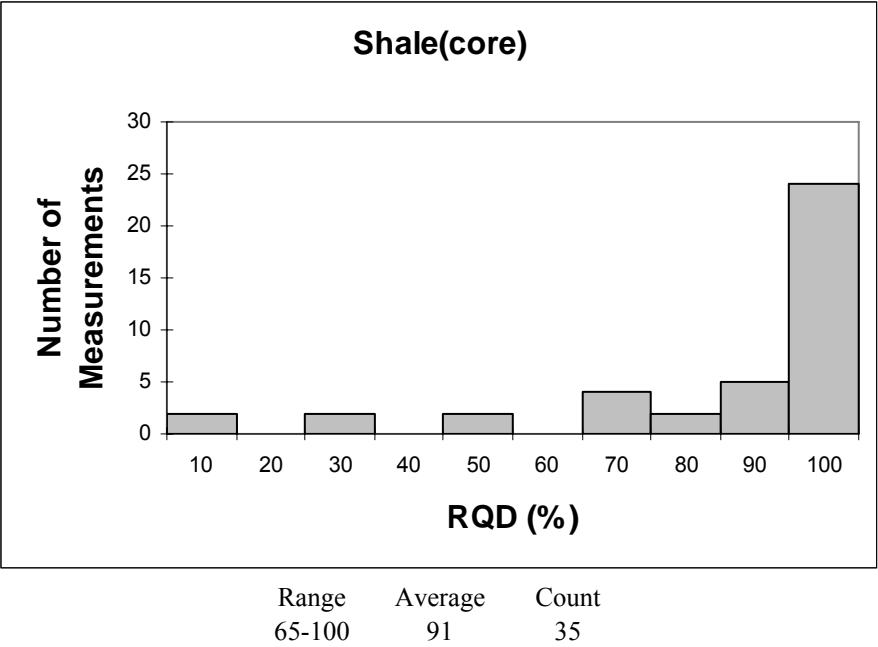
Figure 4.18: Frequency distribution of RQD for shale core.

Range	Average	Count
48-100	82	23
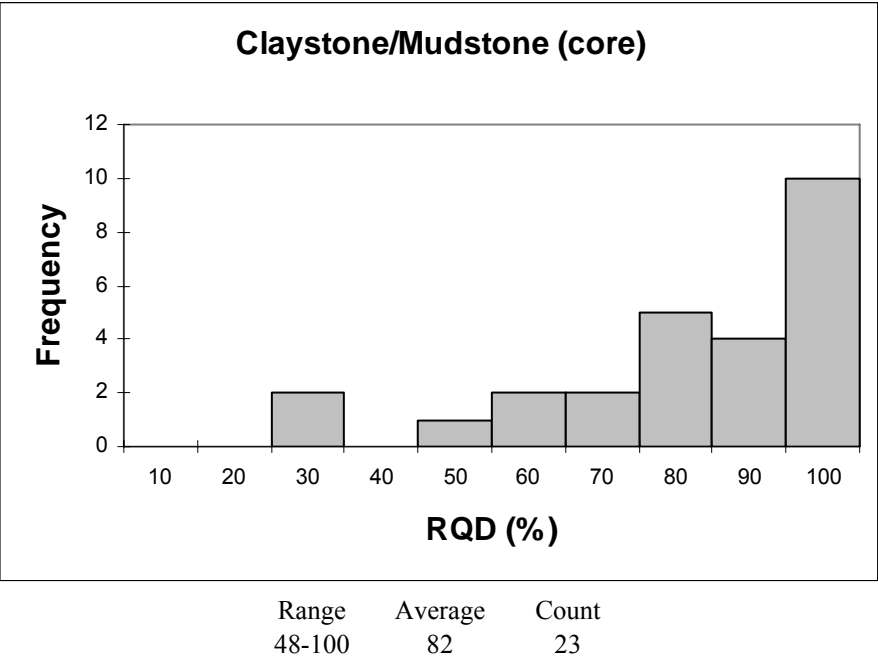
Figure 4.19: Frequency distribution of RQD for claystone/.mudstone core.

Range	Average	Count
0-154	54	59
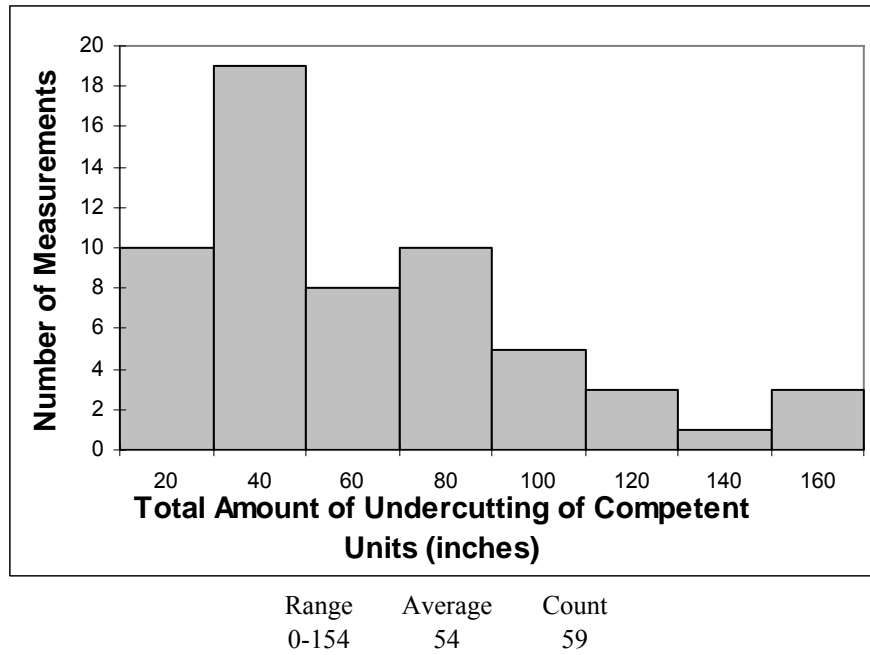
Figure 4.20: Frequency distribution of the total amount of undercutting.

4.1.6.2 Rate of Undercutting

The total amount of undercutting was divided by the age of the cut slope to determine the rate of undercutting, assuming a linear relationship between the two parameters. However, a recent study by Niemann (2009) indicates that the rate of undercutting decreases with time and that undercutting may stop altogether after a certain amount of time. Therefore, the rate of undercutting is less meaningful than the total amount of undercutting.

Descriptive statistics for the rate of undercutting indicate that it ranges from 0–4 inches/year (0–10 cm/year) with one outlier of 8 inches/year (20 cm/year) (Appendix 12-B). The average rate of undercutting is 2 inches/year (5 cm/year). Figure 4.21 shows that the frequency distribution for the rate of undercutting is left-skewed, indicating a higher frequency of relatively lower rates of undercutting (0-3 inches/year/0–8 cm/year).

A more detailed analysis of the factors affecting the amount of undercutting and the variation of the amount of undercutting with slope height is presented in Chapter 5.

4.1.7 Catchment Ditch data

Catchment ditch Data are presented in Appendix 9. The width of catchment ditches ranges from 7-70 ft (2.1-21.2 m) with an average width of 24 ft (7 m). The catchment ditch depth varies between 0.5 ft (0.2 m) and 3 ft (1 m), the average depth being 2 ft (0.6 m).

Davis (2003) conducted a detailed study of catchment ditch design in Ohio using the Oregon Rockfall Catchment Area Design Guide (Pierson et al., 2001) and the CRSP software (Jones et al., 2001). His study indicated average width and depth dimensions for catchment ditches being 18.5 ft (5.6 m) and 1.4 ft (0.4 m), respectively.
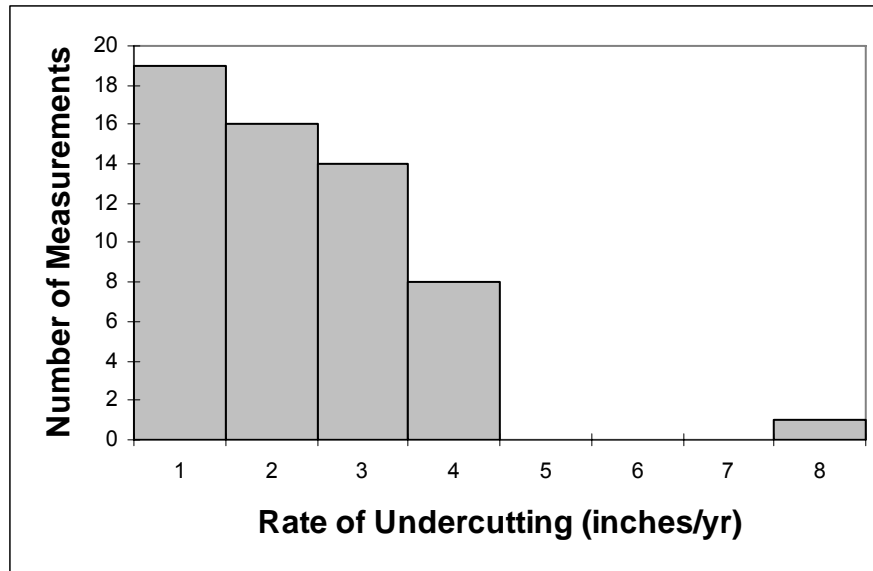
	Range	Average	Count
	0-4	2	57

Figure 4.21: Frequency distribution of the rate of undercutting.

4.1.8 Site Performance Evaluation Data

Based on the extent and frequency of slope stability problems, the performance of 26 study sites was rated as poor, moderate, and good. Table 4.3 shows the performance ratings for these sites. However, these ratings do not indicate if the slope design is effective or not. For example, a slope may experience significant amount of rockfall but its design will be considered effective if all rockfalls are either caught on the benches or retained in the catchment area. Therefore, site performance was also evaluated in terms of the effectiveness of slope design as shown in Table 4.3. Additionally, Site performance was evaluated with respect to types of slope stability problems affecting the 26 sites (Table 4.4).

4.2 Laboratory Data

4.2.1 Unconfined Compressive Strength and Slake Durability Index Data

Unconfined compressive strength and slake durability index data for outcrop samples of both competent and incompetent rock units is presented in Appendix 10-A and those for core samples in Appendix 10-B. Descriptive statistics for these data are included in Appendix 12-C.

4.2.1.1 Unconfined Compressive Strength Data for Competent Rock Units

Outcrop Samples

Unconfined compressive strength values for outcrop samples of limestone range from 3101– 65014 psi (21–448 Mpa) with an average value of 14194 psi (98 Mpa) and an outlier with a value as high as 65014 psi (448 Mpa) (Appendix 12-C). Figure 4.22 shows the frequency distribution for unconfined compressive strength of limestone samples from outcrops. Unconfined compressive strength values for outcrop samples of sandstone range from 1400– 16704 psi (10–115 Mpa) with an average value of 6371 psi (44 Mpa) (Appendix 12-C).

Table 4.3: Site performance ratings, based on slope stability problems and effectiveness of slope design, for the 26 project sites

Site No.	Site Performance With Respect to Slope Stability Problems	Site Performance With Respect to Effectiveness of Slope Design
ADA-32-12	Good	Good
ADA-41-15	Moderate	Good
ATH-33-14	Good	Good
ATH-50-23	Moderate	Good
BEL-470-6	Moderate-Poor	Good
BEL-7-10	Poor	Good
BEL-70-22	Poor	Good
CLA-4-8	Poor	Good
CLA-68-7	Good	Good
CLE-275-5	Moderate	Good
COL-7-5	Poor	Good
FRA-270-23	Poor	Good
GUE-22-6	Poor	Poor
GUE-77-8	Poor	Good
HAM-126-12	Poor	Good
HAM-74-6	Moderate	Good
JEF-CR77-0.38	Poor	Good
LAW-52-11	Poor	Good
LAW-52-12	Poor	Good
LIC-16-28	Good	Good
MEG-33-15	Moderate	Good
MEG-33-6	Moderate	Good
MUS-70-11	Poor	Good
RIC-30-12	Moderate	Good
STA-30-27	Poor	Good
WAS-7-18	Moderate	Good

Table 4.4: Types of slope stability problems observed at the 26 project sites.

Undercutting Induced Plane, Wedge, or Toppling Failure	Raveling	Mudflows	Toppling Failure	Plane Failure	Rotational Failure	No Failure Observed
ADA-41-15	ATH-50-22	CLE-275-5.2	CLA-4-8	COL-7-5	GUE-22-6.9?	ATH-33-14
ATH-50-22	COL-7-5	ADA-32-12	RIC-30-12.5	LIC-16-28		CLA-68-6.9
BEL-470-6	FRA-270-23					MEG-33-15
BEL-70-22	HAM-74-6.4					
BEL-7-10	HAM-126-12					
CLE-275-5.2	STA-30-27					
GUE-77-8.2						
GUE-22-6.9						
HAM-74-6.4						
HAM-126-12						
JEF-CR77-0.38						
LAW-52-11						
LAW-52-12						
MUS-70-11						
MEG-33-6						
STA-30-27						
WAS-7-18						

Range	Average	Count
3010-24542	14194	58

Figure 4.22: Frequency distribution of unconfined compressive strength for outcrop samples of limestone.

Figure 4.23 shows the frequency distribution of compressive strength for sandstones.

Core Samples

Unconfined compressive strength values for limestone from core samples range from

4148–25669 psi (29–177 Mpa) with an average value of 15331 psi (106 Mpa) (Appendix 12-C).

Figure 4.24 shows the frequency distribution of compressive strength for core samples. Samples

from sandstone core have two populations (Figure 4.25). Descriptive statistics (Appendix 12-C)

indicate that strength values within the first population range from 1179-12233 psi (8–84 Mpa),

with an average of 6696 psi (46 Mpa), and in the second population from 15520-21507 psi (107–

148 Mpa), with an average of 17895 psi (123 Mpa). Sandstones falling in the higher strength

population generally contain siliceous cement. Overall, the compressive strength results for core

samples of competent rock units are similar to those of outcrop samples.

4.2.1.2 Unconfined Compressive Strength Data for Incompetent Rock Units

Outcrop Samples

Unconfined compressive strength values for shale samples from outcrops range from

545–7094 psi (4–49 Mpa) with an average value of 2904 psi (20 Mpa) (Appendix 12-C). The

frequency distribution of compressive strength for shale samples is left-skewed (Figure 4.26),

indicating that most strength values are less than 1450 psi (10 Mpa). Unconfined compressive

strength values for claystone/mudstone samples from outcrops range from 107–5618 psi (0.7-39

Mpa) with an average value of 854 psi (6 Mpa) (Appendix 12-C). The frequency distribution for

claystones/mudstones is also left-skewed (Figure 4.27.

Sandstone (outcrop)

Range	Average	Count
1400-16704	6371	49
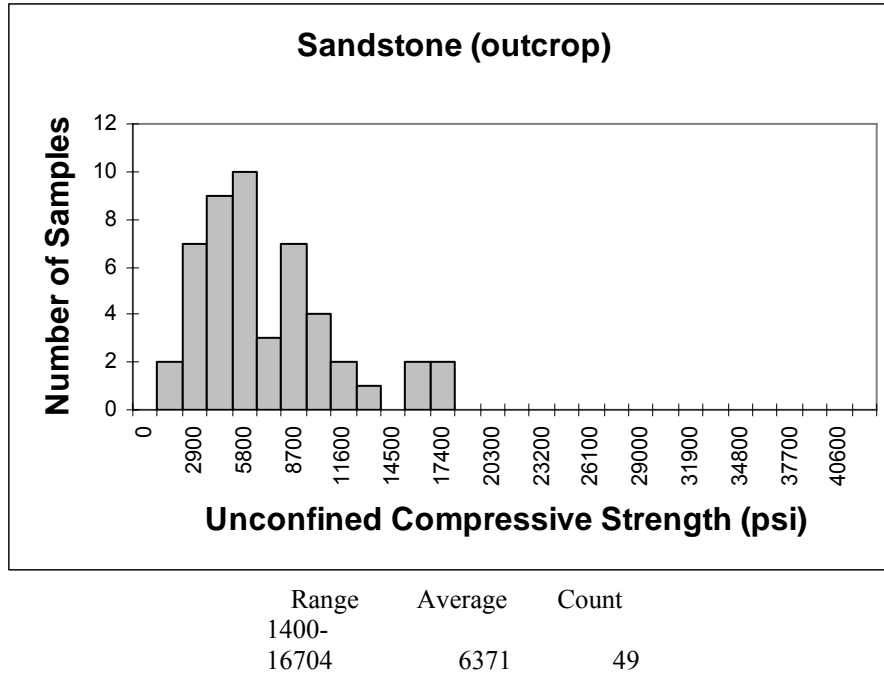
Figure 4.23: Frequency distribution of unconfined compressive strength for outcrop samples of sandstone.

Limestone (core)

Range	Average	Count
4148-25669	15331	23
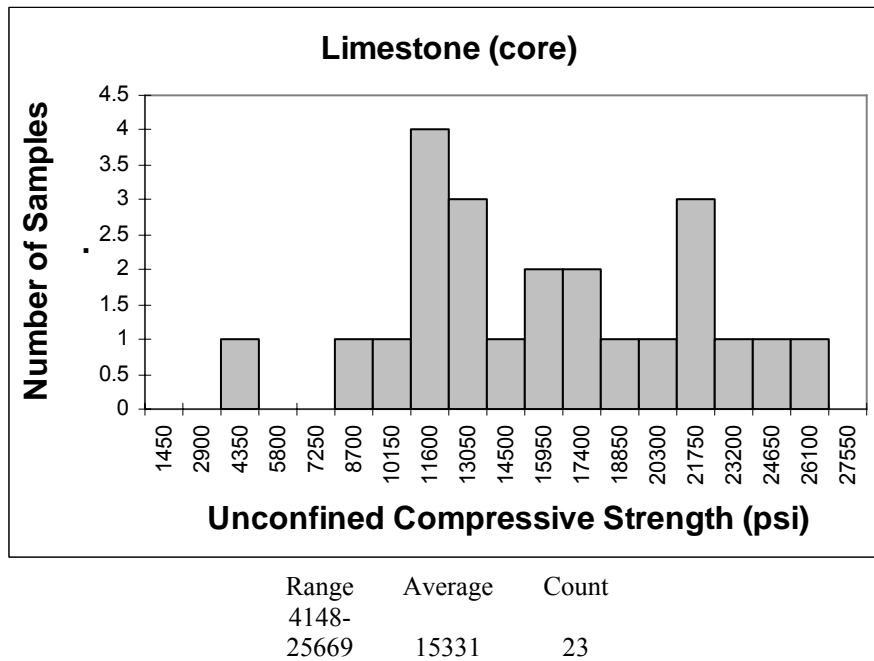
Figure 4.24: Frequency distribution of unconfined compressive strength for core samples of limestone.

Sandstone (core)

Range	Average	Count
1179-12233	6696	27
15520-21507	17895	7
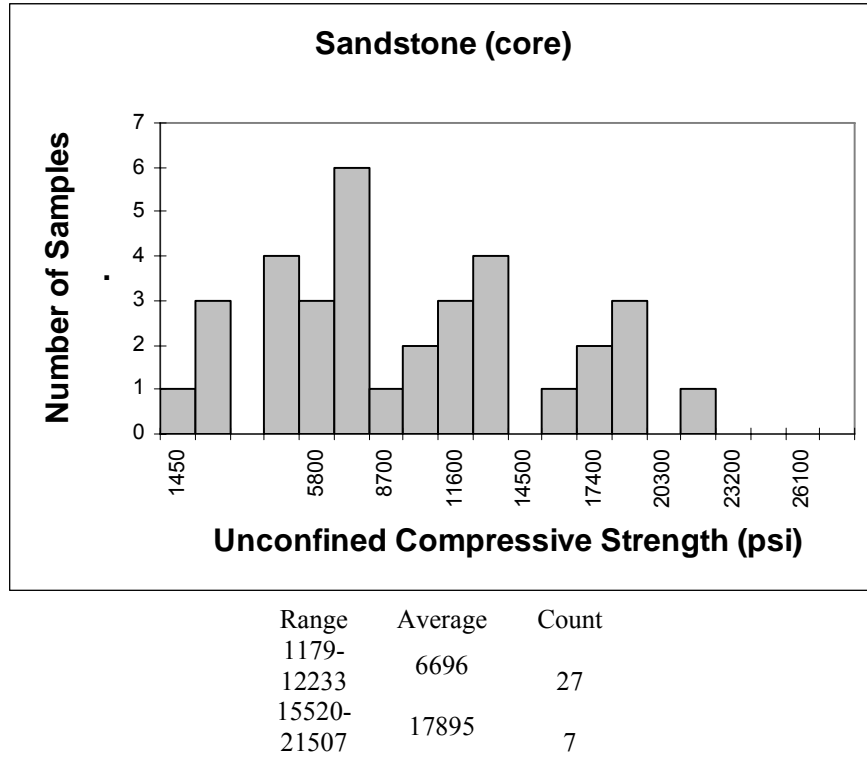
Figure 4.25: Frequency distribution of unconfined compressive strength for core samples of sandstone.

Shale (outcrop)

Range	Average	Count
545-7094	2904	18
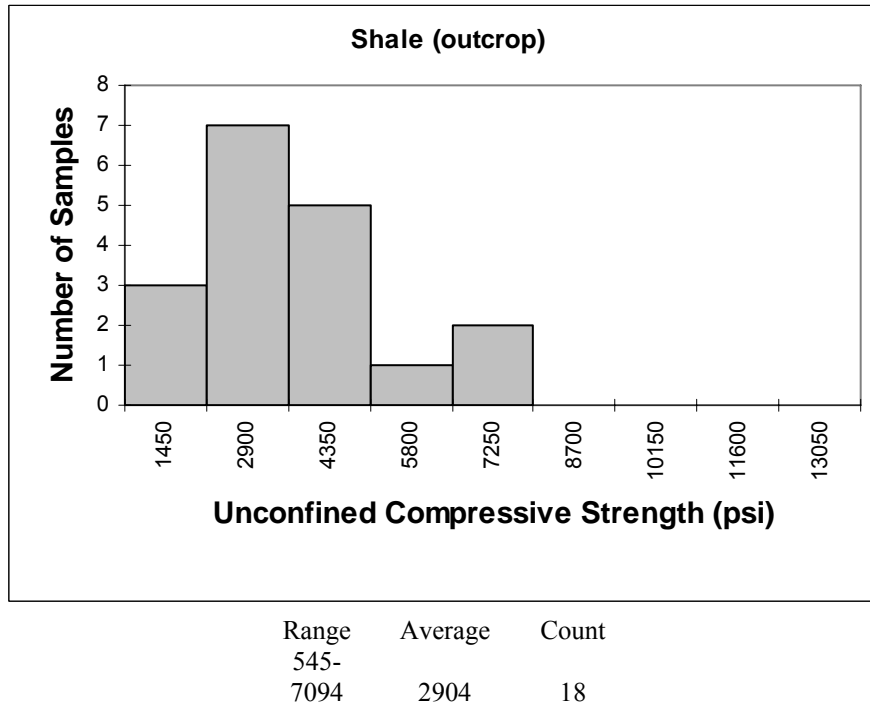
Figure 4.26: Frequency distribution of unconfined compressive strength for outcrop samples of shale.

Claystone/Mudstone (outcrop)

Range	Average	Count
107-5618	854	41
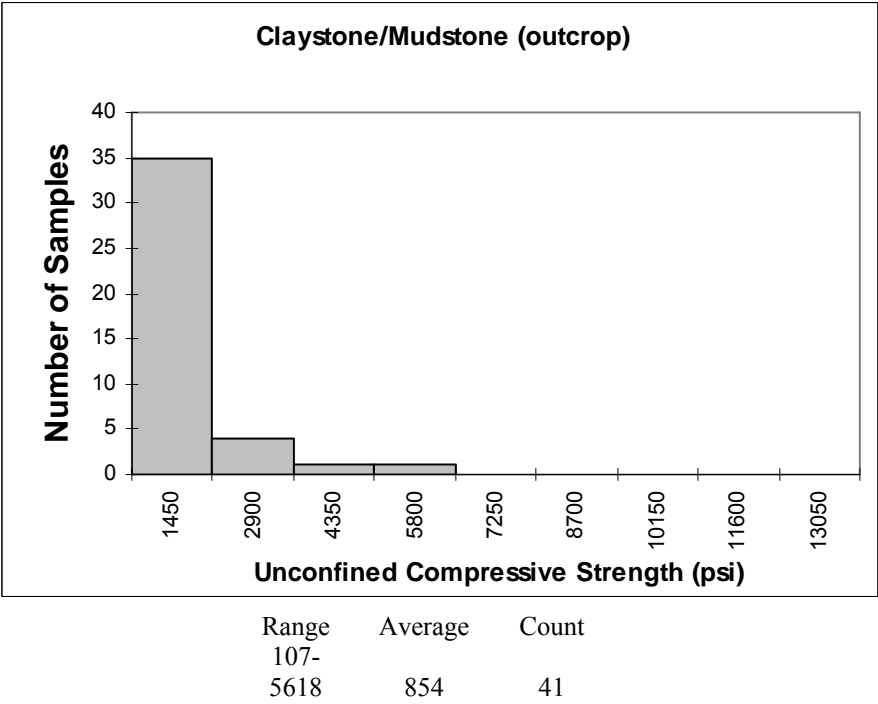
Figure 4.27: Frequency distribution of unconfined compressive strength for outcrop samples of claystone/mudstone.

Core Samples

Unconfined compressive strength values for core samples of shale range from 332–10646 psi (2–73 Mpa) with an average of 2399 psi (17 Mpa) and (Appendix 12-C). Figure 4.28 shows the frequency distribution of strength values core samples from shale. Core samples for claystone /mudstone have strength values ranging from 222–3109 psi (1.5–21 Mpa) with an average of 1557 psi (11 Mpa) (Appendix 12-C). The frequency distribution for core samples of claystone/mudstone is shown in Figure 4.29. The frequency distributions of compressive strength for shale and claystone/mudstone units are left-skewed (Figures 4.28 and 4.29).

4.2.2.1 Slake Durability Index Data for Competent Rock Units

Slake durability index test for competent rock units was conducted on outcrop and core samples obtained from the 26 project sites.

Outcrop Samples

Descriptive statistics (Appendix 12-C) show that slake durability index values for outcrop samples of limestone range from 91–100 % with an average value of 98 %. For outcrop samples of sandstones, slake durability index values range from 82-99 % with an average value of 94 % and some outliers having values as low as 31 % (Appendix 12-C). The frequency distributions of slake durability index for both rock types are right-skewed (Figures 4.30 and 4.31), indicating that most values are greater than 90 %.

Core Samples

Slake durability index values for core samples of limestone range from 86-100 % with an average value of 98 % and those for core samples of sandstone range from 68-99 % with an average value of 93 % (Appendix 12-C). Some outliers for sandstone have values as low as 38

Range	Average	Count
332-10646	2399	43
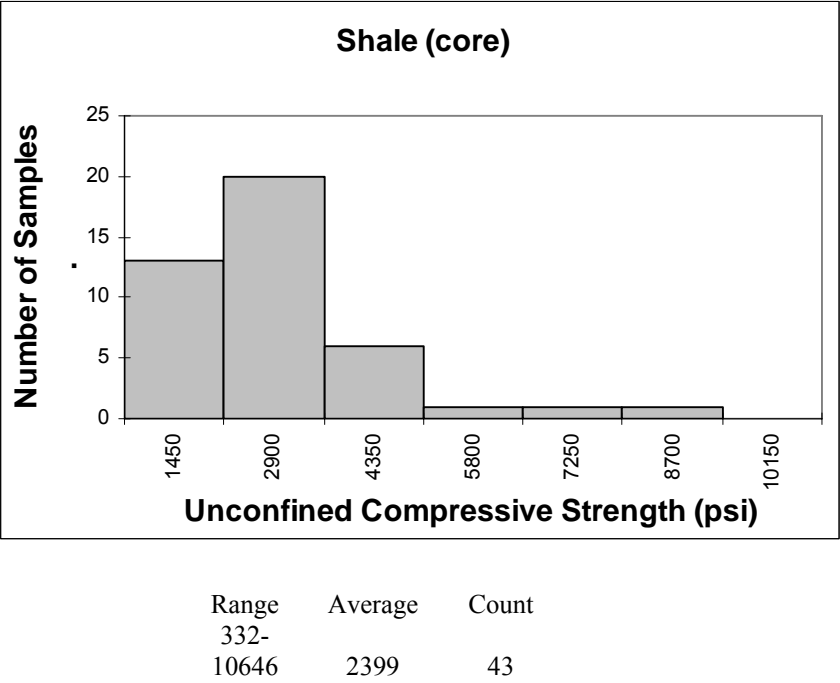
Figure 4.28: Frequency distribution of unconfined compressive strength for core samples of shale.

Range	Average	Count
222-3109	1557	28
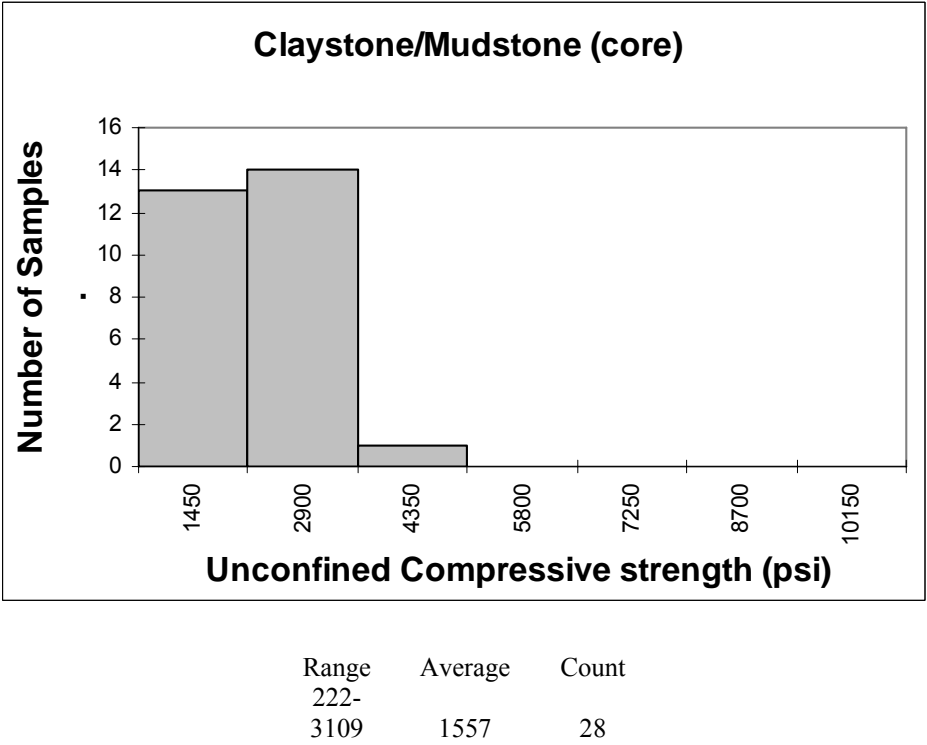
Figure 4.29: Frequency distribution of unconfined compressive strength for core samples of claystone/mudstone.

Limestone (outcrop)

Range	Average	Count
91-100	98	59
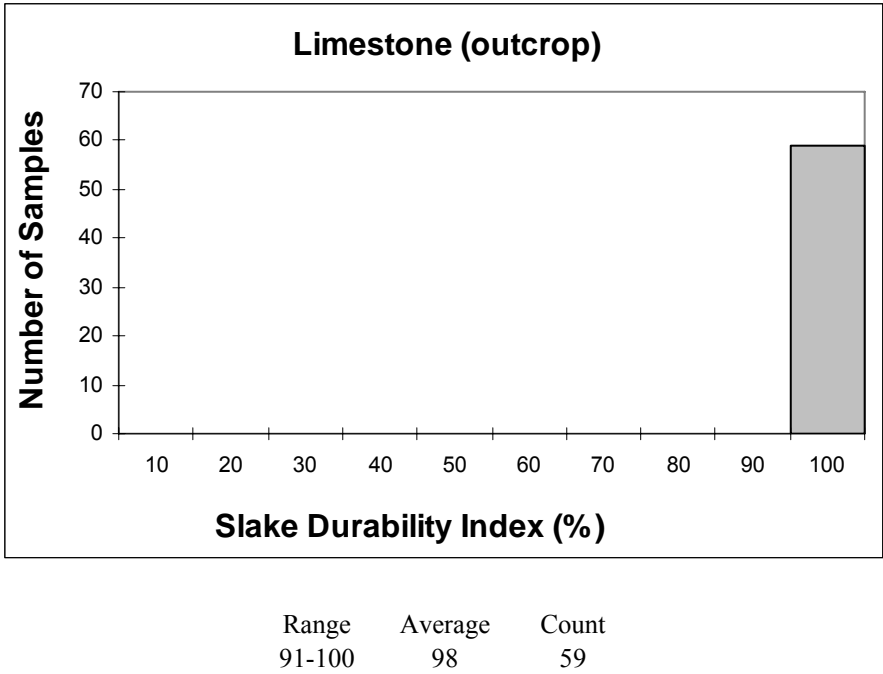
Figure 4.30: Frequency distribution of slake durability index for outcrop samples of limestone.

Sandstone (outcrop)

Range	Average	Count
82-99	94	51
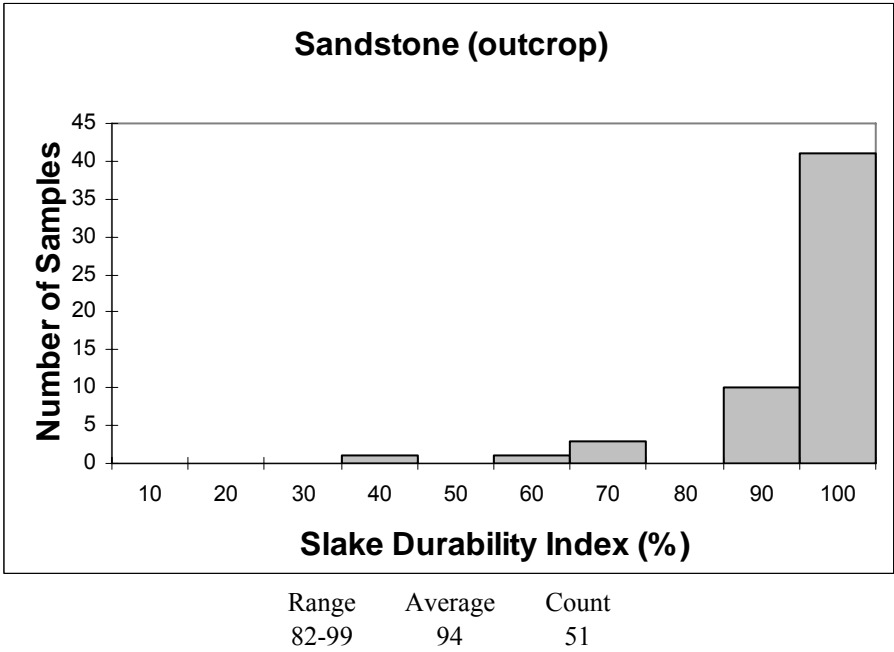
Figure 4.31: Frequency distribution of slake durability index for outcrop samples of sandstone.

%. Figures 4.32 and 4.33 show the frequency distributions of slake durability index for limestone and sandstone, respectively. The frequency distribution for sandstones is right-skewed (Figure 4.33), indicating that most values are greater than 90 %. Slake durability index values for limestones and sandstones are fairly similar for both outcrop and core samples, with sandstones exhibiting slightly lower values due to their clastic nature.

4.2.2.2 Slake Durability Index Data for Incompetent Rock Units

Outcrop Samples

Slake durability index values for shales from outcrops (26 project sites as well as 23 additional sites) range from 72-99 % with an average value of 91 % and some outliers having values as low as 9 % (Appendix 12-C). The frequency distribution of slake durability index for shales is right-skewed (Figure 4.34), indicating the predominance of greater than 90 % values. Slake durability index values for claystone/mudstone samples from outcrops show possibly two populations (Figure 4.35). Descriptive statistics (Appendix 12-C) show that the values for the first population range from 0–10 %, with an average of 4 % and those for the second population range from 18–98 % with an average of 54 %.

Core Samples

Slake durability index values for shales from core samples range from 63-99 %, with an average value of 87 % and some outliers having values as low as 9 % (Appendix 12-C). The frequency distribution of slake durability index for shales is right-skewed Figure 4.36), indicating that most values are greater than 80 %. Slake durability index values for claystone/mudstone core samples show two populations (Figure 4.37), one ranging from 0–34 % with an average of 18 % % and the other ranging from 57-95 % having an average value of 73 % (Appendix 12-C).

Limestone (core)

Number of Samples vs Slake Durability Index (%)

Range	Average	Count
86-100	98	18
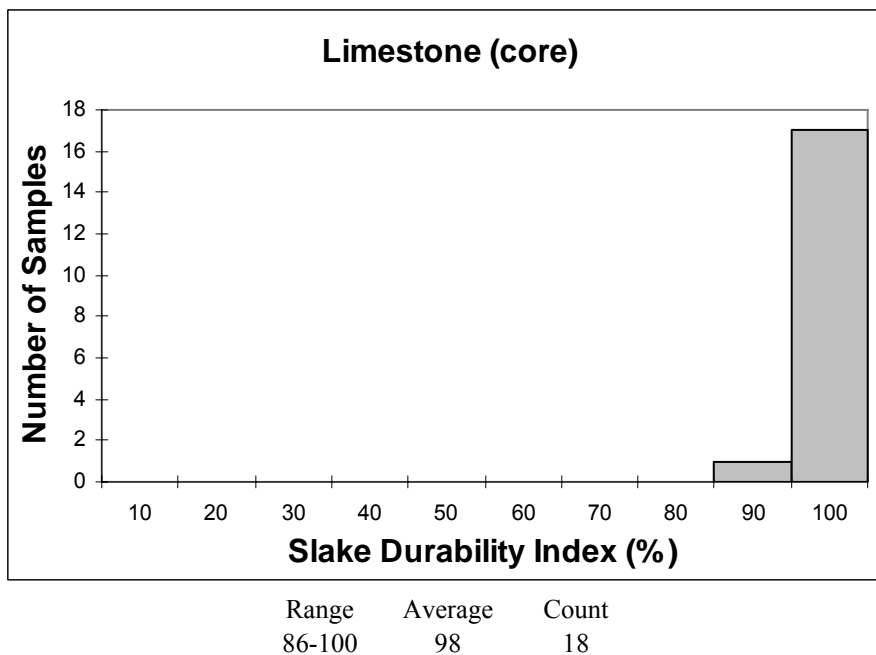
Figure 4.32: Frequency distribution of slake durability index for core samples of limestone.

Sandstone (core)

Number of Measurements vs Slake Durability Index (%)

Range	Average	Count
68-99	93	34
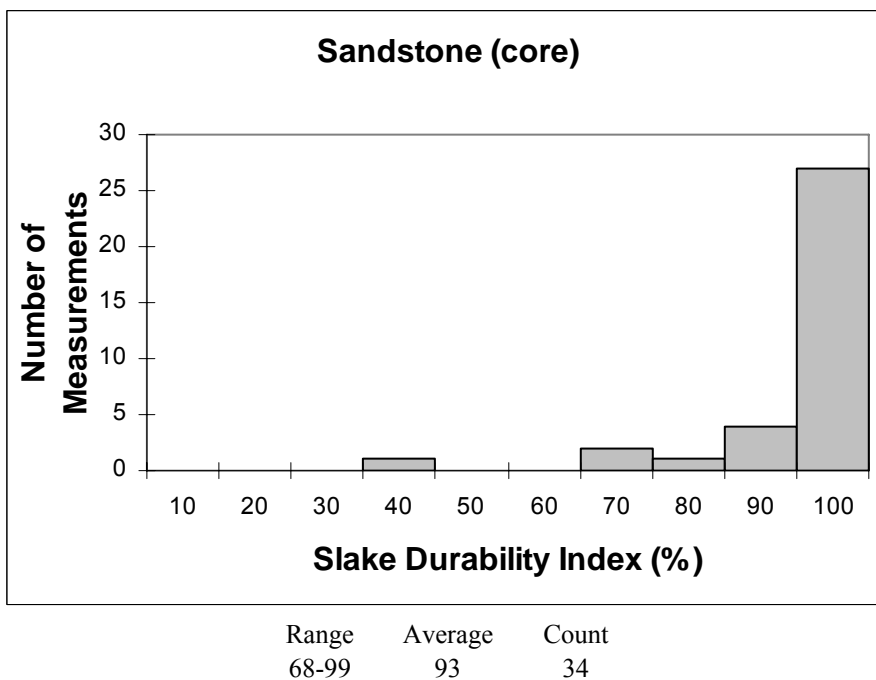
Figure 4.33: Frequency distribution of slake durability index for core samples of sandstone.
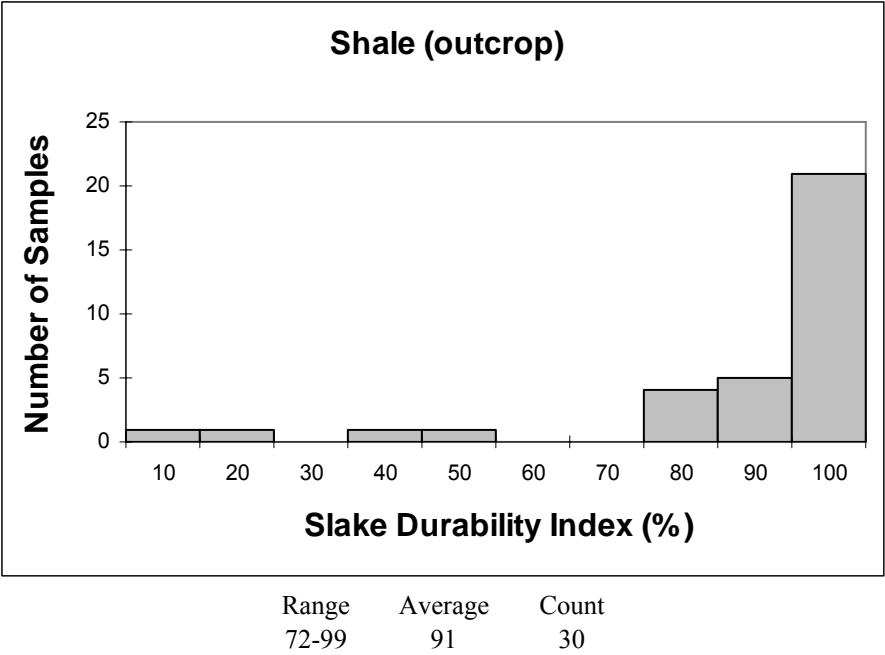
Figure 4.34: Frequency distribution of slake durability index for outcrop samples of shale.
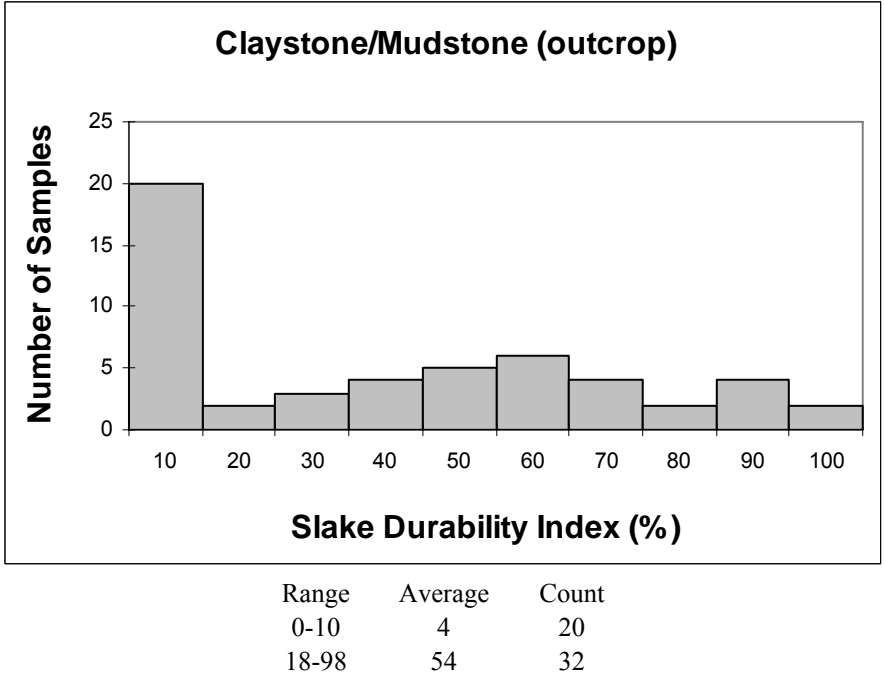
Figure 4.35: Frequency distribution of slake durability index for outcrop samples of claystone/mudstone.

Shale (core)

Number of Samples vs **Slake Durability Index (%)**

Range	Average	Count
63-99	87	43
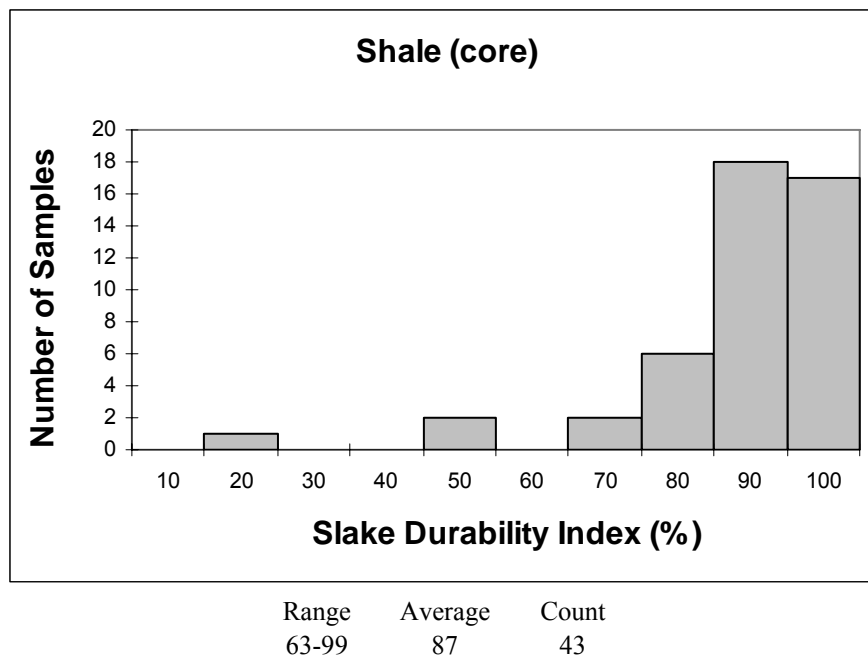
Figure 4.36: Frequency distribution of slake durability index for core samples of shale.

Claystone/Mudstone (core)

Number of Samples vs **Slake Durability Index (%)**

Range	Average	Count
0-34	18	20
57-95	73	12
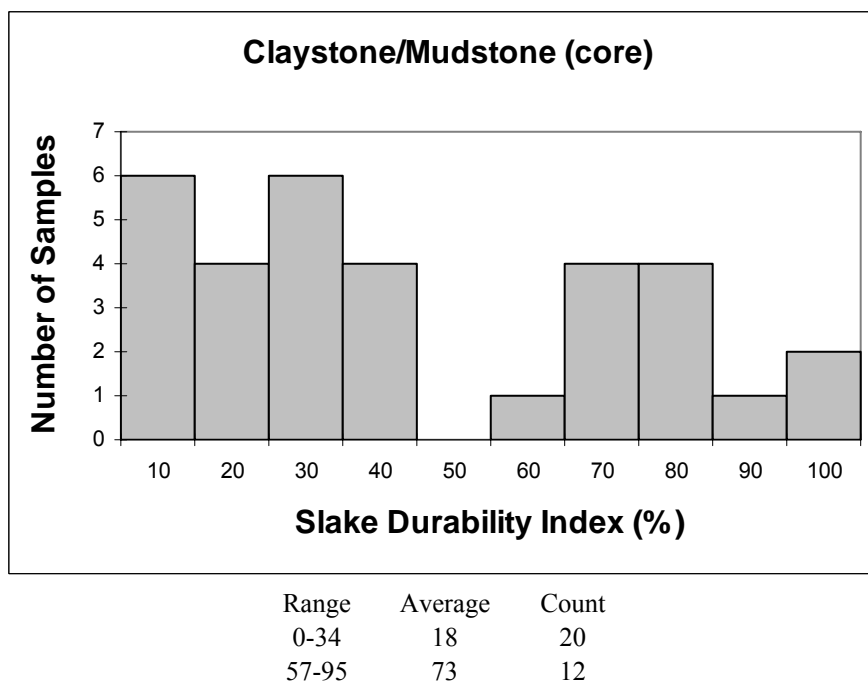
Figure 4.37: Frequency distribution of slake durability index for core samples of claystone/mudstone.

Slake durability index values for outcrop and core samples of shale are fairly close. The slake durability index values for claystones/mudstones are lower than those of shales. There is however, a notable difference in distribution and descriptive statistics between outcrop and core samples for claystones/mudstones, with outcrop samples exhibiting significantly lower values due to their comparatively higher degree of weathering.

4.2.3 Friction Angle Data

Friction angle was determined, using the method proposed by Stimpson (1982), for sandstones from three sites and a limestone from one site. The average friction angle for the three sandstones is 36 degrees (range: 34-39 degrees) and that for limestone 43 degrees (Table 4.5). Although surfaces of sandstone samples appeared rougher, their friction angle values are lower than those of limestones.

4.3.6 Dry Density Data

Dry density was measured for 4 limestone, 7 sandstone, 13 shale, and 8 claystone/mudstone samples from drilled core. Appendix 11-A contains the density data. Average values of density for limestones, sandstones, shales, and claystones/mudstones are 158 lbs/ft^3, 145 lbs/ft^3, 166 lbs/ft^3, and 164 lbs/ft^3, respectively.

4.2.5 Atterberg Limits Data

Atterberg limits were determined to find plasticity index values for selected samples. Plasticity indices of incompetent rock units, having less than 80 % slake durability index values, are needed for application of the Franklin shale rating system (Franklin, 1983), as discussed in Chapter 3. The samples with less than 80 % slake durability index values are mostly claystones/mudstones, with two shale samples. Appendix 11-B contains Atterberg limits data.

Table 4.5: Friction angle data for selected samples of competent rock.

Site No.	Rock Unit	Friction Angle determined by Stimpson method
LIC-16-28	Sandstone	34
RIC-30-12	Sandstone	36
ATH-33-14	Sandstone	39
CLA-68-7	Limestone	43

Outcrop Samples

The plasticity index values for outcrop samples range from 2–21 with an average of 11 (Appendix 12-C). Figure 4.38 shows the frequency distribution of plasticity index for outcrop samples.

Core Samples

The plasticity index for core samples shows a range from 3-15 with an average value of 7 (Appendix 12-C). Figure 4.39 shows the frequency distribution of plasticity index for core samples.

4.3 Correlations Between Engineering Properties

An attempt was made to investigate the presence of any correlations between engineering property data (unconfined compressive strength, slake durability index, RQD) obtained during laboratory and field investigations. The results, presented in Appendix 10-C, indicate that a significant correlation does not exist between these properties.

Range	Average	Count
2-21	11	25
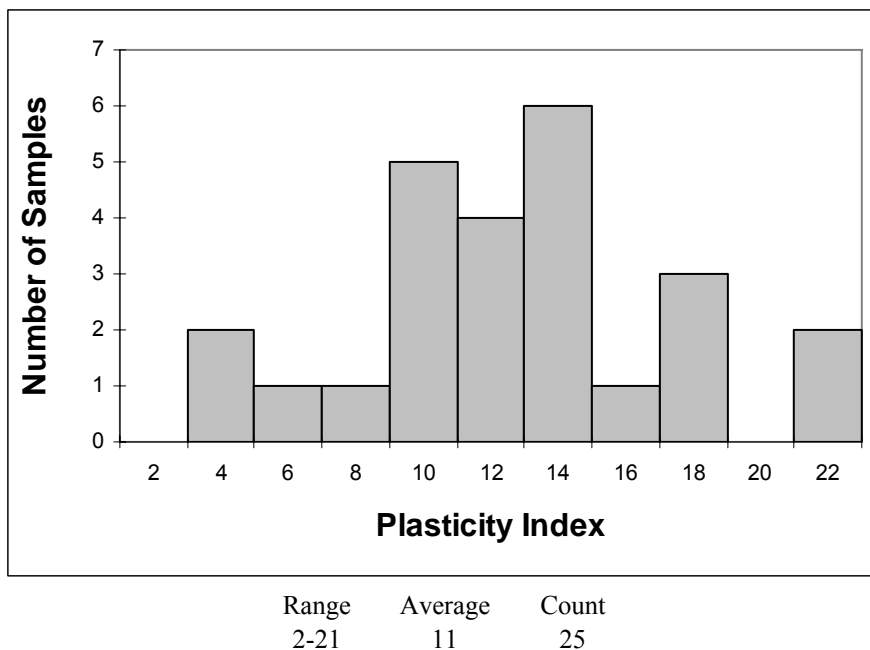
Figure 4.38: Frequency distribution of plasticity index for outcrop samples.

Range	Average	Count
3-15	7	20
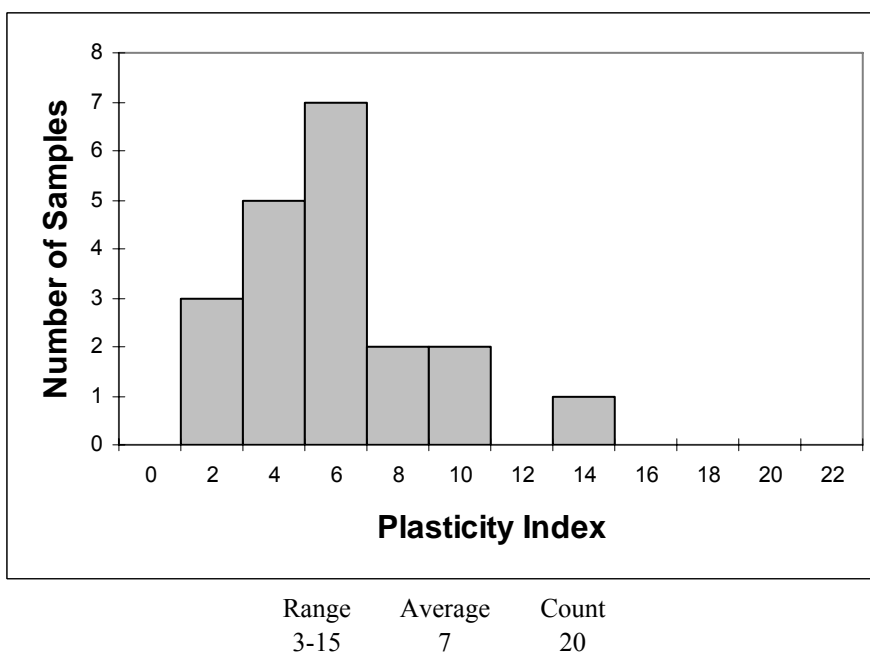
Figure 4.39: Frequency distribution of plasticity index for core samples.

CHAPTER 5

ROCK SLOPE STABILITY ANALYSIS

5.1 Stability Analysis for Slopes Comprised of Competent Rock Units

Twelve of the 26 project sites, comprised of thick (>10 ft/3.3 m) competent rock units, were selected for stability analysis of this category of slopes. Table 5.1 provides information about type and thickness of competent rock unit, slope angle, and slope azimuth for the 12 sites. At all 12 sites, the competent rock units are thick enough for independent design. Four of these sites consist of entirely competent rock units whereas the rest are inter-layered with incompetent rock units. Sandstones are the competent rock units at nine of the sites and limestones at the other three. The stability of slopes at the 12 sites was investigated using the kinematic analysis, rock mass strength analysis, and GB 3 methodology. The results are presented in Appendix 13.

5.1.1 Kinematic Analysis

Kinematic analysis was performed to analyze the potential for plane, wedge, and toppling failures. Because of the steeply dipping nature of discontinuities, plane and wedge failures are rare occurrences in Ohio where the slopes are comprised entirely of sandstones and limestones. However, toppling of rock blocks, bounded by steep and intersecting discontinuity planes, is quite common. This type of toppling is different from that described by Hoek and Bray (1981), and by Goodman (1989), in which toppling occurs along a single set of discontinuity planes dipping into the slope face at steep angles. Therefore, here, toppling is subdivided into two types: (i) *Type A toppling*, similar to the type of toppling described by Hoek and Bray (1981) and by Goodman (1989); and (ii) *Type B toppling* that results when lines of intersection of discontinuities plunge steeply (> 80 degrees) either into the slope face or toward it (Figure 3.2).

Table 5.1: Sites selected for stability analysis of competent rock units.

Site	Rock Unit	Thickness (ft)*	Slope Angle (Degrees)	Slope Azimuth (Degrees)
ADA-32-12	Limestone	59	75	315
ATH-33-14	Sandstone	98	79	50
BEL-470-6	Limestone	23	65	350
CLA-4-8	Limestone	26	69	330
COL-7-5	Sandstone	16	75	175
GUE-77-8	Sandstone	40	59	280
JEF-CR77-0.38	Sandstone	19	76	15
LAW-52-11	Sandstone	32	58	215
LIC-16-28	Sandstone	58	69	170
MUS-70-11	Sandstone	12	75	180
RIC-30-12	Sandstone	36	79	0
WAS-7-18	Sandstone	19	80	130

* 1 ft = 0.3048 m

It is promoted by weathering and removal of weaker beds within the competent units which, in turn, causes the overlying blocks to lose support and fail by toppling. Another factor promoting Type B toppling is the presence of closely (2 in.-1 ft/5 cm-0.3 m) to moderately (1-3 ft/0.3-3 m) spaced joints . Type B toppling is not common in competent rock units with joint spacing exceeding 6 ft (2 m). It is more likely to occur near the edges of sandstone slopes where the joint spacing is usually less than 3 ft (1 m). Many limestone units at the study sites tend to have a uniform joint spacing of less than 1.7 ft (0.5 m) and are susceptible to type B toppling throughout their lateral extent (e.g., CLA-4-8 site). However, ADA-32-12 site contains a thick limestone unit with only isolated zones of closely spaced joints and Type B toppling.

Kinematic analysis for plane, wedge, Type A toppling, and Type B toppling failures was performed using RockPack and DIPS software programs. Although the average friction angle values determined for selected samples of limestone and sandstone are 43 and 36 degrees, respectively, a conservative value of 30 degrees was used for kinematic analysis. Since a method for kinematic analysis of Type B toppling is not available in literature, a new quantitative approach was used to perform kinematic analysis for Type B toppling. Additionally, cartoon models were used to relate slope angle to Type B toppling potential.

5.1.1.1 Kinematic Analysis Using RockPack Software

The RockPack software program is based on Hoek and Bray's (1981) procedures for plane and wedge failures and Goodman's (1989) method for Type A toppling failure. Since RockPack software does not contour poles of discontinuities, the STEREONETT software program was used to contour poles. Principal discontinuity sets were identified using STEREONETT-drawn contours (Figure 5.1) and their corresponding great circles were chosen manually on the RockPack stereonet output (Figure 5.2). Table 5.2 summarizes the results of

0

n=54
max. dens.=16.75 (at 99/ 6)
min. dens.=0.00
Contours at:
0.00,   1.00,   2.00,   3.00,
4.00,   5.00,   6.00,   7.00,
8.00,   9.00,   10.00,   11.00,
12.00,   13.00,   14.00,   15.00,

(Multiples of random distribution)

Equal area projection, lower hemisphere
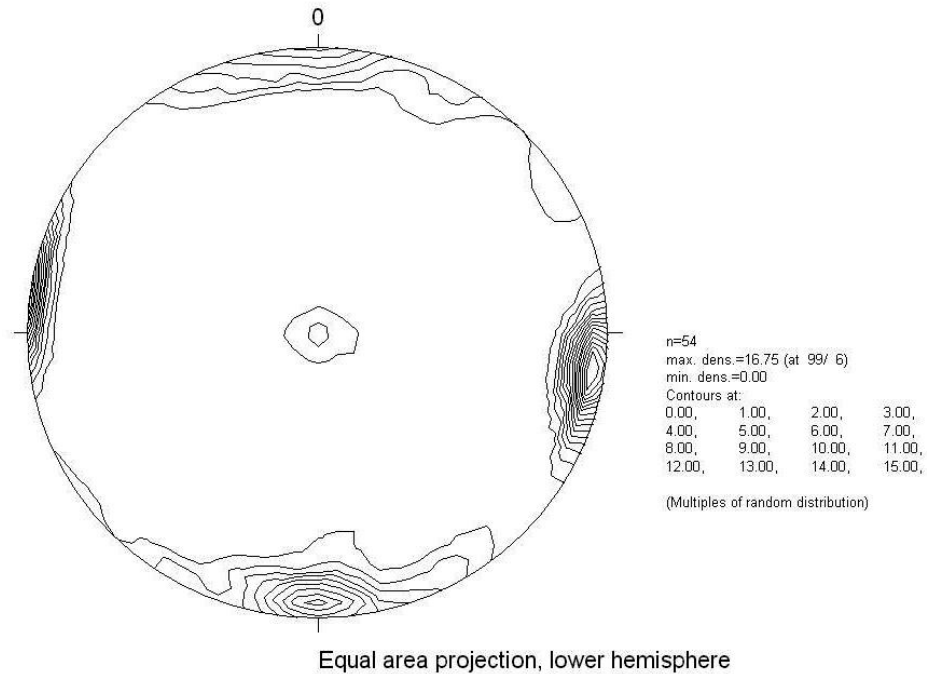
Figure 5.1: Contouring of discontinuity poles using STEREONETT software.
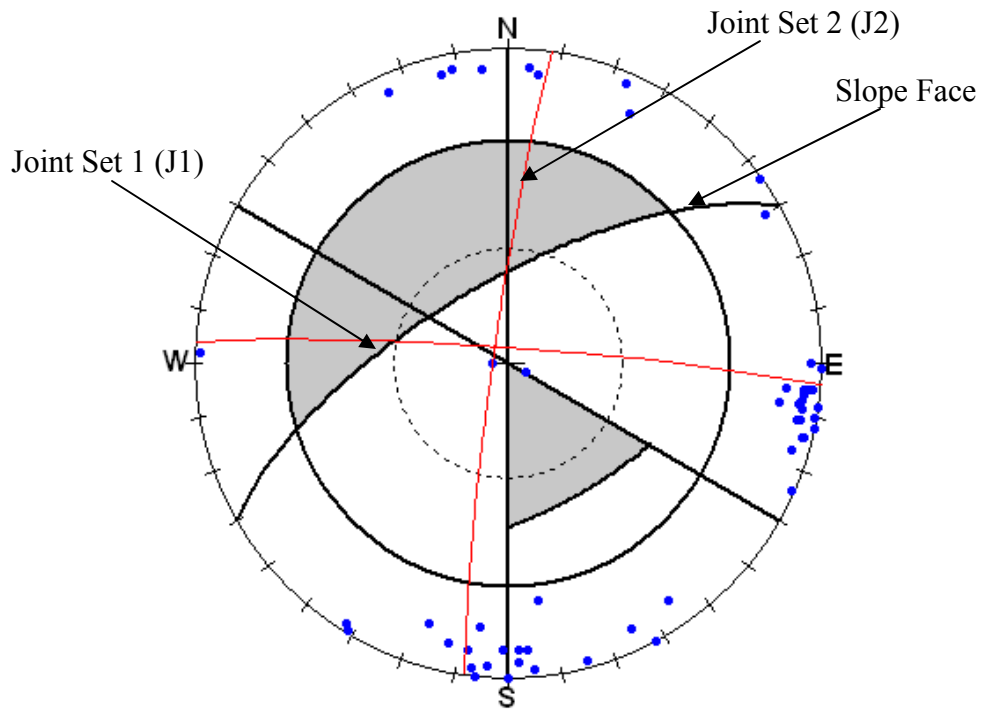
Figure 5.2: An example of manually selected great circles and kinematic analysis by RockPack software.

kinematic analysis for competent rock units and Appendix 13-A includes the stereonet plots for the analysis. As can be seen from Table 5.2, two sites (COL-7-5 and LIC-16-28) show the potential for plane failures and one site (WAS-7-18) shows the potential for wedge failures. Type A toppling is identified at one site (GUE-77-8) and Type B toppling at three sites (ADA-32-12, CLA-4-8, and RIC-30-12). Stereonet plots of kinematic analysis (Appendix 13-A) indicate that slopes cut at 70 degrees will not experience any plane, wedge, or Type A toppling failures.

5.1.1.2 Kinematic Analysis Using DIPS Software

The DIPS software program was developed primarily for analyzing discontinuity orientation data but it can also be used to perform slope stability analysis because of its capability to contour poles and draw great circles as well as the friction circle. The DIPS program does not show the triangular-shaped critical zone for type A toppling (Figure 2.5) or shade the critical zone for plane and wedge failures as done by RockPack (Figures 2.3 and 2.4). However, the program allows for visually examining if discontinuities and their intersections fall in the critical zone. The program also helps to identify lines of intersection of discontinuities that plunge at angles > 80 degrees and cause Type B toppling. Therefore, DIPS program was used to identify plane, wedge, and Type B toppling failures. The advantage of using DIPS program for slope stability analysis is that it can contour poles of discontinuities, unlike RockPack, and generate great circles representing discontinuity sets (Figure 5.3). The program calculates the mean dip direction and dip amount for a cluster of poles representing a discontinuity set. Appendix 13-B provides details of kinematic analysis by the DIPS program and Table 5.3 presents a summary of the results. According to Table 5.3, two sites (COL-7-5, and LIC-16-28) show the potential for plane failures, one site (COL-7-5) shows the potential for wedge failures, and six sites (ADA-32-12, ATH-33-14, BEL-470-6, CLA-4-8, RIC-30-12 and WAS-7-`18) show

Table 5.2: Results of kinematic analysis for slopes comprised of competent rock units, using RockPack software.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Stable Slope Angle by RockPack (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
ADA-32-12-	L.ST.*	57	75	85	No	No	No	Yes
ATH-33-14	S.ST.**	13	79	79	No	No	No	No
BEL-470-6	L.ST.	127	65	78	No	No	No	No
CLA-4-8	L.ST.	55	69	81	No	No	No	Yes
COL-7-5	S.ST	93	75	70	Yes	No	No	No
GUE-77-8	S.ST	87	59	72	No	No	Yes	No
JEF-CR77-0.38	S.ST	39	76	76	No	No	No	No
LAW-52-11	S.ST	51	58	80	No	No	No	No
LIC-16-28	S.ST	28	69	51	Yes	No	No	No
MUS-70-11	S.ST	66	75	75	No	No	No	No
RIC-30-12	S.ST	91	79	90	No	No	No	Yes
WAS-7-18	S.ST	87	80	77	No	Yes	No	No

* L.ST. = Limestone; ** S.ST. = Sandstone
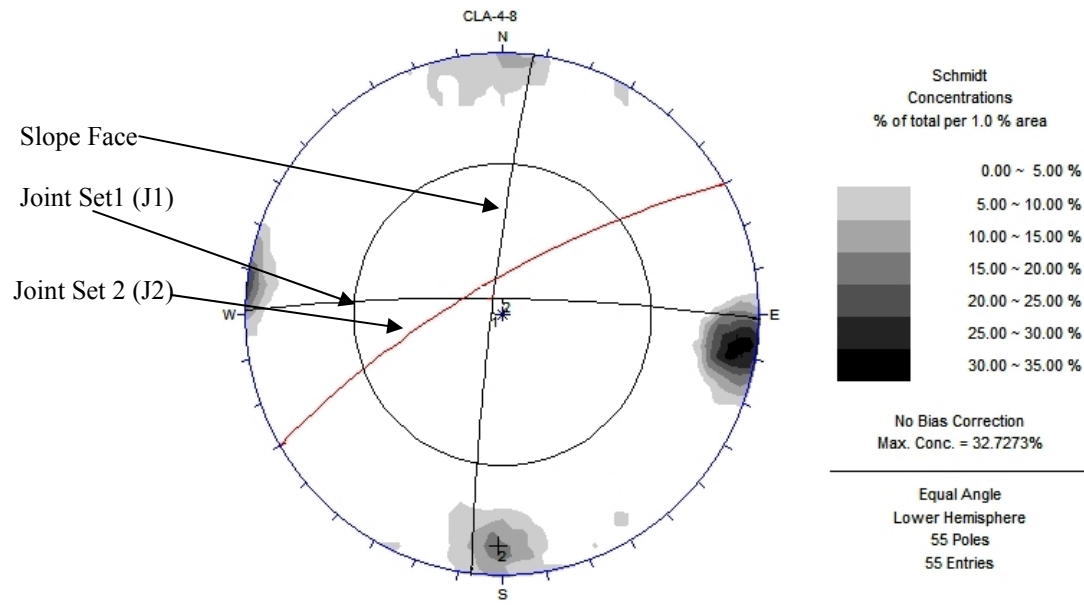
Figure 5.3: An example of kinematic analysis using DIPS software. The great circles, marked J1 and J2, represent the two discontinuity sets. The small circle is the friction circle. No failure is indicated by the kinematic analysis. Notice that DIPS software does not shade the critical zone between the slope face and the friction circle.

Table 5.3: Results of kinematic analysis for slopes comprised of competent rock units, using DIPS software.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Stable Angle by DIPS (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type B Toppling Potential
ADA-32-12-	L.ST.*	57	75	86	No	No	Yes
ATH-33-14	S.ST. **	13	79	84	No	No	Yes
BEL-470-6	L.ST.	127	65	80	No	No	Yes
CLA-4-8	L.ST.	55	69	84	No	No	Yes
COL-7-5	S.ST	93	75	72	Yes	Yes	No
GUE-77-8	S.ST	87	59	67	No	No	No
JEF-CR77-0.38	S.ST	39	76	76	No	No	No
LAW-52-11	S.ST	51	58	77	No	No	No
LIC-16-28	S.ST	28	69	55	Yes	No	No
MUS-70-11	S.ST	66	75	77	No	No	No
RIC-30-12	S.ST	91	79	90	No	No	Yes
WAS-7-18	S.ST	87	80	85	No	No	Yes

* L.ST. = Limestone; ** S.ST. = Sandstone

the potential for Type B toppling. The difference in the results by RockPack and DIPS programs is attributed to the manually chosen great circles in case of RockPack program and the computer-drawn great circles in case of DIPS program. Stereoplots generated by DIPS program indicate that slopes cut at 72 degrees would avoid most of the plane and wedge failures.

5.1.1.3 Kinematic Analysis Using a Quantitative Approach

The RockPack and DIPS software programs are both based on selecting a single great circle, representing a cluster of poles on a stereonet, to define a discontinuity set. The accuracy of the streonet method depends on the extent to which the chosen great circle represents a given discontinuity set. This, in turn, depends on the density of the poles in a cluster, with densely-clustered poles better represented by a single great circle. Figure 5.4 shows how the RockPack software can lead to two different results for the same discontinuity data, depending upon where the great circles are drawn. Due to the presence of a significant amount of scatter in discontinuity data from the study sites, an alternative quantitative approach, which considers separately each discontinuity plane or discontinuity-intersection line, was developed using Microsoft Excel. The approach quantifies the presence of each type of failure in the form of a failure index which is the ratio of the number of discontinuities that cause plane failures or Type A toppling failures, or the number of intersection lines that cause wedge failures or Type B toppling failures, to the total number of discontinuities or intersection lines. A higher index value for a given type of failure indicates a greater chance for that type of failure to occur. In the quantitative approach, the kinematic requirements for plane, wedge, and Type A toppling failures are the same as given in Hoek and Bray (1981) and Goodman (1989). The kinematic criterion required for Type B toppling, analyzed by quantitative approach, is the presence of lines of intersection of discontinuities plunging at angles > 80 degrees.
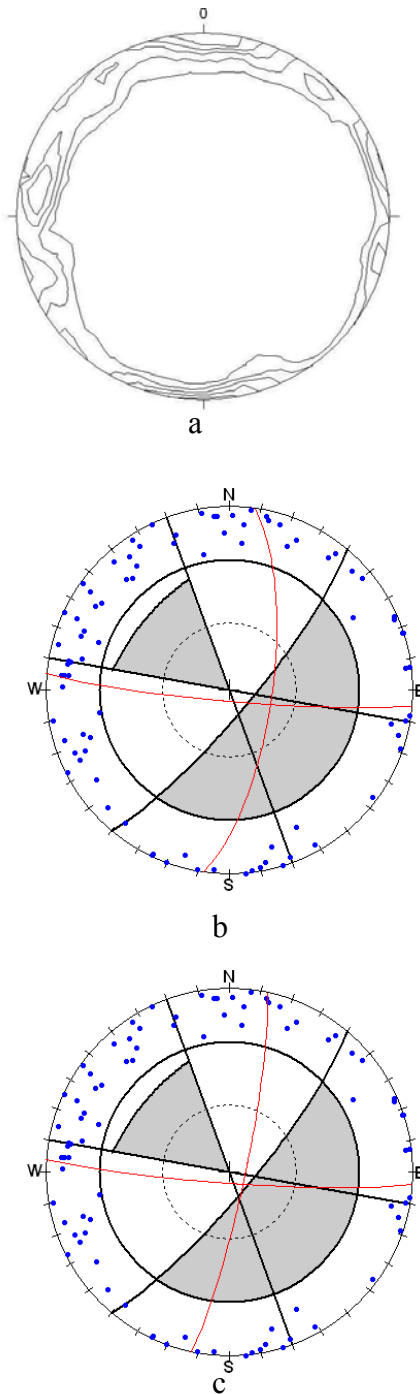
Figure 5.4: An example of scattered discontinuity data from GUE-77-8 site; (a) presence of contours all around the stereonet perimeter indicate absence of distinct joint sets; (b) manually selected great circles, representing two joint sets, indicate a potential wedge failure as their intersection falls in the critical zone; (c) a slight shift in the manually selected great circles for the same discontinuity data indicates that the slope is stable as the point of intersection of two discontinuities lies outside the critical zone.

Quantitative Approach for Plane and Type A Toppling failures

The quantitative approach for plane and type A toppling failures begins with creating a Microsoft Excel spreadsheet that compares each discontinuity orientation (dip direction and amount) with slope azimuth, slope angle, and friction angle to determine if each discontinuity has the potential to cause such failures. It then calculates failure indices by the following formulas:

Plane Failure Index = Total number of discontinuities that cause plane failure /Total number of discontinuities

Type A Toppling Failure Index = Total number of discontinuities that cause Type A toppling/Total number of discontinuities

Figures 5.5 and 5.6 provide flow charts for organizing Microsoft Excel spreadsheets for kinematic analysis of plane and Type A toppling failures.

Quantitative Approach for Wedge and Type B Toppling failures

For wedge and Type B toppling failures, the spreadsheet calculates azimuth and plunge of all possible intersections between discontinuities, using the following equations from Leung and Khoek (1987).

Azimuth of intersection line = $\text{Tan}^{-1}(T1/T2)$

Plunge of intersection line = $\text{Sin}^{-1}\left(|T3|/\sqrt{(T_1^2+T_2^2+T_3^2)}\right)$

Where: T1= - (Cos S1*SinD1*CosD2) + (CosD1*CosS2*SinD2)

T2= - (SinS1*SinD1*CosD2) + (CosD1*SinS2*SinD2)

T3= - (SinS1*SinD1*CosS2*SinD2) + (CosS1*SinS2*SinD2)

S1 = Dip direction of discontinuity 1

S2 = Dip direction of discontinuity 2

1) Create two columns in worksheet 1, one for discontinuity dip amount and the other for dip direction.

2) Create a column in worksheet 2 that compares the strike of each discontinuity with the strike of slope face, and assigns a value of 1 if the discontinuity is sub parallel (within 20 degrees) to the slope face.

3) Create a column in worksheet 3 that compares the dip of each discontinuity with the dip of slope face, and assigns a value of 1 if the discontinuity dip is less than the dip of the slope face.

4) Create a column in worksheet 4 that compares the dip of each discontinuity with the friction angle, and assigns a value of 1 if the discontinuity dip is greater than the friction angle.

5) Create a column in worksheet 5 that adds the results of steps (2), (3), and (4), and assigns a value of 1 if the sum of (2), (3), and (4) is 3.

6) Calculate plane failure index in worksheet 6 by adding all cells which have values of 1 from step (5) and dividing the sum by the total number of discontinuities.

Figure 5.5: Flow chart showing steps involved in determination of plane failure index.

1) Create two columns in worksheet 1, one for discontinuity dip amount and the other for dip direction.

2) Create a column in worksheet 2 that compares the strike of each discontinuity with the strike of slope face, and assigns a value of 1 if the discontinuity is sub parallel (within 30 degrees) to the slope face.

3) Create a column in worksheet 3 that compares the dip direction of each discontinuity with the dip direction of slope face and assigns a value of 1 if the discontinuity dips into the slope face.

4) Create a column in worksheet 4 that compares the (90 -dip of each discontinuity) + friction angle with slope angle (Goodman's 1989 criteria) and assigns a value of 1 if the slope angle is greater of the two values.

5) Create a column in worksheet 5 that adds the results of steps (2), (3), and (4), and assigns a value of 1 if the sum of (2), (3), and (4) is 3

6) Calculate Type A toppling index in worksheet 6 by adding all cells which have values of 1 from step (5) and dividing the sum by the total number of discontinuities.

Figure 5.6: Flow chart showing steps involved in determination of Type A toppling failure index.

D1 = Dip amount of discontinuity 1

D2 = Dip amount of discontinuity 2

In order to calculate the azimuth and plunge of all possible intersections of discontinuities, discontinuity dip directions and amounts are entered in the top two rows and two left columns of a spreadsheet. Each remaining cell in the spreadsheet calculates the azimuth and plunge of intersection of the discontinuities whose dip directions and amounts are entered in the top rows and left columns of the spreadsheet. This is explained in Tables 5.4 and 5.5. After calculating the azimuth and plunge of the intersection, the spreadsheet evaluates if each of the possible discontinuity intersections can cause wedge and Type B toppling failures. Finally, it calculates the failure indices using the following equations:

Wedge Failure Index = Total number of discontinuity intersections that cause wedge failure/ Total number of discontinuity intersections

Type B Failure Index = Total number of discontinuity intersections that plunge at greater than 80 degrees/ Total number of discontinuity intersections

Figures 5.7 and 5.8 provide flow charts for organizing Microsoft Excel spreadsheets for kinematic analysis of wedge and Type B toppling failures.

The results of quantitative analysis for the twelve sites are given in Table 5.6. The choice of an acceptable failure index value, above which the risk of failure is too high to be acceptable, leads to different results. For example, if indices greater than 0.3 are considered unacceptable, no site shows the potential for either plane failures or Type A toppling, 2 sites indicate the potential for wedge failures, and 5 sites have the potential for Type B toppling failure. If, on the other hand, failure index values greater than 0.1 are considered to be unacceptable, 2 sites show the potential for plane failures, 7 for wedge failures, one for Type A toppling failure, and 8 for Type B toppling failure.

Table 5.4: An example of a grid of azimuths of lines of intersection of discontinuities. In the table, dip directions and dip amounts of three discontinuities are arranged in the left two columns and the top two rows. The remaining cells in the table indicate the azimuths of all possible lines of intersection between the three discontinuities. For example, the highlighted cell is the azimuth of the intersection line between discontinuity orientations 334/72 and 285/85 (dip direction/dip amount).

		Dip Direction (Degrees)	334	285	185
Dip Direction (Degrees)	Dip Amount (Degrees)	Dip Amount Degrees)	72	85	69
334	72		0	1	258
285	85		1	0	207
185	69		258	207	0

Table 5.5: An example of a grid of plunge values of lines of intersection of the three discontinuities whose data are given in Table 5.4. The highlighted cell is the plunge of the intersection line between discontinuity orientations 334/72 and 285/85 (dip direction/dip amount).

		Dip Direction (Degrees)	334	285	185
Dip Direction (Degrees)	Dip Amount (Degrees)	Dip Amount (Degrees)	72	85	69
334	72		0	70	37
285	85		70	0	67
185	69		37	67	0

1) Create two grids, one for azimuth and the other for plunge, of all possible discontinuity intersections in two separate worksheets (worksheets 1&2) (see Tables 5.4 & 5.5 for examples of intersection azimuth and plunge grids)

2) Create a grid in worksheet 3 that compares discontinuity intersection azimuths with the slope azimuth, and assigns a value of 1 if the intersection azimuth plunges is in the same direction as the slope face.

3) Create a grid in worksheet 4 that checks if wedge sliding can take place on both discontinuity surfaces, and assigns a value of 1 if a wedge can slide on both intersecting discontinuities (Markland's criteria refined by Hocking, 1976)

4) Create a grid in worksheet 5 that compares the plunge of discontinuity intersection and apparent dip of slope face, and assigns a value of 1 if plunge of discontinuity intersection is less than the apparent dip of the slope face.

5) Create a grid in worksheet 6 that compares discontinuity intersection plunge and friction angle, and assigns a value of 1 if discontinuity intersection plunge is greater than friction angle.

6) Create a grid in worksheet 7 that evaluates results of steps (2), (3), (4), and (5), and assigns a value of 1 if the sum of steps (2), (3), (4), and (5) is 4

7) Calculate wedge failure index in worksheet 8 by adding the number of cells that have a value of 1 from worksheet 7 and dividing the sum by the total number of discontinuity intersections.

Figure 5.7: Flow chart showing steps involved in determination of wedge failure index.

1) Create a grid in worksheet 1 for plunge values of all possible discontinuity intersections.

2) Create a grid in worksheet 2 that assigns a value of 1 for plunge values greater than 80 degrees.

3) Calculate Type B toppling failure index in worksheet 3 by adding the number of cells that have a value of 1 from worksheet 2 and dividing the sum by the total number of possible discontinuity intersections.

Figure 5.8: Flow chart showing steps involved in the determination of Type B toppling failure index.

Table 5.6: Results of kinematic analysis for slopes comprised of competent rock units, using the quantitative approach.

Site	Rock Unit	Plane Failure Index	Wedge Failure Index	Type A Toppling Failure Index	Type B Toppling Failure Index
ADA-32-12-	L.ST.*	0	0.04	0.23	0.53
ATH-33-14	S.ST.**	0.07	0.30	0	0.01
BEL-470-6	L.ST.	0.01	0.09	0.02	0.82
CLA-4-8	L.ST.	0	0.08	0.07	0.36
COL-7-5	S.ST	0.21	0.29	0.03	0.19
GUE-77-8	S.ST	0.02	0.07	0.07	0.26
JEF-CR77-0.38	S.ST	0.09	0.08	0.01	0.01
LAW-52-11	S.ST	0.09	0.14	0.02	0.04
LIC-16-28	S.ST	0.28	0.19	0.07	0.01
MUS-70-11	S.ST	0.05	0.32	0.03	0.22
RIC-30-12	S.ST	0	0.14	0.04	0.69
WAS-7-18	S.ST	0.07	0.36	0.07	0.59

* L.ST. = Limestone; **S.ST. = Sandstone

The quantitative approach can also be used to perform a sensitivity analysis showing the variation of failure index with change in slope angle. The Microsoft Excel spreadsheet used in the quantitative approach automatically updates failure indices as the slope angle is changed. The variation of failure index with change in slope angle (40, 50, 60, 70, 80, and 90 degrees) was investigated for the 12 sites. Such an analysis can help determine a stable slope angle (failure index almost zero). Since Type B toppling index considers only the presence of steep (> 80 degrees) lines of intersection without considering the effect of slope angle, sensitivity analysis cannot be performed for Type B toppling index. Figure 5.9 shows an example of sensitivity analysis for the CLA-4-8 site and Appendix 13 provides the results of sensitivity analysis for all 12 sites. Figures 5.10, 5.11, and 5.12 show plots of failure index versus slope angle (40, 50, 60, 70, 80, 90 degrees) for plane, wedge, and Type A toppling failures, respectively, for all 12 sites. Table 5.7 summarizes the results presented in Figures 5.10 - 5.12, indicating the number of sites that have failure index values greater than 0.1 and 0.3 for a given slope angle. It can be seen from Table 5.7 that none of the 12 sites has an index value greater than 0.1 at slope angles less than or equal to 50 degrees, indicating that all sites can be stable at angles less than 50 degrees. In the case of Type A toppling, which is least sensitive to changes in slope angle, only one site has a failure index value greater than 0.1 at all slope angles (40-90 degrees). None of the sites has a failure index value greater than 0.3 at slope angles less than or equal to 70 degrees (Table 5.7), indicating that all sites can be stable at those angles with respect to all types of failure.

5.1.1.4 Kinematic Analysis for Type B Toppling Failure Using Cartoon Models

As stated previously, Type B toppling is caused by steep lines of intersection of discontinuities and is aided by the weathering of weaker beds within a competent rock unit. The mechanics of Type B toppling failure are similar to undercutting induced failures. As the weaker
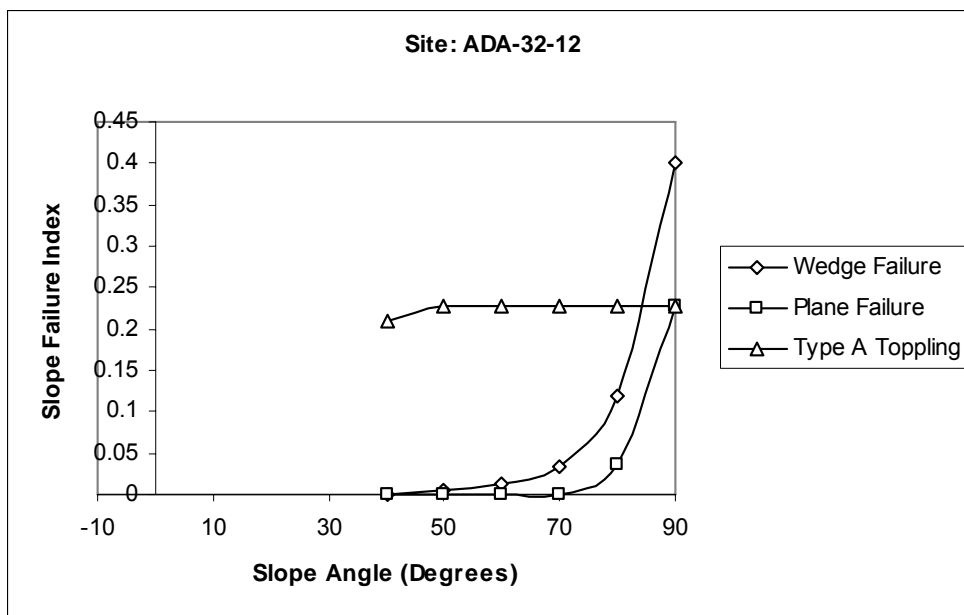
Figure 5.9: An example of sensitivity analysis performed for CLA-4-8 site, using the quantitative approach.
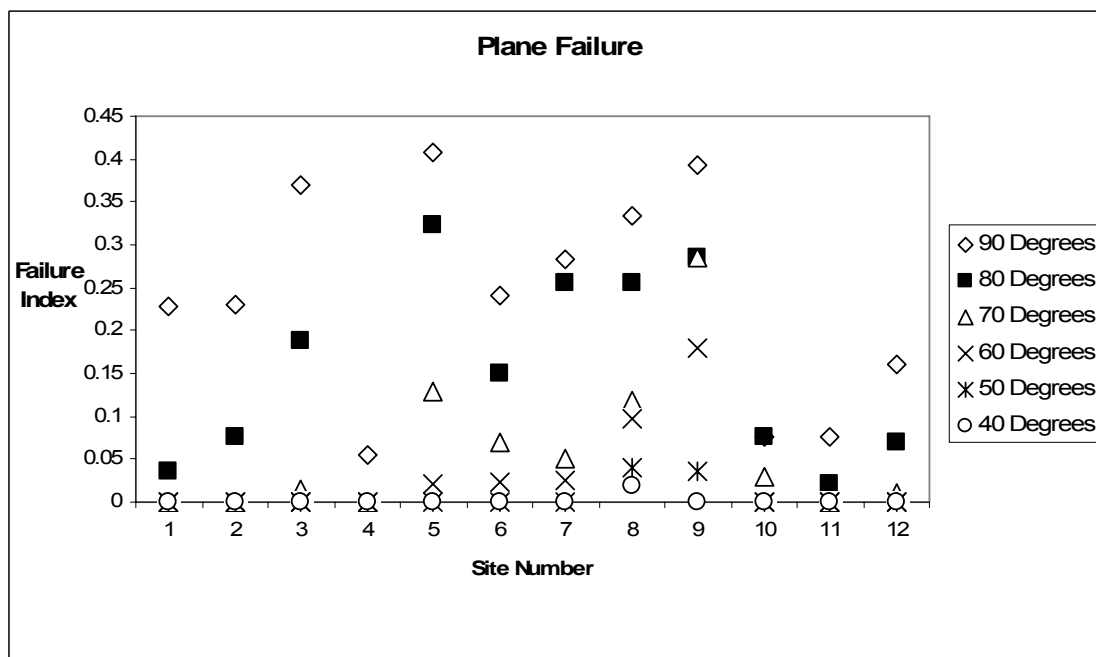
Figure 5.10: Variation of plane failure index with variation in slope angle for the 12 sites.
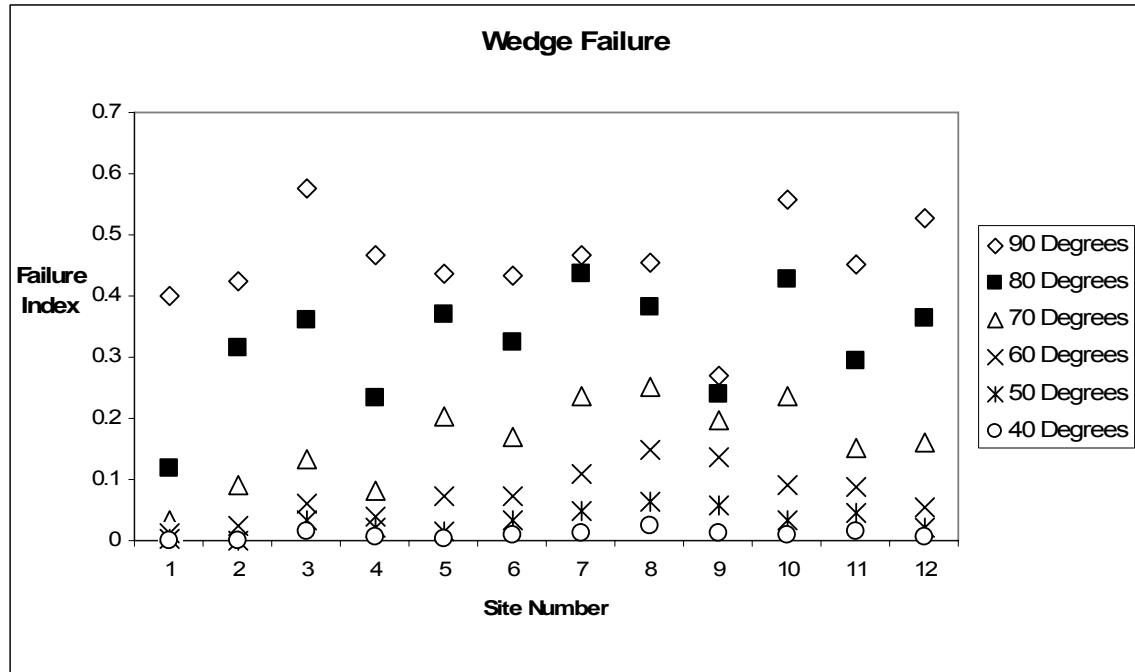
Figure 5.11: Variation of wedge failure index with variation in slope angle for the 12 sites.
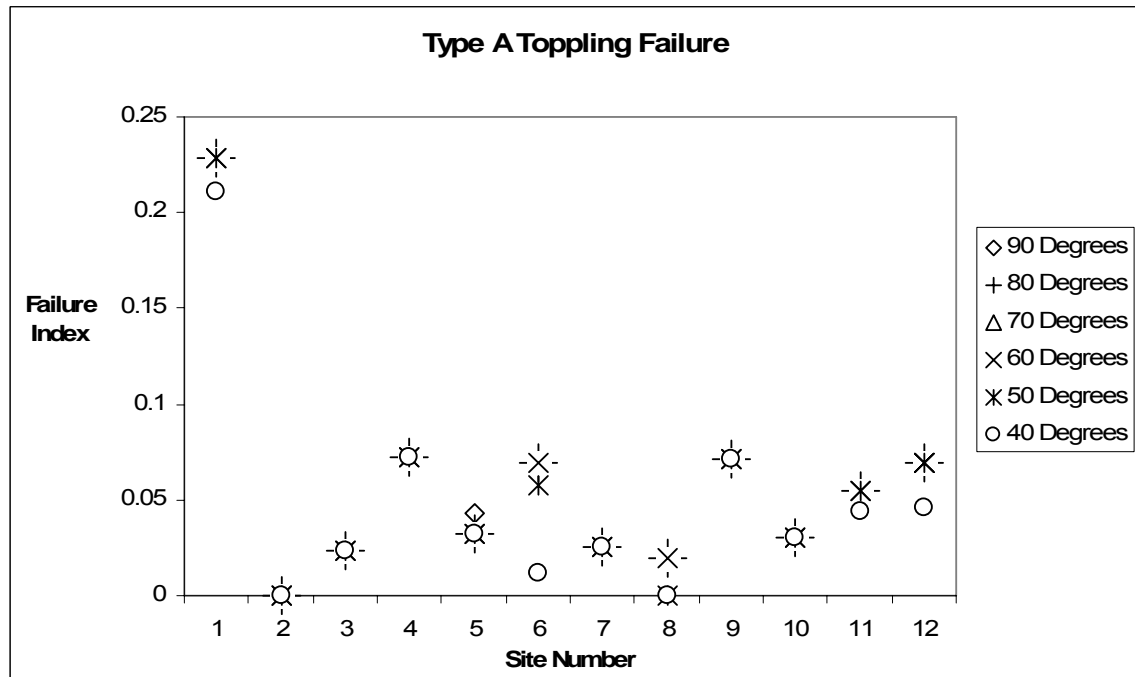
Figure 5.12: Variation of Type A failure index with variation in slope angle for the 12 sites.

Table 5.7: Number of sites, out of 12, with failure index values greater than 0.1 and 0.3 for different types of failure and varying slope angles.

Slope Angle	No. of sites with plane failure index of > 0.3	No. of sites with plane failure index of > 0.1	No. of sites with wedge failure index of > 0.3	No. of sites with wedge failure index of > 0.1	No. of sites with Type A toppling failure index of > 0.3	No. of sites with Type A toppling failure index of > 0.1
90	4	9	11	12	0	1
80	1	6	8	12	0	1
70	0	3	0	9	0	1
60	0	2	0	3	0	1
50	0	0	0	0	0	1
40	0	0	0	0	0	1

layer erodes, the center of gravity of the rock block lying above the weak bed falls outside the slope face, causing Type B toppling failure.

Figure 5.13 shows cartoon models displaying the effect of changing slope angle on the potential for Type B toppling. An ideal slope, having equi-dimensional rock blocks bounded by equally spaced horizontal bedding planes and vertical joints, is used in the figure. Four slope angles are chosen to illustrate the models: 90 degrees, 76 degrees (0.25:1 slope), 63 degrees (0.5:1 slope), and 45 degrees (1:1 slope). The purpose of the analysis is to investigate the maximum number of rock blocks that are destabilized as one rock block at the bottom left most corner of the slope is removed. This mimics the process of weathering and removal of weak rock layers that would cause Type B toppling. In the case of a vertical cut, all nine of the overlying blocks fail when one block from the bottom left corner is removed. If the slope is cut at 0.25:1, the maximum number of overlying rock blocks that are destabilized are two, whereas only one block is affected for a 0.5:1 slope and none for a 1:1 slope. This suggests that 1:1 slope is the most stable with respect to Type B toppling compared to the other slope angles.

5.1.2 Rock Mass Analysis

Rotational failures of slopes in competent rocks can occur due closely spaced jointing, resulting in low rock mass strength and the rock mass behaving as a soil-like material. Both RMR and GSI systems can be used for estimating strength for stability analysis of such failures, using the SLIDE software program. However, only the GSI system is used in this study because of its applicability to all three design units. The RMR and GSI values for the 12 sites are provided in Tables 5.8 and 5.9, respectively.

Slope Angle: 0:1 (90 degrees)

Slope Angle: 0.25:1 (76 degrees)

Slope Angle: 0.5:1 (63 degrees)

Slope Angle: 1:1 (45 degrees)
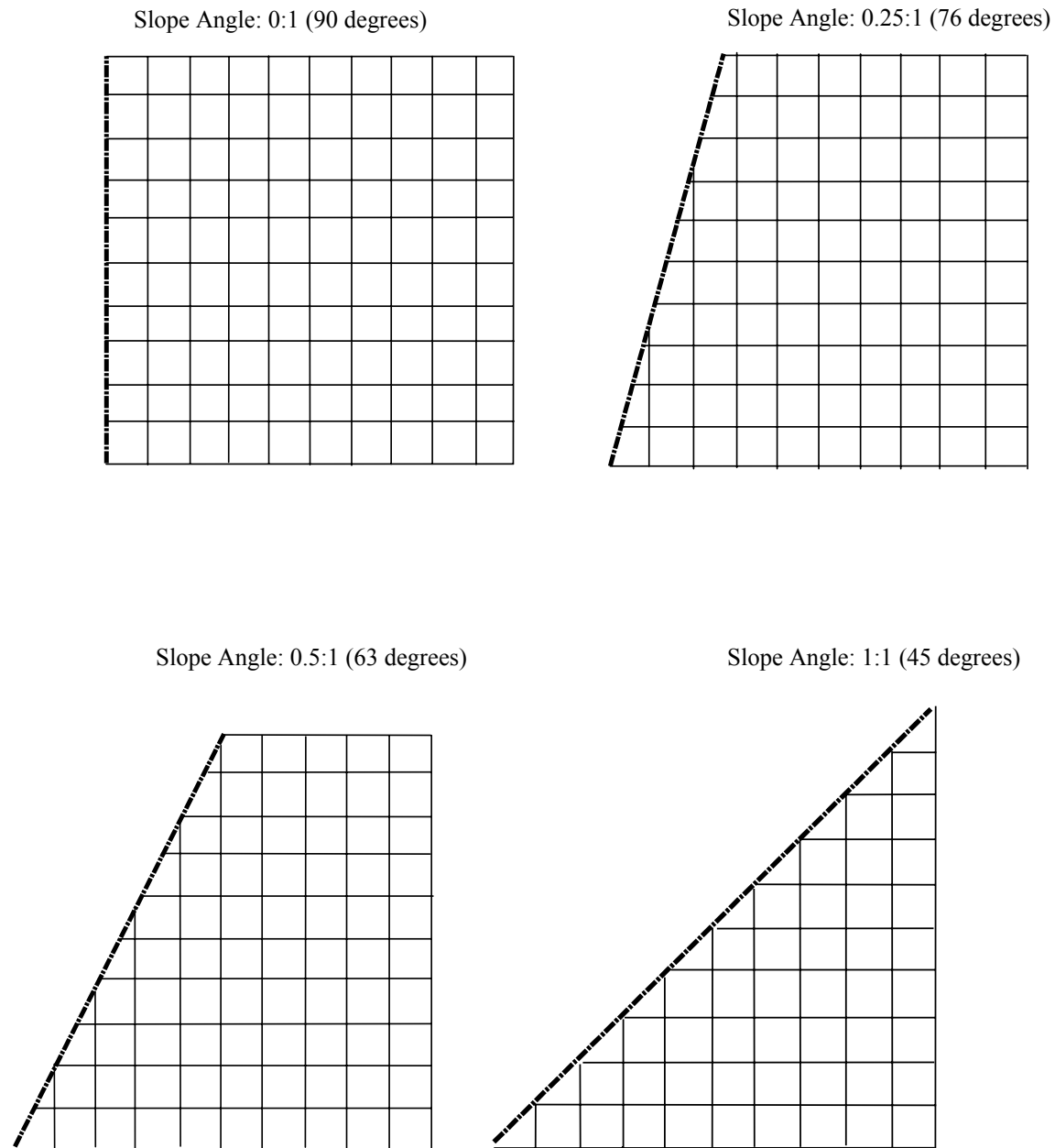
Figure 5.13: Cartoon models used to analyze the effect of slope angle on Type B toppling. The models show that if left-most block at the bottom is removed, the largest number of overlying blocks will be destabilized in case of a 90 degree slope, no overlying block will be destabilized in case of a 45 degree slope, and an intermediate number of blocks will be destabilized for other slope angles

Table 5.8: Rock mass ratings for the 12 sites comprised of competent rock units.

Site	Rock Unit	UCS (Mpa)	UCS Rating	RQD	RQD Rating	Joint Spacing (m)	Joint Spacing Rating	Aperture of Joints (mm)	Joint Conditions Rating	Groundwater Condition Rating	RMR	Rock Mass Description
ADA-32-12	L.ST.*	89	7	95***	20	0.4 – 1.3	23	0.5-2.5	6	-10	56	Good Rock
ATH-33-14	S.ST**	18	2	96	20	0.6	20	>10	0	-10	42	Fair Rock
BEL-470-6	L.ST.	138	12	100	20	0.9	20	0.1-0.25	12	-10	64	Good rock
CLA-4-8	L.ST.	109	12	78	17	0.5	20	>10	0	-10	41	Fair Rock
COL-7-5	S.ST	43	4	40	17	0.8	20	0.25-0.5	12	-10	44	Fair Rock
GUE-77-8	S.ST	42	4	100	20	0.8	20	0.5-2.5	6	-10	50	Fair Rock
LAW-52-11	S.ST	26	4	100	20	2	25	2.5-10	0	-10	49	Fair Rock
JEF-CR77-0.36	S.ST	35	4	77	17	0.7	20	0.1-0.25	12	-10	53	Good Rock
LIC-16-28	S.ST	19	2	50	13	0.4	20	0.25-0.5	12	-10	47	Fair Rock
MUS-70-11	S.ST	32	4	98	20	1.0	20	>10	0	-10	44	Fair Rock
RIC-30-12	S.ST	18	2	43	8	0.4	20	0.1-0.25	12	-10	42	Fair Rock
WAS-7-18	S.ST	65	7	100***	20	1.1	25	0.5-2.5	6	-10	58	Good Rock

* L.ST. = Limestone; **S.ST. = Sandstone; *** RQD obtained from outcrop measurements

Table 5.9: Results of stability analysis for slopes comprised of competent rock units, using GSI and the SLIDE software.

Site No.	Rock Unit	Existing Slope Angle	Average Dry Density (lbs/ft3) ***	Average UCS (psi)****	GSI	Hoek and Brown Constant (mi)	Disturbance Factor, D (Based on Hoek and Brown, 1997)	Factor of Safety
ADA-32-12	L.ST.*	75	158	12885	57	9	0.5	11.9
ATH-33-14	S.ST.**	79	145	2579	57	17	0.7	3.1
BEL-470-6	L.ST.	65	158	19950	30	9	0.7	15.8
CLA-4-8	L.ST.	69	158	15752	45	9	0.3	15.9
COL-7-5	S.ST.	75	145	6221	57	17	0.7	5.8
GUE-77-8	S.ST.	59	145	6596	50	17	0.9	3.8
JEF-CR77-.38	S.ST.	76	145	5011	57	17	0.7	4.7
LAW-52-11	S.ST.	58	145	3764	57	17	0.7	3.9
LIC-16-28	S.ST.	69	145	2925	65	17	0.7	3.9
MUS-70-11	S.ST.	75	145	4573	57	17	0.7	9.2
RIC-30-12	S.ST.	79	145	2571	57	17	0.7	2.7
WAS-7-18	S.ST.	80	145	9478	57	17	0.7	40.0

* L.ST. = Limestone; **S.ST. = Sandstone; ***62.4 lbs/ft^3 = 1 Mg/m^3; ****145psi = 1Mpa

5.1.2.1 Rock Mass rating (RMR) Determination

Although RMR is not directly used in this study, it is discussed here because it can be used to estimate GSI. The ratings for various parameters that contribute to the overall rock mass ratings were determined using the methodology described in Chapter 1. Point load strength index was used to determine unconfined compressive strength. RQD values were obtained from core samples except for two sites (ADA-32-12; WAS-7-5) that were not drilled. Joint spacing was obtained from field data. Since the joints in all cases are smooth, un-filled, and show no evidence of shear movement, aperture was used as the main parameter to characterize joint condition. Discontinuities at all sites show evidence of water flow, but no water flow was observed during the time of investigation and, therefore, all sites resulted in the same groundwater rating. The results of RMR determination show that all 12 sites have ratings greater than 40. Based on the overall RMR ratings, 4 sites are rated as having good rock and 8 as having fair rock (Table 5.8).

5.1.2.2 Stability Analysis Using Geological Strength Index (GSI)

GSI ratings for the twelve sites were determined using the GSI chart for competent rocks, as described in Chapter 1, and stability analysis, based on Hoek and Brown's failure criterion, was performed using the SLIDE software program. The results are presented in Appendix 13-D. Input data for the SLIDE program included unconfined compressive strength, density, mi value, and disturbance factor (D). Point load strength index data were used to obtain unconfined compressive strength and average density values were obtained from laboratory measurements for selected sandstone and limestone samples. Typical mi values of 17 for limestone and 9 for sandstone were used, as suggested by the SLIDE program. A disturbance factor of 0.7 was used for sites that were pre-splitted and 0.9 for mechanically excavated slopes. The factor of safety calculated by the SLIDE software ranges from 2.7 to 40 with an average value of 10.1 (Table

5.9). These results show that there is little likelihood of a rotational failure occurring in competent rock units. An example of rock mass analysis by the SLIDE software is shown in Figure 5.14.

5.1.3 Stability Analysis Using GB 3 Methodology

ODOT design manual GB 3 uses RQD, slake durability index, and unconfined compressive strength values of a rock unit to select slope angles. Two design angles, an upper and a lower, are suggested for rocks having unconfined compressive strength values greater than 3000 psi (20.7 MPa) for all rock index classifications except for poor rock. Analysis based on GB 3 methodology indicates an upper cut-slope angle of 76 degrees for 10 of the 12 competent rock design units and 45 degrees for the remaining two design units (Table 5.10). With respect to the lower angle, 10 design units need to be cut at 63 degrees and the remaining two design units at 34 degrees (Table 5.10).

5.1.4 Comparison of Methods

Kinematic analysis, quantitative approach, and GB 3 methodology indicate stable slope angles of 70-72 degrees, 70 degrees, and 63-76 degrees, respectively. This suggests that use of 0.5 H:1 V to 0.25 H:1 V slopes can prevent most failures in competent rocks except Type B toppling which requires a 1 H:1 V slope. Since a 1 H:1 V slope is too gentle for competent rocks, a 0.5 H:1 V slope may be the best compromise. Rock mass strength analysis does not indicate a potential for global rotational failure in competent rocks nor was such a failure observed in the field.
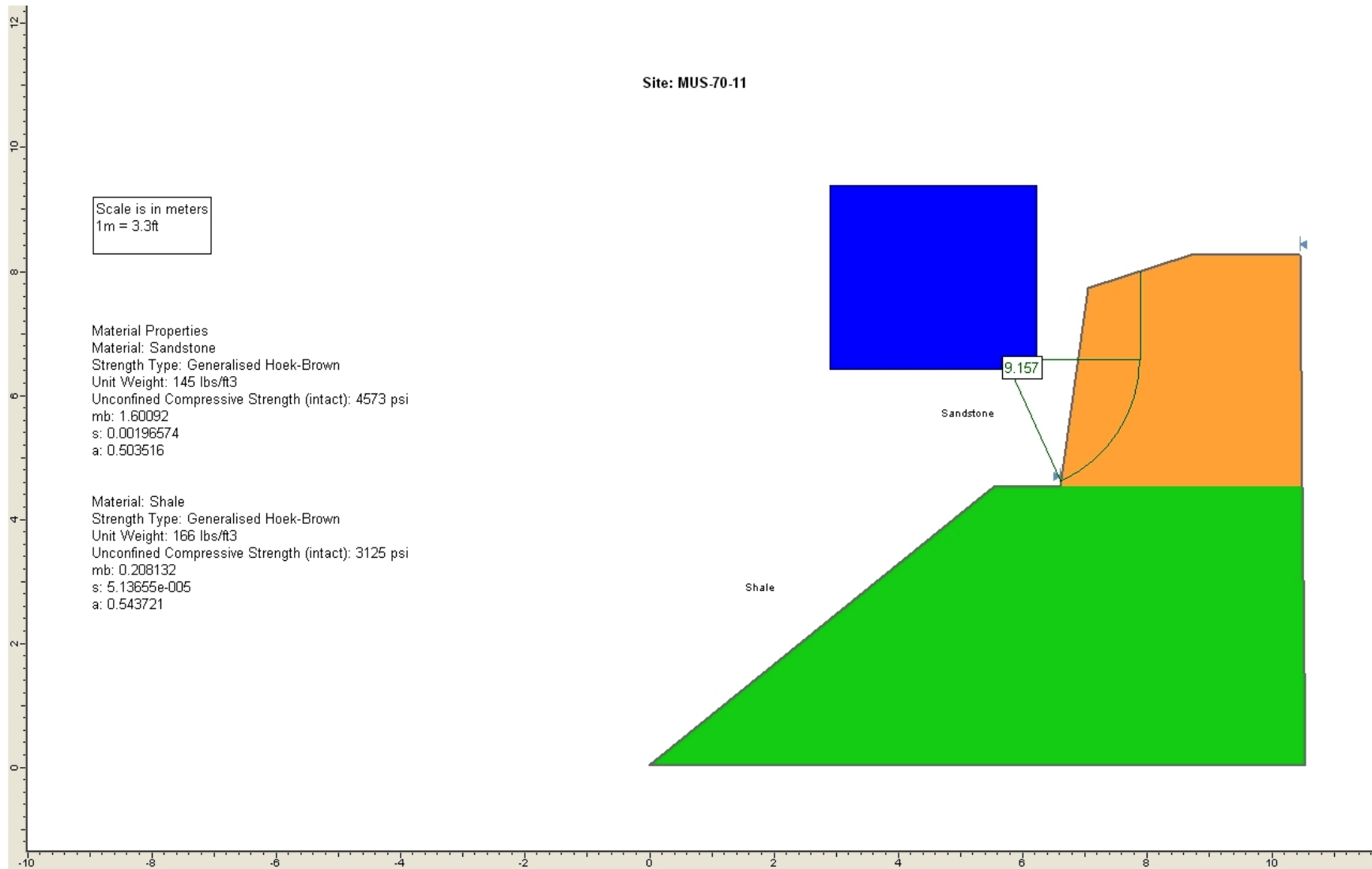
Figure 5.14: An example of stability analysis by the SLIDE software showing the failure circle with the lowest factor of safety value of 9.15. Note: The scale of the diagram is in meters. Although the input data are given in the English units, the software used metric equivalents of the data to compute the factor of safety.

Table 5.10: Result of stability analysis for slopes comprised of competent rock units, using GB 3.

Site No.	Rock Unit	Existing Slope Angle	Average UCS (psi)*****	RQD (%)	Average Id2 (%)	Rock Index (per GB 3)	Upper and Lower Angles by GB 3 Methodology	
ADA-32-12	L.ST. *	75	12885	95 (Outcrop)	99	VG***	76	63
ATH-33-14	S.ST**	79	2579	96 (Core 44 -148ft)	78	VG	76	63
BEL-470-6	L.ST.	65	19950	100 (Core 227- 237)	99	VG	76	63
CLA-4-8	L.ST.	69	15752	78 (Core CLA-68; 10-52ft)	99	VG	76	63
COL-7-5	S.ST	75	6220	40 (ODOT Archives; Core RA-10, 13.5 - 30 ft)	98	VG	76	63
GUE-77-8	S.ST	59	6596	100 (Core 101-150ft)	97	VG	76	63
JEF-CR77-.38	S.ST	76	5011	77 (ODOT Archives; Core JEF-22-13, J-9, 31.1- 86.2 ft)	98	VG	76	63
LAW-52-11	S.ST	58	3764	100 (Core 118-159 ft)	90	VG	76	63
LIC-16-28	S.ST	69	2925	50 (Core 11-53 ft)	71	F****	45	34
MUS-70-11	S.ST	75	4573	98 (ODOT Archive; Core MUS-70-11, 31.9 - 63.9 ft)	89	VG	76	63
RIC-30-12	S.ST	79	2571	43 (Core 3 – 50 ft)	69	F	45	34
WAS-7-18	S.ST	80	9478	100 (Outcrop)	98	VG	76	63

* L.ST. = Limestone; **S.ST. = Sandstone; ***VG = Very Good Rock; ****F = Fair Rock; *****145psi = 1Mpa

5.2 Stability Analysis for Slopes Comprised of Incompetent Rock Units

Seven of the 26 project sites, with significant thicknesses (>10 ft) of incompetent rock units, were selected for stability analysis using currently available methods (Franklin shale rating system and rock mass analysis) and new approaches (use of natural slope angles and talus angles). The incompetent units at these sites are thick enough to be designed independently.

5.2.1 Stability Analysis Using Franklin Shale Rating System

Franklin (1983) developed a relationship between stable slope angle and shale rating. The shale rating is based on slake durability index, plasticity index, and point load strength index. Using the shale rating, two slope angles, an upper angle (if unfavorable discontinuities do not exist) and a lower angle (if unfavorable discontinuities exist) can be obtained from Figure 1.13. These angles are considered to be stable slope angles against an overall (global) rotational failure. The method does not apply to failures caused by surficial weathering (Franklin (1983).

Table 5.11 shows the results of stability analysis using the Franklin shale rating system. The average upper and lower angles are 48 and 25 degrees, respectively. Four of the 7 sites (COL-7-5, FRA-270-23, GUE-22-6, JEF-CR77-0.38) have existing slope angles that are less than the upper angles suggested by Franklin shale rating system, indicating that the incompetent units at these sites are stable against global rotational failure. Two of the sites (ADA-32-12), MUS-70-11) have slope angles that are 5-6 degrees higher than upper slope angles, indicating that the incompetent rock units at these sites are marginally stable. Only one site (JEF-CR77-0.38) has the existing angle less than the lower angle given by the Franklin system. The upper-angle values given by the Franklin shale rating system appear to be more reasonable for this study because the seven sites analyzed do not have unfavorably oriented discontinuities. Therefore, the seven sites are stable to marginally stable against a global rotational failure.

Table 5.11: Results of stability analysis for incompetent rock units, using the Franklin shale rating system.

Site No.	Rock Unit	Existing Slope Angle (Degrees)	Average Is50 (Mpa)	Average Id2, (%)	Average Plasticity Index of Incompetent Units	Franklin Shale Rating	Upper and Lower Angles by Shale Rating	
ADA-32-12	Grey claystone/ mudstone	27	0.4	3	16	2.1	21	11
COL-7-5	Shale/ siltstone	57	2.0	96	*NA	7.4	64	34
FRA-270-23	Shale	35	2.7	99	*NA	7.8	66	35
GUE-22-6	Shale	45	2.3	96	*NA	7.4	64	34
JEF-CR77-0.38	Shale	27	2.0	96	*NA	7.4	64	34
MUS-70-11	Shale	40	1.9	70	14	4.1	35	19
WAS-7-18	claystone/ mudstone (redbeds)	45	0.3	3	12	2.3	23	13

*NA represents rocks whose average second-cycle slake durability index is > 80%.

5.2.2 Stability Analysis Using Rock Mass Strength

RMR analysis is not applicable to incompetent rock units because they do not usually

contain well developed joints. The GSI method by Hoek and Brown (1997), however, can be

used for slopes comprised predominantly of incompetent rocks. The stability of

incompetent rock units present at the 7 selected sites was evaluated by the GSI method, using the

SLIDE program. Input data for the SLIDE program included unconfined compressive strength,

density, mi value, and disturbance factor (D). Unconfined compressive strength values were

obtained from the point load strength index data. Density values were measured for selected core

samples of shale and claystone/mudstone. A mi value of 4 was assigned for claystone/mudstone,

6 for shale, and 7 for inter-layered shale/siltstone units as suggested by the SLIDE program. A

disturbance value of 0.3 was assigned to slopes that were mechanically excavated and a value of

0.5 for slopes that were pre-splitted. A very low GSI value of 20 (the range being 10 to 70) was

chosen for all sites. The results are presented in Appendix 14-A, and summarized in Table 5.12.

Three sites, ADA-32-12 and COL-7-5, JEF-CR77-0.38 resulted in factor of safety values less

than 2 (Table 5.12). Upon recommendations from consultants to this project, these three sites

were further analyzed for saturated conditions (water table assumed to be on the ground surface

by the SLIDE software) which resulted in factor of safety values of 1.0, 0.3, and 0.3, respectively

(Table 5.12). The remaining sites showed factor of safety values of greater than 2.0, suggesting

that they also would be stable under saturated conditions. The factor of safety values of 1 or less

than 1 require additional explanation. If the factor of safety for a rock slope under dry conditions

happens to be greater than 2, it is common to assume that the slope will also be stable under

saturated conditions (Hoek and Bray, 1981). If the factor of safety for dry conditions turns out to

be less than 2, the slope is further analyzed for saturated conditions to evaluate its stability.

Table 5.12: Results of stability analysis for incompetent rock units, using the SLIDE software. Note that factor of safety values for saturated conditions were determined only for those cases where the factor of safety values for dry conditions were found to be less than 2.

Site No.	Rock Unit	Existing Slope Angle (Degrees)	Average Dry Density (lbs/ft3) ***	Average UCS (psi) ****	GSI	Hoek and Brown Constant (mi)	Disturbance Factor, D (Based on Hoek and Brown, 1997)	Factor of Safety (Dry)	Factor of Safety (Saturated)
ADA-32-12	Grey claystone/ mudstone	27	164	626	20	4	0.3	1.6	1.0
COL-7-5	Shale/ siltstone	57	156	2878	20	7	0.5	1.3	0.3
FRA-270-23	Shale	35	166	3854	20	6	0.3	3.3	
GUE-22-6	Shale	45	166	3302	20	6	0.3	2.7	
JEF-CR77-0.38	Shale	27	166	2906	20	6	0.5	1.6	0.3
MUS-70-11	Shale	40	166	3125	20	6	0.3	3.4	
WAS-7-18	Claystone/ mudstone (redbeds)	45	164	428	20	4	0.3	2.3	

***62.4 lbs/ft^3 = 1 Mg/m^3; ****145psi = 1Mpa

Although the three sites analyzed for stability under saturated conditions are found to be

unstable, it is unlikely that completely saturated conditions, with water table at the ground

surface, will develop during the service life of these cut slopes because of the low permeability

of incompetent rock units and because of the fact that ground water table was not encountered at

any of the 15 drilled sites. However, a significant decrease in factor of safety upon saturation

does suggest the need for provision of surface drains to minimize infiltration.

5.2.3 Stability Analysis Using Natural Slope Angle and Talus Angle

The stability problems observed on slopes consisting of incompetent rock units are associated

mainly with surficial weathering. Raveling is the most common form of slope degradation in

incompetent rocks, accompanied by mudflows in some cases. Stability analyses based on

Franklin shale rating system and rock mass strength are applicable to rotational failures which

were not observed at the study sites. Therefore, it was considered prudent to examine the natural

angles of repose that slopes consisting of incompetent rock units reach after undergoing years of

weathering and erosion. The methods used to determine the natural angles of repose were: 1)

measuring natural slope angles adjacent to cut slopes of the study sites and 2) measuring the

angle of raveled material that had accumulated as talus material at the base of the slope. Ten

sites, nine from the additional 23 sites and one from the 26 project sites, were selected for

determining these two types of angle.

5.2.3.1 Slope Stability Evaluation Using Natural Slope Angle

The ten sites selected for determination of natural slope angle consist of either entirely

incompetent rock units or incompetent rock units with minor competent rock units. The natural

angles of slopes adjacent to the selected sites were measured using the methods described in

Chapter 2. Histograms (Figure 5.15) of natural angles of selected slopes are given in Appendix 14-B. It is very likely that the natural slope angles calculated by the method used in this study include data representing flat hill tops or valley bottoms. Therefore, the maximum angle is considered to represent the natural slope angle. Table 5.13 shows the average and the maximum natural slope angle values for each site. The average maximum natural angle is found to be 17 degrees which is too gentle to use for design purposes. A plot of natural slope angle versus slake durability index did not show any relationship.

5.2.3.2 Slope Stability Evaluation Using Talus Angle

The angle of repose of the raveled material was measured as the talus angle (Table 5.13). The talus angle ranges from 25–40 degrees with an average of 35 degrees. It can be assumed that if slopes are cut at angles close to the talus angle, the raveled material would drape the slope face reducing further degradation and allowing vegetation growth. Field observations of incompetent rock units show that shales, which have high slake durability index values, have higher talus angles than claystones/mudstones which have low slake durability index values. Therefore, a regression analysis was performed to further investigate the relationship between talus-slope angles and slake durability index (Figure 5.16). Although a moderately strong correlation is observed the data are not normally distributed, having three clusters around slake durability index values of < 10%, 70%, and > 90%, which limits its usefulness. However, the relationship between lithology and talus angles (Table 5.14) shows that the red claystone/mudstone units have the smallest angle of 24 degrees as compared with the gray claystones/mudstones and shales which have talus angles of 39 and 37 degrees, respectively. The talus angle data suggest that cut slope angles of approximately 25 degrees or less for redbeds and 35-40 degrees for other incompetent rocks can help reduce the amount of degradation.
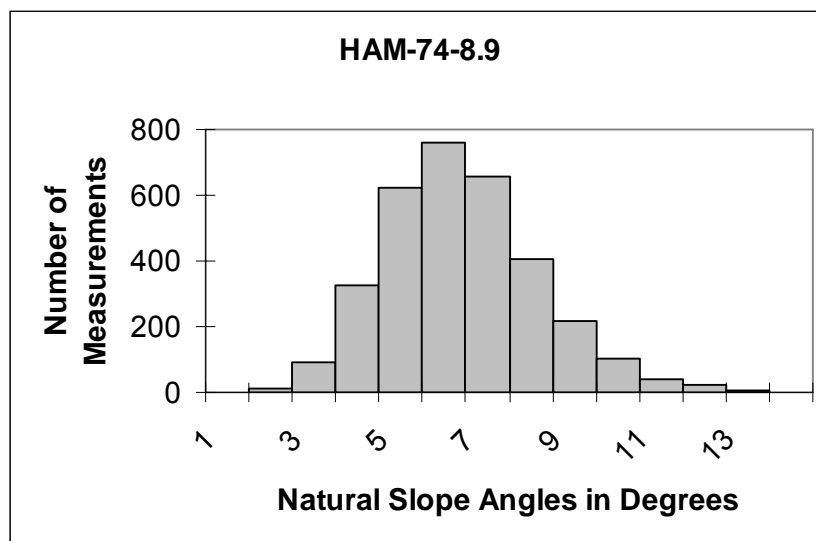
HAM-74-8.9

Figure 5.15: Frequency distribution of natural slope angles for HAM-74-8.9 site.

Table 5.13: Natural slope angle and talus angle values for the 10 sites selected from the 23 additional sites.

Site	Rock Unit	Slake Durability Index (%)	Mean Natural Angle (Degrees)	Maximum Natural Angle (Degrees)	Average Talus Angle (Degrees)
ATH-33-23	Red claystone/mudstone (redbeds)	3.2	4	12	25
ATH-50-28	Red claystone/mudstone (redbeds)	2.8	4	12	26
COL-11-16	Shale	90.8	20	36	40
COL-30-30	Shale	96.7	14	29	40
FRA-270-23	Shale	99.3	15	23	36
GUE-77-21	Shale	93.8	5	10	35
GUE-70-12.9	Shale	96.3	4	13	37
HAM-74-8.9	Gray claystone/mudstone	65.9	6	11	37
HAM-74-12	Gray claystone/mudstone	67.0	6	10	39
HAM74-16.6	Gray claystone/mudstone	68.0	6	11	39
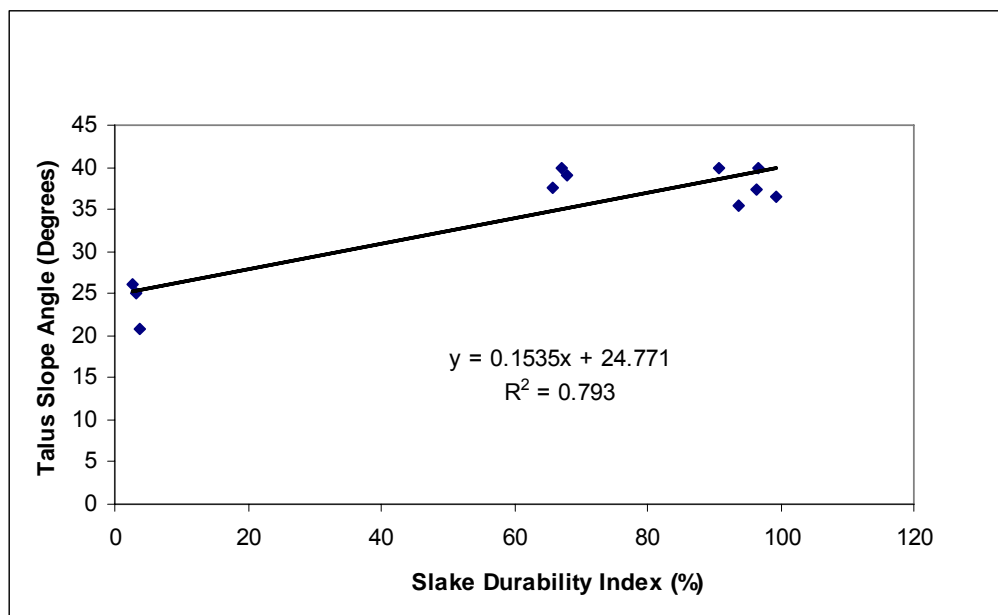
Figure 5.16: Relationship between talus slope angle and slake durability index.

Table 5.14: Maximum natural slope angle and average talus angle values for various litholgies.

Lithology	Maximum Natural Slope Angle (Degrees)	Average Talus Angle (Degrees)
Red claystone/mudstone (redbeds)	12	24
Shale	22	37
Gray claystone/mudstone	11	39
All incompetent rock units	17	34

5.2.3.3 Stability Analysis Using GB 3 Methodology

Cut slope angles for incompetent rock units, as determined by the methodology recommended in GB 3, are given in Table 5.15. Based on GB 3 methodology, slope angles as steep as 76 degrees and as gentle as 45 degrees are recommended. Two sites require special design (substantial flattening of slopes) due to their low unconfined compressive strength values. GB 3 also recommends special design for slopes which happen to be located within certain groups/formations (Conemaugh group, Monongahela group, Washington formation, Kope formation, Miamitown formation), containing redbeds or highly weatherable shales. Two of the 7 sites with incompetent-rock design units require special design because they belong to one of the formations requiring special design. However, GB 3 does not recommend any design-angle value for a substantially flattened slope.

5.2.3.4 Comparison of Methods

The Franklin shale rating indicates average values of 45 and 24 degrees, respectively, for the upper and lower slope angles for incompetent rocks. GB 3 recommends upper angles of 63-76 degrees, lower angles of 45-63 degrees, and flatter angles for weaker rocks such as redbeds. Talus angle approach suggests cut slope angles of 38 degrees for shales and 33 degrees for claystones/mudstones. The natural angle approach is too conservative to be feasible for design purposes. Based on a comparison of all the approaches discussed above, it can be stated that a 1 H:1V slope can be used for shales, especially those which are silty in nature, and a 1.5H:1V or flatter (25 degrees or less) slope is needed for claystones/mudstones including redbeds.

Table 5.15: Result of stability analysis for slopes comprised of incompetent rock units, using GB 3.

Site No.	Rock Unit	Existing Slope Angle (Degrees)	Average UCS (psi)*****	RQD (%)	Average Id^2 (%)	Special Design Requirement Due to Geological Formation (Per GB 3)	Rock Index (per GB 3) *	Upper and Lower Angles by GB 3	
ADA-32-12	Grey claystone/mudstone	27	626	0 (Outcrop)	3		VP*	Special Design****	
COL-7-5	Shale/ siltstone	57	2878	0 (Outcrop)	96		VG**	45	
FRA-270-23	Shale	35	3854	0 (Outcrop)	99		VG	76	63
GUE-22-6	Shale	45	3302	20 (ODOT Archives; Core GUE-22-6, 32.5 – 44 ft)	96		VG	76	63
JEF-CR77-0.38	Shale	27	2906	0 (Outcrop)	96	Required	VG	45	
MUS-70-11	Shale	40	3125	82 (ODOT Archives, Core MUS-70-11, 63.9 - 101.1 ft)	70		G***	63	45
WAS-7-18	Claystone mudstone/ (redbeds)	45	428	0 (Outcrop)	3	Required	VP	Special Design	

* VP = very poor rock, **VG = very good rock, ***G = good rock
**** Special design required due to low (< 1500 psi) unconfined compressive strength; ***** 145 psi = 1 MPa

5.3 Stability Analysis for Slopes Comprised of Inter-Layered Competent and Incompetent Rock Units

As discussed in Chapter 1, undercutting-induced rockfalls are the predominant mode of failure affecting slopes comprised of inter-layered rock units. Specific methods for analyzing the stability of slopes subject to undercutting-induced failures are not available in literature. Therefore, the currently available methods, such as Franklin shale rating system and rock mass strength analysis, were used to evaluate the potential for a global rotational failure at sites containing inter-layered rock units. In addition, a statistical approach was used to evaluate the stability of these slopes with respect to total amount of undercutting, total amount of recession of the undercut rock units, and fate and volume of rockfalls.

5.3.1 Stability Analysis Using Franklin Shale Rating System

Fourteen inter-layered design units from 12 of the 26 project sites were selected (Table 5.16) for analysis using the Franklin shale rating system. Appendix 15-A provides the data used for Franklin shale rating system. Weighted average values of slake durability and point load strength indices were used to rate rocks according to shale rating system. The plasticity index values of only the incompetent rock units were used for this purpose. The upper and lower bounds of stable angles were obtained using Figure 1.13. The upper slope angle ranges from 24–64 degrees with an average of 39 degrees (Table 5.16) whereas the lower slope angle ranges from 14–35 degrees with an average of 21 degrees. For 11 of the 14 design units, the upper angles given by shale rating are less than the existing slope angles (Table 5.16) implying that these slopes are not completely stable. For all 14 design units, the lower angles suggested by shale rating are found to be less than the existing slope angles, indicating that the existing slope

Table 5.16: Result of stability analysis for slopes comprised of inter-layered competent and incompetent rock units, using the Franklin shale rating system.

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted Is_{50} (Mpa)	Weighted Id^2 (%)	Plasticity Index of Incompetent Units From Outcrop Samples *	Franklin Shale Rating	Upper and Lower Angles by Shale Rating	
ADA-41-15	Limestone Inter-layered with grey claystone/mudstone	60	40	43	2.8	66	14	3.9	34	17
ATH-50-23	Limestone and sandstone inter-layered with claystone/mudstone (redbeds)	50	50	33	1.7	65	10	4	35	18
BEL-470-6	Limestone inter-layered with green shale	26	74	50	1.6	76	10	4.4	36	19
BEL-7-10	Limestone inter-layered with green shale	47	53	53	3.9	78	13	4.5	36	20
BEL-7-10	Sandstone inter-layered with green shale	30	70	53	3.1	92	5**	7.3	63	32
BEL-70-22	Minor sandstone and limestone inter-layered with shale	30	70	42	1.9	65	13	3.9	34	17
CLE-275-5	Grey claystone/mudstone inter-layered with minor limestone	15	85	38	1.2	57	17	3.5	30	16
HAM-126-12	Limestone inter-layered with grey claystone/mudstone	62	38	45	3.3	73	17	4.2	35	19

Table 5.16 (contd.):

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted Is^{50} (Mpa)	Weighted Id^2 (%)	Plasticity Index of Incompetent Units From Outcrop Samples *	Franklin Shale Rating	Franklin's Upper and Lower Angles	
HAM-74-6	Grey claystone/mudstone inter-layered with minor limestone	40	60	36	2.1	76	11	4.4	36	19
LAW-52-11	Sandstone inter-layered with grey shale	15	85	70	1.4	85	3.3**	5.5	44	24
LAW-52-11	Sandstone with minor limestone inter-layered with shale	57	43	58	2.1	74	5	4.3	35	19
MEG-33-15	Claystone/mudstone (redbed) inter-layered with minor sandstone	15	85	38-50	0.4	22	9	2.7	24	14
MEG-33-6	Claystone/mudstone (redbed) inter-layered with minor sandstone	60	40	40	0.8	70	6**	4.2	35	19
STA-30-27	Shale inter-layered with minor siltstone	24	76	71	2.8	94		7.4	64	34

*Plasticity index values from outcrop samples are preferred for analysis as the plasticity index obtained from core samples can be unreliable since the material used for determining the Atterberg limits test was obtained from what was left after performing the slake durability test on core samples and had lost some of the fine material. ** Core samples

angles (Table 5.16) are too steep. Since unfavorable discontinuities were not observed at the 12

sites, using the upper angle values is considered to be more appropriate.

5.3.2 Stability Analysis Using Rock Mass Strength

The 14 inter-layered design units were also evaluated for global failure using rock mass strength,

as given by GSI, and the SLIDE software. The input parameters for determining factor of safety

included density, unconfined compressive strength, GSI, mi value, and disturbance factor (D).

Because of the inter-layered nature of these design units, density, unconfined compressive

strength, and mi values of competent and incompetent units were weighted based on their

respective thicknesses. The GSI values assigned for the inter-layered design units with

competent rock unit thickness being 40–60 %, < 30 %, and <10 % of total thickness were 35, 25,

and 20, respectively. Appendix 15-A presents the data used for rock mass strength analysis and

Appendix 15-B provides the results of analysis by the SLIDE software.

The results of stability analysis show that two inter-layered design units have factor of

safety values less than 1.5 (Table 5.17), indicating that they are marginally stable under dry

conditions. SLIDE analysis for saturated conditions for the three design units (BEL-470-6, BEL-

7-10, and LAW-52-11) that have factor of safety values less than 2 under dry conditions (Table

5.17) yields factor of safety values of 0.3, 0.7, and 0.1, respectively (Table 5.17). As stated in

Section 5.2.2, saturated conditions (water table on ground surface), are unlikely to occur.

5.3.3 Stability Analysis Using GB 3 Methodology

Cut slope angles for inter-layered design units by the methodology recommended in GB

3, are given in Table 5.18. Input parameters for GB 3 analysis were weighted based on their

respective thicknesses. The results of analysis indicate that upper and lower cut slope angles of

Table 5.17: Results of stability analysis for inter-layered competent and incompetent rock units, using GSI and the SLIDE software.

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted Average Dry Density (lbs/ft^3)*	Weighted UCS (psi)**	GSI	Weighted Hoek and Brown Constant (mi)	Disturbance Factor, D (Based on Hoek and Brown (1997)	Factor of Safety (dry)	Factor of Safety (saturated)
ADA-41-15	Limestone Inter-layered with grey claystone/mudstone	60	40	43	159	9309	35	7	0.3	14.9	
ATH-50-23	Limestone and sandstone inter-layered with claystone/mudstone (redbeds)	50	50	33	161	4957	35	6.5	0.3	3.3	
BEL-470-6	Limestone inter-layered with green shale	26	74	50	164	4138	25	6.5	0.7	1.3	0.3
BEL-7-10	Limestone inter-layered with green shale	47	53	53	162	11535	35	6.5	0.7	3.3	
BEL-7-10	Sandstone inter-layered with green shale	30	70	53	160	7407	25	12	0.7	1.8	0.7
BEL-70-22	Minor sandstone and limestone inter-layered with shale	30	70	42	160	5368	25	7.9	0.3	2.9	
CLE-275-5	Grey claystone/mudstone inter-layered with minor limestone	15	85	38	163	3400	25	4	0.3	2.8	

Table 5.17 (contd.):

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted Average Dry Density (lbs/ft^3)*	Weighted UCS (psi)**	GSI	Weighted Hoek and Brown Constant (mi)	Disturbance Factor, D (Based on Hoek and Brown (1997)	Factor of Safety (dry)	Factor of Safety (saturated)
HAM-126-12	Limestone inter-layered with grey claystone/mudstone	62	38	45	160	10648	35	7	0.3	6.2	
HAM-74-6	Grey claystone/mudstone inter-layered with minor limestone	40	60	36	162	6950	35	6	0.3	4.9	
LAW-52-11	Sandstone inter-layered with grey shale	15	85	70	163	3149	25	10.5	0.7	1.2	0.1
LAW-52-11	Sandstone with minor limestone inter-layered with shale	57	43	58	154	6135	35	12	0.7	3.6	
MEG-33-15	Claystone/mudstone (redbed) inter-layered with minor sandstone	15	85	38-50	161	1083	25	5.9	0.3	2.1	
MEG-33-6	Claystone/mudstone (redbed) inter-layered with minor sandstone	60	40	40	153	2716	25	11.8	0.3	3.2	
STA-30-27	Shale inter-layered with minor siltstone	24	76	71	161	5649	25	8.6	0.3	2.9	

*62.4 lbs/ft^3 = 1 Mg/m^3; **145psi = 1Mpa

Table 5.18: Result of stability analysis for incompetent design units, using GB 3.

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted UCS (psi)*	RQD (%)	Weighted Id^2 (%)	Rock Index (per ODOT)**	ODOT Upper and Lower Angle	
ADA-41-15	Limestone Inter-layered with grey claystone/mudstone	60	40	43	9309	46 (Core 14-50ft)	66	F	63	45
ATH-50-23	Limestone and sandstone inter-layered with claystone/mudstone (redbeds)	50	50	33	4957	0 (Outcrop)	65	F	63	45
BEL-470-6	Limestone inter-layered with green shale	26	74	50	4138	94 (Core 201-227)	76	VG	76	63
BEL-7-10	Limestone inter-layered with green shale	47	53	53	11535	79 (Core 194-245ft)	78	G	76	63
BEL-7-10	Sandstone inter-layered with green shale	30	70	53	7407	94 (Core 146-194ft)	92	VG	76	63
BEL-70-22	Minor sandstone and limestone inter-layered with shale	30	70	42	5368	73 (Core 81-140ft)	65	G	76	63
CLE-275-5	Grey claystone/mudstone inter-layered with minor limestone	15	85	38	3400	28 (Core 17-70ft)	57	P	45	34
HAM-126-12	Limestone inter-layered with grey claystone/mudstone	62	38	45	10648	56 (Core 15-100ft)	73	F	63	45

Table 5.18 (contd.):

Site No.	Rock Unit	Competent Unit Proportion (%)	Incompetent Unit Proportion (%)	Existing Slope Angle	Weighted UCS (psi)*	RQD (%)	Weighted Id^2 (%)	Rock Index (per ODO)T**	ODOT Upper and Lower Angle	
HAM-74-6	Grey claystone/mudstone inter-layered with minor limestone	40	60	36	6950	0 (Outcrop)	76	F	63	45
LAW-52-11	Sandstone inter-layered with grey shale	15	85	70	3149	85 (Core 26-118ft)	85	G	63	45
LAW-52-11	Sandstone with minor limestone inter-layered with shale	57	43	58	6135	94 (Core 159-174ft)	74	VG	76	63
MEG-33-15	Claystone/mudstone (redbed) inter-layered with minor sandstone	15	85	38-50	1083	0 (Outcrop)	22	VP	45	34
MEG-33-6	Claystone/mudstone (redbed) inter-layered with minor sandstone	60	40	40	2716	91 (Core 21-90ft)	70	VG	45	
STA-30-27	Shale inter-layered with minor siltstone	24	76	71	5649	29 (Core 7-72ft)	94	VG	76	63

* 145 psi = 1 MPa; **VG = very good rock, G = good rock, F = fair rock, P = poor rock

76 and 63 are recommended for 6 of the 12 inter-layered rock design units. Upper and lower cut slope angles of 63 and 45 are recommended for five of the inter-layered design units. Gentle upper cut slope angles of 45 degrees are recommended for three design units. Twelve of the 14 design units have existing slope angles less than the upper angles suggested by GB 3, implying that the existing slopes are stable. Based on the lower angle values recommended by GB 3, 9 of the 14 design units are stable.

5.3.4 Stability Analysis Using a Statistical Approach

Neither the Franklin shale rating system nor the GSI method was developed for analyzing stability problems associated with undercutting-induced rockfalls. In order to develop a rational slope design (slope angle, bench location, and stabilization techniques) for rocks subject to differential weathering, factors influencing the process of undercutting and undercutting-induced rockfalls were studied using statistical methods. The purpose of statistical analysis was to address the following questions:

1. What are the geological and geotechnical parameters of the undercut and the undercutting rock units that influence the total amount of undercutting?

2. What are the geological and geotechnical parameters that influence the amount of recession of the undercut unit (undercut units receding slowly generate much fewer rockfalls than fast receding units)?

3. Where will the undercutting-induced rockfalls end up with respect to the slope geometry (on the slope face, on the bench, in the catchment ditch)?

4. Is there a final stable angle that undercutting units reach after which further undercutting does not occur?

The answers to the above stated questions are expected to provide a better insight into the undercutting process and associated rockfall activity, providing basis for design considerations.

5.3.4.1 Total Amount of Undercutting

Field investigation lead to the following relationships with respect to the total amount of undercutting:

1. Amount of undercutting is greater near the crest of a slope than the toe of a slope.

2. Competent rock units underlain by shales are undercut to a much lesser extent than those underlain by claystones and mudstones.

3. Undercutting rock units with steeper slope angles result in greater amount of undercutting than those with gentler slope angles.

Based on the above observations, the following seven parameters pertaining to the undercut unit were chosen for detailed study:

1. Distance from the bottom of the undercut unit to the slope crest.

2. Relative position of the undercut unit on the slope face. This was calculated by dividing the distance from the bottom of the undercut unit to the slope crest by the total height of the cut slope. The relative position was used to normalize the effect of varying slope heights and use a standardized value.

3. Total thickness of the undercut rock unit.

4. Spacing of orthogonal joins within the undercut unit. Joint spacing is directly related to permeability of the undercut unit.

5. Slake durability index value of the undercutting unit.

6. Age of the cut slope.

7. Original slope angle of the undercutting unit

Thirty nine undercut rock units from 19 sites were selected for studying the role of the seven undercutting-related parameters listed above. For each site, a vertical profile was drawn using the laser range finder. The profile was used to measure the amount of undercutting, distance of the undercut rock unit from slope crest and adjacent bench, thickness of the undercut rock unit, and slope angle of the undercutting unit. For the undercut rock unit under consideration, the average joint spacing data and average slake durability index value of the underlying rock unit were recorded. A single vertical profile was used for an undercut unit of uniform thickness and joint spacing. In cases where total thickness of the rock unit and joint spacing varied, especially within sandstones, multiple profiles were used to obtain the relevant data.

Bivariate and multiple regression methods were used to investigate the effect of seven parameters (independent variables) on the total amount of undercutting (dependent variable), using the SPSS software. Appendix 15-C summarizes the data pertaining to dependent and independent variables and the corresponding descriptive statistics (range, minimum, maximum mean, median, variance, standard deviation, skewness, kurtosis, confidence interval).

<u>Bivariate Regression Analysis</u>

Scatter plots are frequently used to investigate if a linear or nonlinear relationship exists between dependent and independent variables. Scatter plots between each of the seven independent variables and total amount of undercutting were made and R^2 values were determined for the best fit lines. R^2 indicates how much of the variation observed in the dependent variable is explained by the independent variables with values close to 1 indicating that the regression equation explains nearly 100 % of the total variation of the dependent variable. Table 5.19 lists R^2 values for various relationships. Distance from bottom of the

Table 5.19: Results of bi-variate regression analysis between total amount of undercutting and various parameters influencing the amount of undercutting.

Parameter	R^2
Distance of undercut rock unit from slope crest (ft)	0.35
Total thickness of undercut rock unit (ft)	0.07
Relative position of undercut rock unit from slope crest (ratio)	0.32
Slake durability index of undercutting rock unit (%)	0.14
Spacing of orthogonal joints within undercut rock unit (in)	0.22
Original slope angle of undercutting rock unit (yr)	0.05
Age of road cut (yr)	0.06

undercut unit to slope crest, relative position of the undercut unit from slope crest, and spacing of orthogonal joints within the undercut unit show low R^2 values of 0.35, 0.32, and 0.22, respectively (Table 5.19). The remaining four independent variables resulted in even lower R^2 values.

Multiple Regression Analysis

The result of bivariate regression analysis showed that a single parameter cannot explain the variation observed in the total amount of undercutting. Therefore, the effect of multiple parameters on the total amount of undercutting was investigated using multiple regression analysis. The objective was to determine which independent variables have the most effect on the dependent variable (total amount of undercutting) and, therefore, should be given due consideration during design. The method results in a model, expressed in the form of a linear equation, which explains the empirical relationship that independent variables (X_1-Xn) have with the dependent variable (Y) as shown below:

$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots bnXn$, where b_0 is a constant, Y is the dependent variable, X1...Xn are the independent variables, and $b_1 \ldots b_n$ are the coefficients of independent variables.

In multiple regression analysis, the R^2 value is a measure of how well the regression model explains the total variation. R^2 for multiple regression analysis is calculated by dividing SSR (sum of squares representing the variation explained by the regression) by SST (sum of squares representing the variation of the dependent variable) (Dielman, 2001).

$SST = \sum_{i=1-n} (Y_i - \bar{Y})^2$,

$SSR = \sum_{i=1-n} (Y\hat{}_i - \bar{Y})^2$,

$SSE= \sum_{i=1-n} (Y_i-Y\hat{}_i)^2$,where Yi are values of the dependent variable,

$\bar{Y}$ is the average of the dependent variable, $Y\hat{}$ is the predicted value of

the dependent variable.

The sum of SSR and SSE gives SST. SSE is the sum of squares representing the variation

of the dependent variable that is unexplained by the regression.

The significance of the obtained R^2 is evaluated using the F statistic which is calculated

using the following equation (Dielman, 2001).

$F = (SSR/K)/(SSE/n-K-1)$, where n is the number of data and K is the number of

independent variables.

According to Dielman (2001), the null hypothesis to be tested using the F statistic is that

all coefficients of the dependent variable are zero and the alternative hypothesis is that at least

one of the coefficients is not equal to zero. "Acceptance of the null hypothesis implies that the

independent variables are of little or no use in explaining the dependent variable and its rejection

implies that at least one of the independent variables explains the variation of the dependent

variable" (Dielman, 2001). If the probability of the F value, which depends on the number of

data and independent variables, is less than 0.01 (1 % level of significance), the null hypothesis

can be rejected. One percent level of significance means that the probability of null hypothesis

being rejected, when it should not have been rejected, is less than 1% (Davis 2001).

A partial F statistic is used to test if any subset of variables is useful in explaining any

variation in the dependent variable and is calculated using the following equation:

$F= (SSE_r- SSE_f /K-L)/ (SSE_f/n-K-1)$, where subscript r stands for the subset model and

subscript f stands for the full model. L is the number of variables in the subset.

If the regression model passes the F test, indicating that at least one of the independent variables explains the dependent variable, the next step is to check which of the independent variables do not significantly contribute to the regressions model's ability to explain the dependent variable (Dielman, 2001). The t statistic is used for this purpose.

$T = b_n/s_{bn}$ where b_n is the nth coefficient and s_{bn} is the standard deviation of b_n.

The null hypothesis to be tested with the t test is that b_n is zero and the alternative is that b_n is different from zero (Dielman, 2001). To reject the null hypothesis and, thereby, confirm that the independent variable with coefficient of b_n contributes to the regression model, the probability of the calculated t value should be < 0.05 at 5% level of significance (Dielman, 2001).

The ideal assumptions of a multiple regression, according to (Dielman, 2001), are:

1. There is a linear relationship between each of the independent variables and the dependent variable.

2. The variance around the regression model is constant. This means that the residuals, difference between the predicted dependent variable value and the actual dependent variable value, are normally distributed and have a constant variable. Consequently, the scatter plot between the residuals and standardized predicted dependent variables should have a non-systematic or scattered distribution and the histogram of residuals should be normally distributed.

3. The independent variables should not be correlated among each other. The presence of correlation between independent variables, termed as multicolinearity, results in unstable regression coefficients. The variance influence factor (VIF), which is equal to $1/(1-R^2)$,

or its inverse, tolerance, are used to assess multicolinearity. If the tolerance value is less

than 1-R^2, there is probably a problem with multicolinearity (Leech, 2008).

The initial task in performing multiple regression analysis is to evaluate if both the

independent and dependent variables are normally distributed. Data that are not normally

distributed can be transformed into normally distributed data.

In multiple regression analysis, the independent variables can be simultaneously or

hierarchically (entering one variable at a time) entered into the regression model. Hierarchical

entry is useful in checking how entering each variable affects the overall regression model

(Leech, 2008). One of the hierarchical methods is the stepwise regression method which begins

by entering the variable with the largest partial F statistic and checking the importance of the

coefficient of the variable. This method keeps adding more variables, each time resetting the

coefficients and removing the variables if they are found unimportant based on F and t tests.

During the incorporation of a variable into the model, the partial F statistic of the already

entered variable changes and might cause it to be unimportant. The operation stops when the

model has incorporated the variables with the most significant contribution and discarded the

least significant ones (Dielman, 2001).

Data Evaluation and Transformation

Histograms of the independent and dependent variables were plotted to check for

normality (Appendix 15-C). None of the variables showed normal distribution.

All data were transformed using each of the transformation methods listed in Table 5.20.

The normality of each of the transformed data was checked using Q-Q plots (quantile-quantile

plots) that plot quantiles of given data against quantiles of a theoretical normal distribution. If the

data are normally distributed (Figure 5.17), the Q-Q plot will show data points falling on a

Table 5.20: Different functions of transformation.

Type of Transformation	Equation
Squared	X^2
Cubed	X^3
Inverse	$1/X$
Square Root (SQRT)	$X^{1/2}$
Negative reciprocal square root	$-1/X^{1/2}$
Logarithm (Log)	$\text{Log } X$
Adjusted square root	$(X+1-X_{smallest})^{1/2}$
Adjusted logarithm	$\text{Log}(X+10-X_{smallest})$
Adjusted inverse	$2-(1/(X+1-X_{smallest}))$
Reflected adjusted square root	$1+A-(1+X_{largest}-X)^{1/2}$, Where $A = (1+X_{largest}-X_{smallest})^{1/2}$
Reflected adjusted inverse	$2-(1/(1+X_{largest}-X_{smallest}))+(1/(1+X_{largest}-X))$
Reflected adjusted log	$1+A-\text{Log}(X_{largest}-X)$, Where $A = \text{Log }(10+X_{largest}-X_{smallest})$

Histogram

Mean =0.873
Std. Dev. =0.5808
N =49
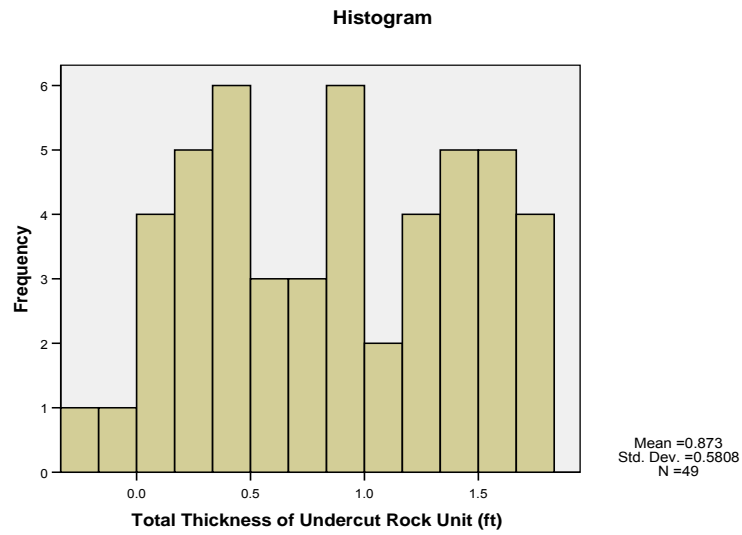
Figure 5.17: An example of a histogram for normally distributed data.
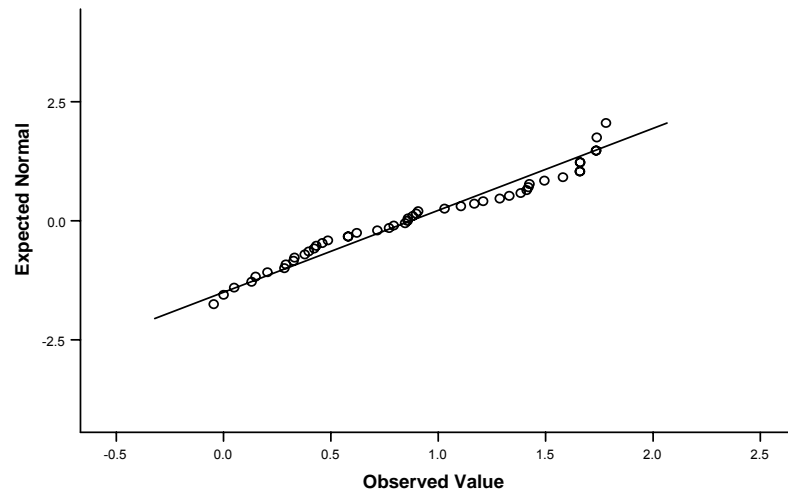
Figure 5.18: An example of a Q-Q plot corresponding to the histogram shown in Figure 5.17.

straight line (Figure 5.18). The Q-Q plots, provided in Appendix 15-C, were used to select the following transformed data for multiple regression analysis:

a) Adjusted square root of distance of the undercut rock unit from slope crest.

b) Adjusted square root of relative position of the undercut rock unit from slope crest.

c) Log of total thickness of the undercut rock unit.

d) Log of spacing of orthogonal joints within the undercut rock unit.

e) Reflected adjusted square root of slake durability index of the undercutting rock unit.

f) Adjusted square root of age of road cut.

g) Squared original slope angle of undercutting rock unit.

The dependent variable (total amount of undercutting) was transformed into log of total amount of undercutting.

Multiple Regression Model

The relationships between transformed data of independent and dependent variables were evaluated using the scatter plots (Appendix 15-D). A correlation matrix relating all transformed variables (Table 5.21) was generated using SPSS. According to the correlation matrix, the transformed values of distance of the undercut rock unit from slope crest, relative position of the undercut rock unit from slope crest, and spacing of orthogonal joints within the undercut rock show the highest correlation coefficient values of -0.62, -0.60, and -0.55 respectively (Table 5.21). Distance of the undercut rock unit from slope crest and relative position of the undercut rock unit from slope crest exhibited high colinearity (Table 5.21). Both simultaneous and stepwise methods of entering independent variables were used to perform the multiple regression analysis. Due to colinearity between distance of the undercut unit form slope crest and the relative position of the undercut unit, either one of these two variables can be included in the list

Table 5.21: Correlation matrix for transformed independent and dependent variables.

	Distance of the undercut rock unit from slope crest (adjusted SQRT)	Total thickness of the undercut rock unit (Log)	Relative position of the undercut rock unit from slope crest (adjusted SQRT)	Slake durability index of the undercutting rock unit (reflected adjusted SQRT)	Spacing of orthogonal joints within the undercut rock unit (Log)	Age of road cut (adjusted SQRT)	Original slope angle of the undercutting unit (squared)	Total amount of undercutting (Log)
Distance of undercut rock unit from slope crest (ft) (adjusted SQRT)	1							
Total thickness of undercut rock unit (ft) (Log)	-0.03							
Relative position of undercut rock unit from slope crest (ratio) (adjusted SQRT)	0.88	0.10	1					
Slake durability index of the undercutting rock unit (%) (reflected adjusted SQRT)	0.38	0.07	0.17	1				
Spacing of orthogonal joints within the undercut rock unit (in) (Log)	0.33	0.44	0.37	-0.01	1			

Table 5.21 (contd.):

	Distance of the undercut rock unit from slope crest (adjusted SQRT)	Total thickness of the undercut rock unit (Log)	Relative position of the undercut rock unit from slope crest (adjusted SQRT)	Slake durability index of the undercutting rock unit (reflected adjusted SQRT)	Spacing of orthogonal joints within the undercut rock unit (Log)	Age of road cut (adjusted SQRT)	Original slope angle of the undercutting unit (squared)	Total amount of undercutting (Log)
Age of road cut (yr) (adjusted SQRT)	-0.09	0.05	-0.09	0.37	-0.55	1		
Slope angle of the undercutting unit (Squared)	0.25	0.11	0.31	-0.08	0.67	-0.31	1	
Total amount of the undercutting (in) (Log)	-0.62	-0.22	-0.60	-0.34	-0.55	0.23	0.24	1

of variables for regression analysis. Therefore, two sets of independent variables, one including the distance of the undercut unit from slope crest and the other with the relative position of the undercut unit, were used for both types of regression methods. The simultaneous regression method resulted in an adjusted R^2 value of 0.62 for the variable set that included the relative position of the undercut unit (Table 5.22), whereas the set with the distance of the undercut unit showed an adjusted R^2 value of 0.59. For the purpose of further discussion, the set that includes the relative position of the undercut unit is used due to its slightly higher R^2 value.

Table 5.23 shows that total thickness of the undercut rock unit and age of slope cut do not contribute much to the regression as indicated by the t-test. Table 5.23 also shows that spacing of orthogonal joints has low tolerance (1/VIF) value of 0.23, implying that it has multicolinearity problem with one or more of the other variables. The distribution of the residuals is normal (Figure 5.19) and the scatter plot between the residuals and the standardized predicted values shows a good scatter (Figure 5.20), implying that a major multiple regression assumption (constant variation of the residuals) is not violated.

Stepwise regression analysis was performed by entering one variable into the model based on the significance of partial F statistic as discussed earlier. Variables with the significance level (partial F value) of < 0.05 were entered and variables with significance level > 0.1 were removed during the operation. Two sets of variables, one containing the distance of the undercut rock unit from slope crest and the other containing the relative position of the undercut rock unit, were used. The former resulted in an R^2 value of 0.59 and the latter, 0.61 (Table 5.24). The variable set containing the relative position is used for further discussions due to its higher R^2 value. Table 5.24 shows that the t test on the coefficients of independent variables results in levels of significance less than 0.05, implying that all variables contribute to the regression. The tolerance

Table 5.22: Model summary and ANOVA for multiple regression using the simultaneous variable entry method.

Model Summary

Model*	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.811	.658	.616	.1824

ANOVA

Model*		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.137	6	.523	15.716	.000
	Residual	1.630	49	.033		
	Total	4.768	55			

*Model's Variables
Independent Variables: (Constant), original slope angle of the undercutting rock unit (Squared), slake durability index of the undercutting rock unit (Reflected Adjusted SQRT), total thickness of the undercut rock unit (Log), relative position of the undercut rock unit from slope crest (Adjusted SQRT), age of road cut (Adjusted SQRT), spacing of orthogonal joints within the undercut rock unit (Log)
Dependent Variable: total amount of undercutting (Log-Transformed)

Table 5.23: Coefficients of independent variables for the multiple regression analysis, using the simultaneous variable entry method.

Model		Unstandardized Coefficients of Variables		Standardized Coefficients of Variables	t	Sig.	Colinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	3.357	.306		10.986	.000		
	Total thickness of the undercut rock unit (Log)	.016	.056	.031	.284	.778	.573	1.744
	Relative position of the undercut rock unit from slope crest (Adjusted SQRT)	-1.195	.257	-.428	-4.651	.000	.825	1.212
	Slake durability index of the undercutting rock unit (reflected adjusted SQRT)	-.046	.012	-.372	-3.705	.001	.691	1.447
	Spacing of orthogonal joints within the undercut rock unit (Log)	-.265	.082	-.566	-3.222	.002	.226	4.422
	Age of road cut (adjusted SQRT)	.032	.024	.174	1.344	.185	.418	2.392
	Original slope angle of the undercutting unit (Squared)	7.27E-005	.000	.316	2.552	.014	.454	2.201
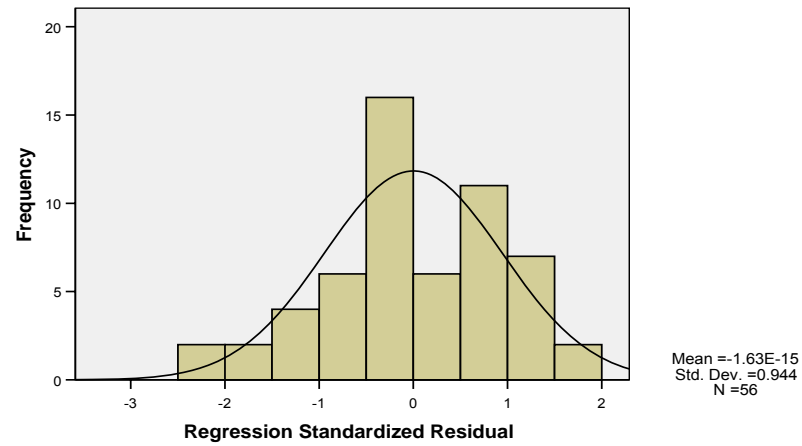
Figure 5.19: Frequency distribution histogram of residuals for the simultaneous variable entry method.
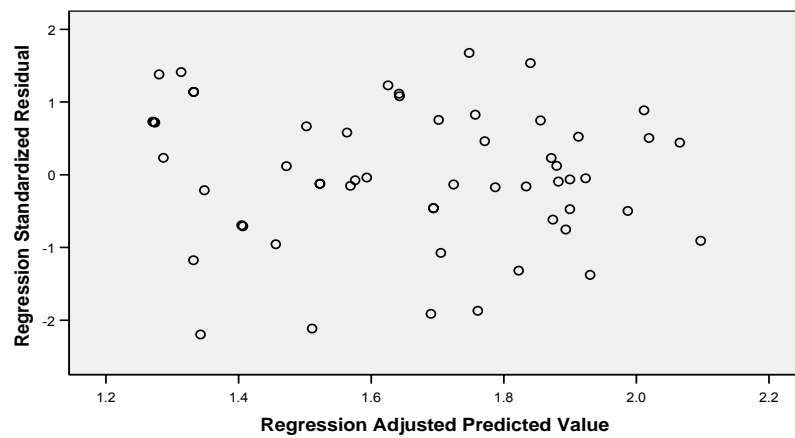
Figure 5.20. Scatter plot of adjusted predicted values vs. residuals for the simultaneous variable entry method.

Table 5.24: Model summary and ANOVA for multiple regression using the stepwise variable entry method.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
a	.608	.370	.359	.2358
b	.707	.499	.480	.2122
c	.764	.583	.559	.1955
d	.799	.638	.609	.1840

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
a	Regression	1.765	1	1.765	31.751	.000(a)
	Residual	3.002	54	.056		
	Total	4.768	55			
b	Regression	2.381	2	1.190	26.428	.000(b)
	Residual	2.387	53	.045		
	Total	4.768	55			
c	Regression	2.780	3	.927	24.250	.000(c)
	Residual	1.987	52	.038		
	Total	4.768	55			
d	Regression	3.041	4	.760	22.456	.000(d)
	Residual	1.727	51	.034		
	Total	4.768	55			

a - Entered variables: (Constant), relative position of the undercut rock unit from slope crest (adjusted SQRT)
b - Entered Variable: (constant), relative position of the undercut rock unit from slope crest (adjusted SQRT), spacing of orthogonal joints within the undercut rock unit (Log)
c - Entered Variable: (constant), relative position of the undercut rock unit from slope crest (adjusted SQRT), spacing of orthogonal joints within the undercut rock unit (Log), slake durability index of the undercutting rock unit (reflected adjusted SQRT)
d - Entered Variable: (constant), relative position of the undercut rock unit from slope crest (adjusted SQRT), spacing of orthogonal joints within the undercut rock unit (Log), slake durability index of the undercutting rock unit (reflected adjusted SQRT), original slope angle of the undercutting unit (Squared)
Dependent Variable: total amount of undercutting (Log)

values for all variables are greater than 0.39 (1-R^2) indicating that there is no significant problem of multicoliniearity (Table 5.25).

Based on Table 5.25, the first variable entered during stepwise regression analysis was the relative position of the undercut rock unit which accounted for 35.9% ($R^2 = 0.359$) of the total variation. Spacing of joints raised the R^2 value to 0.48, a 33.7% increase. The addition of slake durability index increased the R^2 to 0.56, an increase of 16.7%. The last variable entered was the original slope angle of the undercutting unit, which increased the R^2 value to 0.61, a 9 % increase. Frequency distribution histogram of the residuals (Figure 5.21) shows normal distribution and the scatter plot (Figure 5.22) between the residuals and the standardized predicted values shows a good scatter. Relative position of the undercut rock unit, spacing of joints within the undercut unit, slake durability index of the undercutting rock unit, and the original slope angle of the undercutting unit explain 61 % percent of the variation of the total amount of undercutting. The relative position of the undercut unit and the original slope angle of the undercutting unit have the highest and the lowest contribution, respectively, to the total amount of undercutting. Age of the cut slope and thickness of the undercut unit did not show any contribution to the regression model.

Lithology and Total Amount of Undercutting

This section describes the relationship of joint spacing within the undercut rock unit and slake durability index of the undercutting unit with the lithologic composition of the undercut and undercutting rock units. As shown in Chapter 4, limestone units have an average joint spacing of 16 inches (40 cm), whereas sandstones units have an average joint spacing of 34 inches (86 cm). Based on the result of the multiple regression analysis, limestone units are expected to experience greater amount of undercutting than sandstone units.

Table 5.25: Coefficients of independent variables for the multiple regression analysis, using the stepwise variable entry method.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Colinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	3.708	.365		10.145	.000		
	Relative position of the undercut rock unit from slope crest (adjusted SQRT)	-1.700	.302	-.608	-5.635	.000	1.000	1.000
2	(Constant)	3.572	.331		10.792	.000		
	Relative -position of the undercut rock unit from slope crest (adjusted SQRT)	-1.321	.290	-.473	-4.552	.000	.875	1.143
	Spacing of orthogonal joints within the undercut rock unit (Log)	-.180	.049	-.384	-3.696	.001	.875	1.143
3	(Constant)	3.542	.305		11.611	.000		
	Relative position of the undercut rock unit from slope crest (adjusted SQRT)	-1.131	.274	-.405	-4.131	.000	.835	1.198
	Spacing of orthogonal joints within the undercut rock unit (Log)	-.200	.045	-.426	-4.407	.000	.860	1.163
	Slake durability index of the undercutting rock unit (reflected adjusted SQRT)	-.037	.011	-.297	-3.234	.002	.951	1.052

Table 5.25 (contd.):

4	(Constant)	3.525	.287		12.277	.000		
	Relative position of the undercut rock unit from slope crest (adjusted SQRT)	-1.185	.258	-.424	-4.587	.000	.830	1.205
	Spacing of orthogonal joints within the undercut rock unit (Log)	-.302	.056	-.644	-5.355	.000	.490	2.039
	Slake durability index of the undercutting rock unit (reflected adjusted SQRT)	-.037	.011	-.296	-3.423	.001	.951	1.052
	Original slope angle of the undercutting unit (Squared)	7.48E-005	.000	.326	2.775	.008	.516	1.939
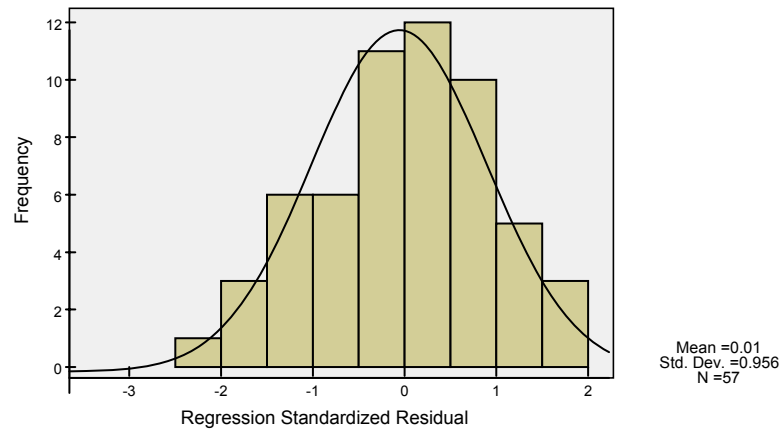
Figure 5.21. Frequency distribution histogram of residuals for the stepwise variable entry method.

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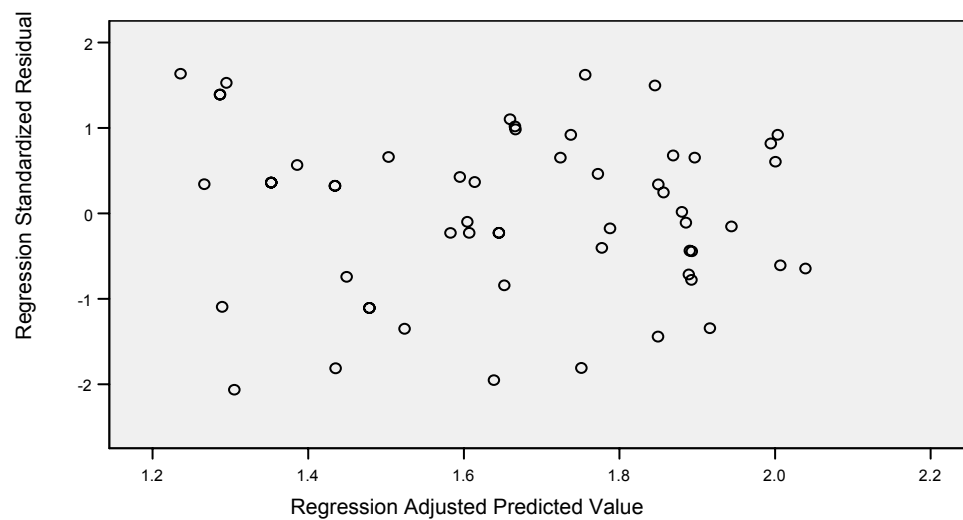
Figure 5.22: Scatter plot of residuals vs. adjusted predicted values for the stepwise variable entry method.

There is also a marked difference between the slake durability index values of shales and claystones/mudstones for both core and outcrop samples. Shales show average slake durability index values of 91 % and 81 % for outcrop and core samples, respectively. Claystones and mudstones show two populations for outcrop and core samples. The average values for the two populations of outcrop samples are 4 and 54 %, whereas for the core samples the average values are 18 % and 74 %. The slake durability values for claystones and mudstones are much lower than those of shales indicating that they promote higher amount of undercutting. These relationships suggest that limestones underlain by claystones and mudstones experience the highest total amount of undercutting than sandstones underlain by shales.

5.3.4.2 Amount of Recession of the Undercut Unit

In addition to the total amount of undercutting, the amount of recession of the undercut rock unit is important for studying undercutting-induced rockfalls. The amount of recession is the difference between the total amount of undercutting that occurred since the construction of the cut and the present amount of undercutting (Figure 5.23) and is directly proportional to the amount of the rockfalls. A zero value for the amount of recession indicates that the undercut rock unit has not resulted in any rockfalls. If, on the other hand, the amount of recession is greater than zero, the undercut rock unit must have resulted in rockfalls in the past. It was observed in the field that, in some cases, the recession does not affect the entire thickness of an undercut unit and only a portion of the undercut unit recedes. In order to account for this variation, the amount of recession was adjusted by multiplying it by the proportion of the rock unit thickness that had receded. This proportioning is equivalent to the ratio of the portion of rock unit thickness that is released as a rockfall to the total thickness of the undercut unit. Appendix 15-C contains data
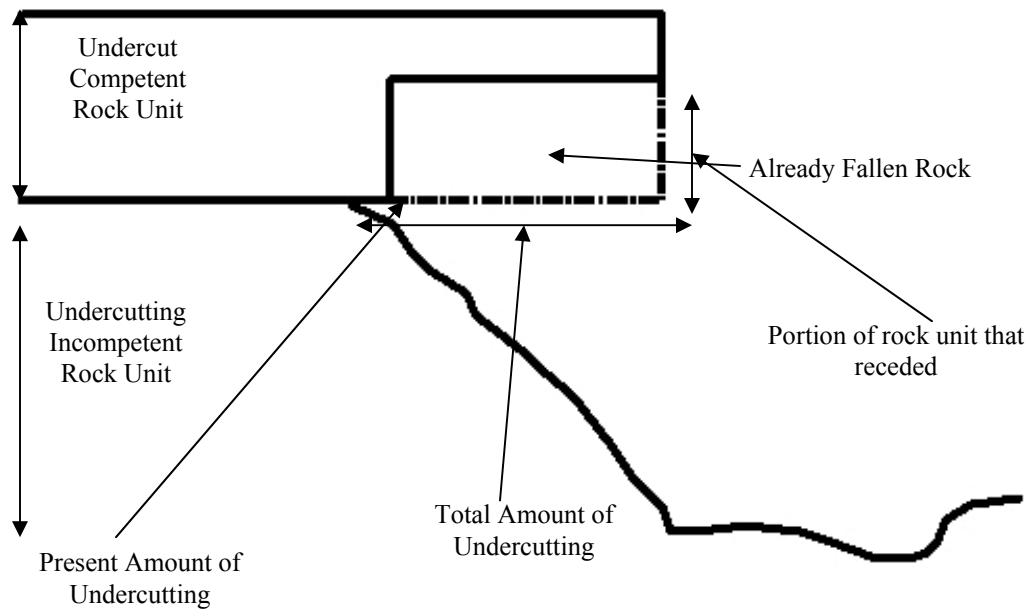
Figure 5.23: Diagram showing the total and the present amounts of undercutting.
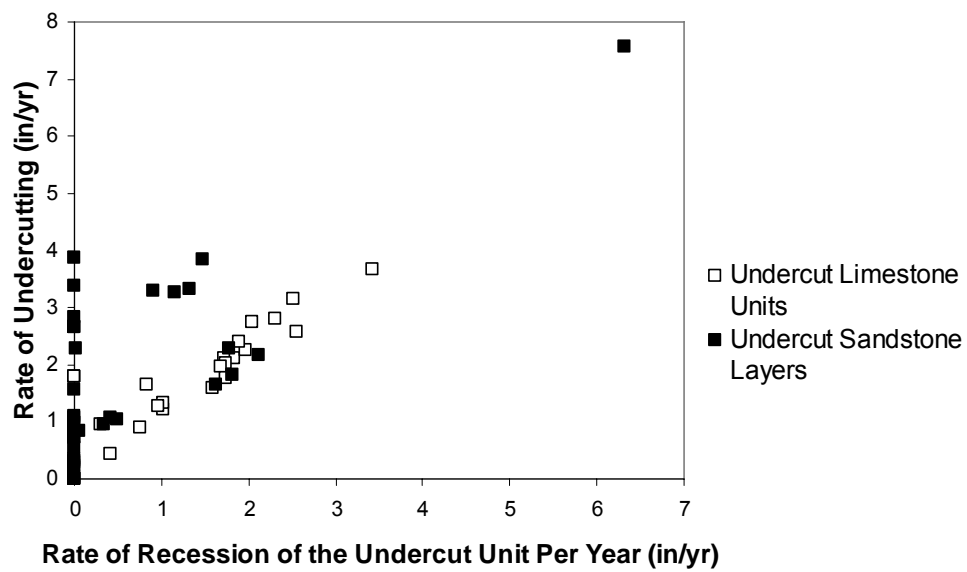
Figure 5.24: Relationship between rate of undercutting and rate of recession.

about the total amount of undercutting, the existing amount of undercutting, and the amount of recession. Field observations show that the amount of recession is influenced by joint spacing within the undercut unit. Undercut limestone units with closer joint spacing have higher amount of recession than sandstones with wider joint spacing. This implies that for the same amount of undercutting, limestone units result in more rockfalls than sandstone units. Plots of rate of undercutting versus rate of recession for limestone and sandstone units (Figure 5.24) support this conclusion. The limestone units show a positive relationship, indicating that undercutting and recession progresses concurrently, generating more frequent rockfalls. For most sandstones, however, the recession rate is much slower compared to the rate of undercutting (Figure 5.24), resulting in fewer rockfalls.

5.3.4.3 Fate and Volume of Rockfalls

Another aspect of undercutting-induced rockfalls, investigated in this research, is the fate and volume of rockfalls. The fate (landing site) of rockfalls is an important aspect to study since the ultimate concern regarding rockfalls is the likelihood of their reaching the roadway and causing accidents. Two types of investigations were performed to study the fate and volume of rockfalls:

1. Effect of shape and lithologic composition of rockfalls on their fate and volume.

2. Effect of slope angle, slope height, and stratigraphy on the final landing site of rockfalls (i.e. weather they will be retained on benches or in catchment ditches). This is similar to evaluating the effectiveness of benches and catchment ditches in containing rockfalls.

Effect of Shape and Lithologic Composition on Fate and Volume of Rockfalls

Field observations suggest that the shapes of rockfalls govern whether the fallen blocks stay on the slope face, travel into the catchment ditch, or possibly reach the roadway. Cubic

(nearly equi-dimensional) rockfalls travel much farther than flat rockfalls which are usually held on the slope face. The effect of joint spacing and bedding thickness on fate and volume of rockfalls was investigated using Microsoft Excel data analysis tool.. The ratio of the shortest dimension to the longest dimension of a rock block was used to quantify its shape. This is basically the ratio of bedding thickness, C, (the shortest dimension), to joint spacing, A, (the longest dimension). C/A values approaching 1 indicate a cubic rockfall, whereas small values indicate flat rockfalls. The frequency distribution plots of C/A ratios for rockfalls found in catchment ditches and on slope faces are given in Figures 5.25 and 5.26, respectively. The plots show that rockfalls in catchment ditches have higher mean C/A ratios than those caught on slope faces.

The volume of rockfalls is an important parameter as the hazard posed by bigger rockfalls is significantly different than that of smaller rockfalls. Volume of rockfalls was calculated by multiplying all three dimensions (A*B*C), where B is the intermediate dimension. Frequency distribution plots of rockfall volumes (Figures 5.27 and 5.28) show that rockfalls from limestone units have a mean volume of 0.7 ft^3 (0.02 m^3) (Figure 5.27) and those from sandstone units have a mean volume of 19.2 ft^3 (0.5 m^3) (Figure 5.28).

The influence of lithology on shapes and volumes of rockfalls was investigated by comparing bedding thickness to joint spacing ratios for various lithologic units. The non-fossiliferous limestones have higher average ratio of 0.96 (Figure 5.29) compared to the fossiliferous limestones with an average ratio of 0.19 (Figure 5.30). Sandstone units have an average bedding thickness to joint spacing ratio of 0.53 (Figure 5.31). Both fossiliferous limestones and sandstones tend to produce flatter rockfalls. The narrower range of frequency distribution of ratios for fossiliferous limestones (Figure 5.29), as compared to sandstones

Rockfalls in Catchment Ditch
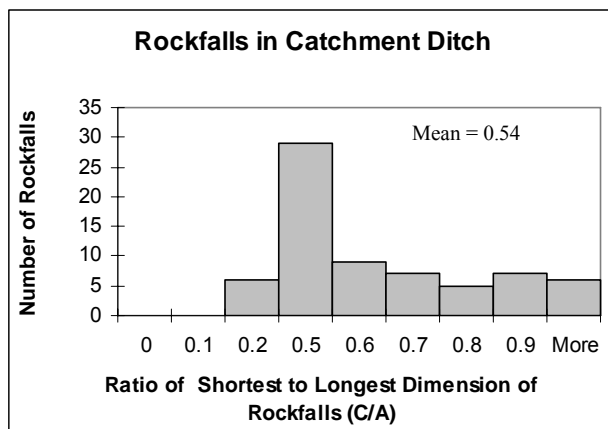
Figure 5.25: Frequency distribution of rockfalls of varying sizes in catchment ditches.

Rockfalls on Slope Face
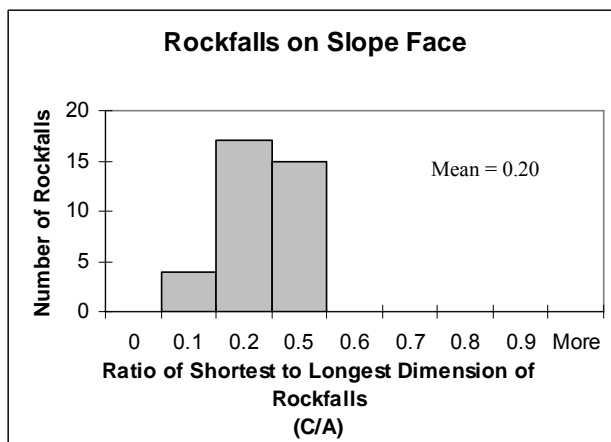
Figure 5.26: Frequency distribution of rockfalls of varying sizes on slope faces.

Limestone Rockfalls
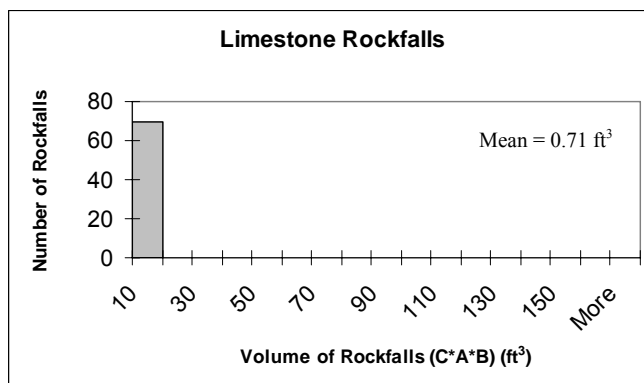
Figure 5.27: Frequency distribution by volume of the limestone rockfalls.
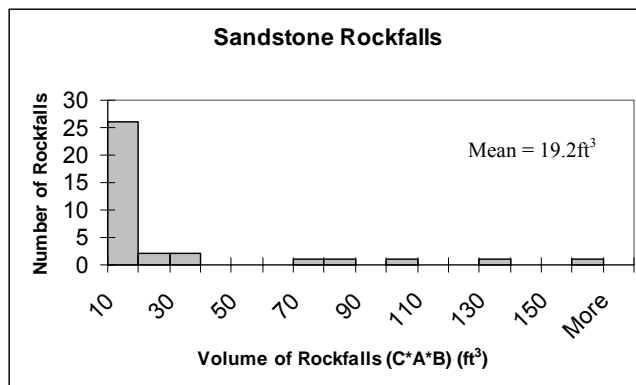
Figure 5.28: Frequency distribution by volume of the sandstone rockfalls.
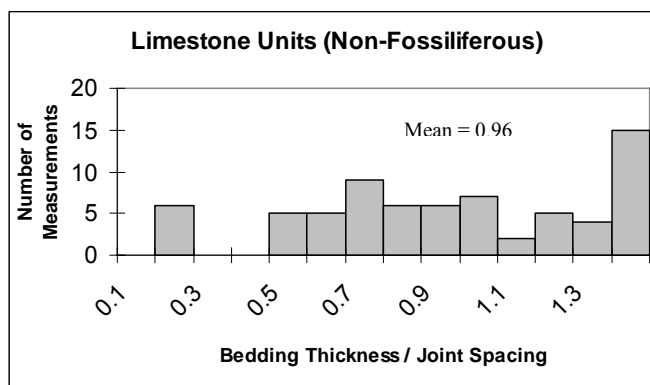
Figure 5.29: Frequency distribution of bedding thickness to joint spacing ratios for the non-fossiliferous limestone units.
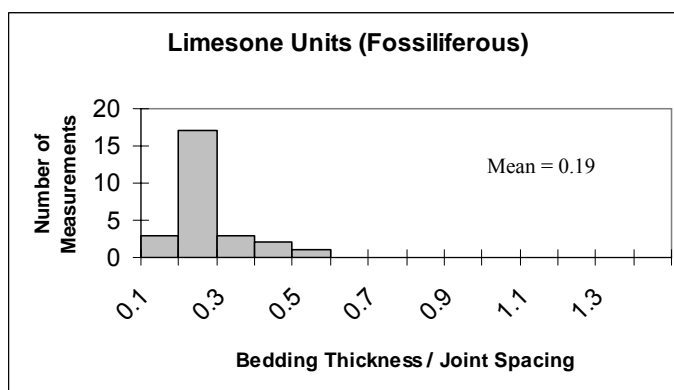
Figure 5.30: Frequency distribution of bedding thickness to joint spacing ratios for the fossiliferous limestone units.
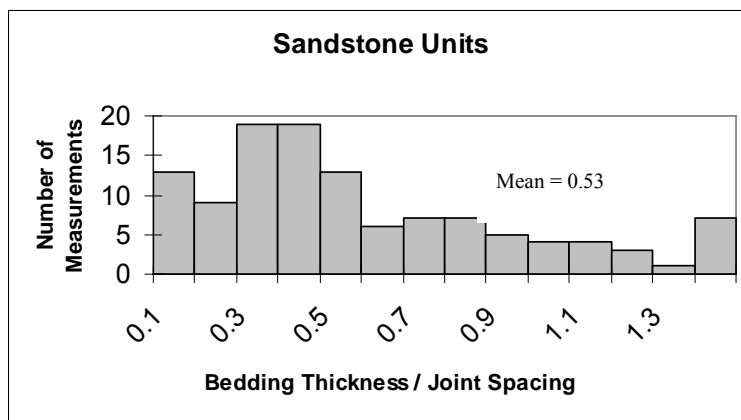
Figure 5.31: Frequency distribution of bedding thickness to joint spacing ratios for the sandstone units.

(Figure 5.31), indicates that fossiliferous limestones have a greater likelihood of generating flat rockfalls. Some sandstones also have higher ratios, as shown in Figure 5.31, indicating that sandstones could result in cubic rockfalls in addition to flat rockfalls.

The product of bedding thickness and joint spacing of a rock unit is proportional to the volume of the rockfalls that would be generated. Large values of the product of bedding thickness and joint spacing indicate large–size rockfalls. The limestone units have a much lower average value of the product of bedding thickness and joint spacing of 1.56 ft^2 (0.14 m^2), whereas the sandstone units have a much higher value of 24.4 ft^2(2.3 m^2) as shown in Figures 5.32 and 5.33, respectively. This is in line with the average smaller volume of limestone rockfalls than sandstone rockfalls, as discussed previously.

Rockfall Analysis Using RocFall Software

Rockfall simulation software programs are widely used for designing cut slopes. These software programs calculate, and graphically show, the trajectory and the final landing site of a rockfall released from any user defined point on the slope face. The RocFall software program was used for this study. RocFall uses a similar algorithm as the widely used CRSP and, therefore, similar results should be expected by the two software programs. The purpose of RocFall analysis was to simulate rockfall trajectories for different slope heights, slope angles, bench widths, and catchment ditch dimensions for the common types of inter-layered stratigraphy in Ohio. Several combinations of the above attributes (slope height, slope angle, etc.), with a user defined sources of rockfalls, were simulated to study the final landing sites of rockfalls. In order to perform the analysis, slope profiles were created and entered into RocFall. The site of rockfall generation, known as the seeder, was chosen anywhere on the slope profile and the program was run for a specified number of rocks. Figure 5.34 provides an example of

Limestone Layers

Mean = 1.56 ft^2

Number of Measurements

*Joint Spacing * Bedding Thickness (ft^2)*
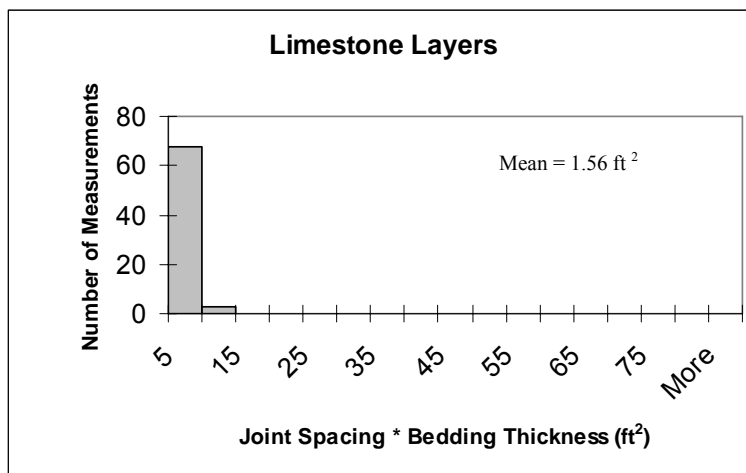
Figure 5.32: Frequency distribution of the product of joint spacing and bedding thickness for limestone units.

Sandstone Layers

Mean = 24.4 ft^2

Number of Mesurements

*Joint Spacing * Bedding Thickness (ft^2)*
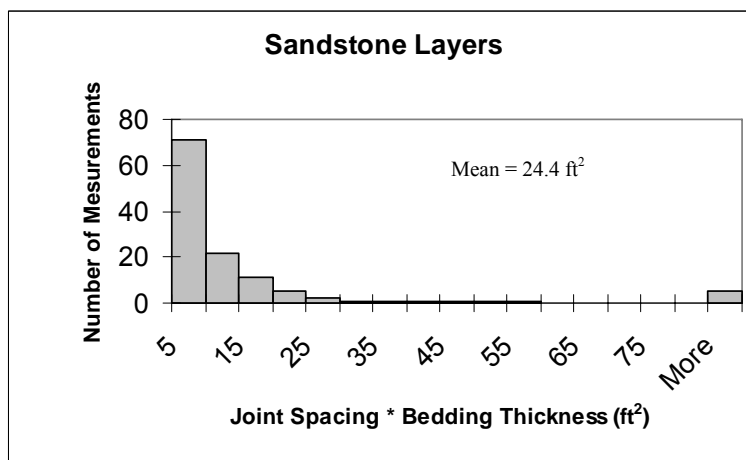
Figure 5.33: Frequency distribution of the product of joint spacing and bedding thickness for sandstone units.

Horizontal Location of Rock End-points
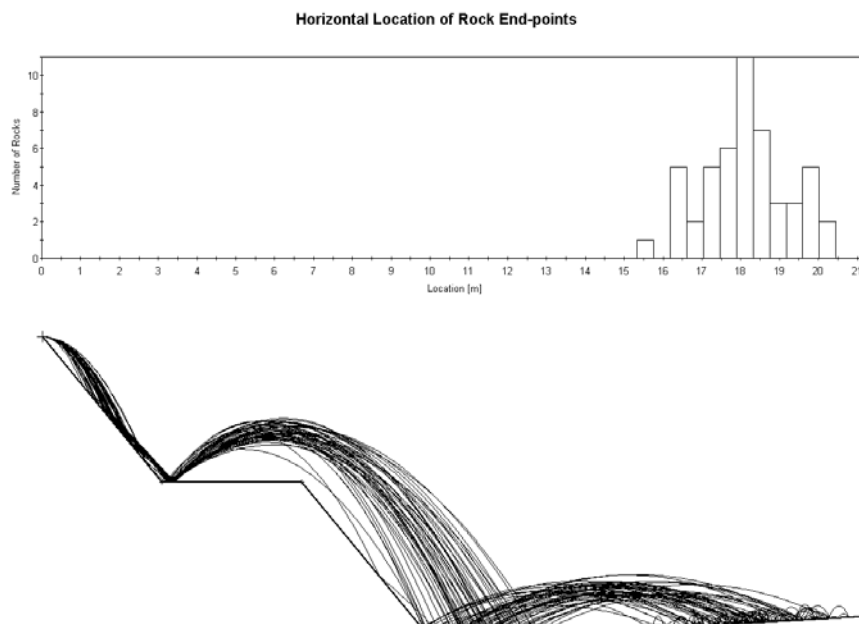
Figure 5.34: An example of a RocFall output showing trajectories and landing sites of rockfalls. The output also generates a histogram showing the distribution of rockfalls along the slope face and catchment area (diagram taken from RocFall user manual).

Bounce Height Distribution at x=0.000

Edge of Catchment Ditch
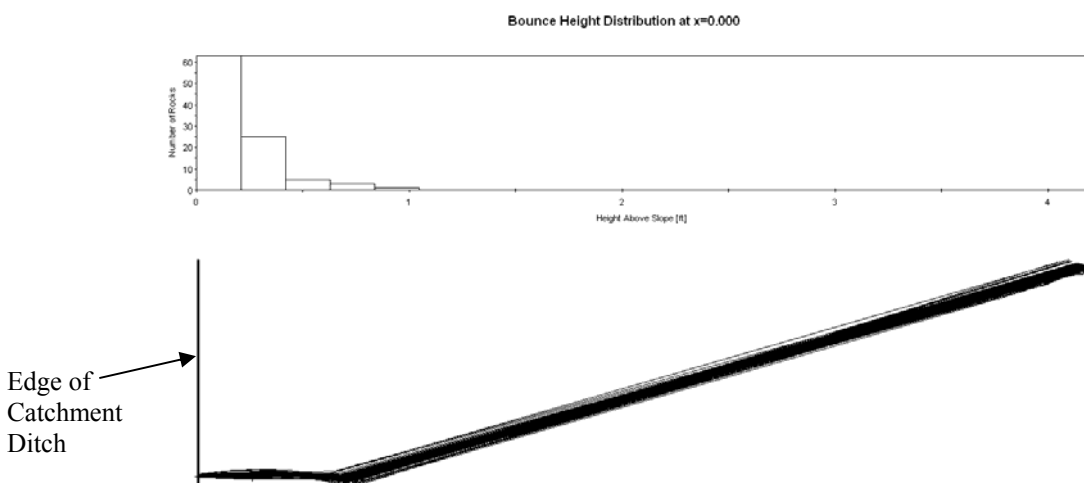
Figure 35: An example of a RocFall output showing distribution of bounce heights of rockfalls at the edge of a catchment ditch.

RocFall output showing the trajectories and landing sites of all rockfalls. RocFall plots the frequency of rockfalls at their final landing site (Figure 5. 34). RocFall also provides frequency distribution of bounce heights at any point within a catchment ditch (Figure 5. 35)

Parameters for RocFall Software

The parameters that need to be defined for the rock seeder (user defined source of rockfall) include the weight, initial values of angular, horizontal, and vertical velocities, and the number of rockfalls. The program allows the use of standard deviation for each value. The parameters for various types of rock material on the slope face include (Rocscience, 2003):

1) Friction Angle: A friction angle value between the rockfall and the rock material on the slope face is assigned for each type of rock on the slope face. A higher friction angle value is assigned if the rockfall is expected to slide on the slope face and a zero value of friction angle is appropriate if it is likely to roll. Rounded rockfalls move by rolling on the slope face whereas flat-shaped rockfalls move by sliding.

2) Coefficient of normal restitution (Rn): This measures the degree of elasticity of a rock material when a rockfall collides with it.

3) Coefficient of tangential restitution (Rt): This measures the frictional resistance of a rock material to a bouncing rockfall in the direction parallel to the slope face.

4) Surface roughness: This parameter accounts for local variations in slope angle. The value is approximated by entering a standard deviation to the slope angle. Based on the standard deviation, RocFall creates normally distributed slope angles and calculates the trajectory of a rockfall for each slope angle. If the standard deviation is zero, the slope face is treated as straight. Increasing the standard deviation value can mimic more pronounced surface irregularities.

Determination of RocFall Parameters

Two methods can be used to obtain RocFall parameters. The first method consists of using the available literature which contains coefficient values (Rt, Rn) for different rock types. The second method involves using an existing slope where a rockfall has already occurred and its weight and landing site are known. Using this information, the correct parameters that would result in a similar landing site as the observed rockfall are then obtained through trial and error. Five representative stratigraphic types, designated as Type I, Type II, Type III, Type IV, and Type V, were identified for selecting RocFall parameters and subsequent analysis.

Type I: Sandstone

Type II: Sandstone underlain by shale

Type III: Sandstone inter-layered with shale or claystone/mudstone in equal proportions

Type IV: Limestone inter-layered with claystone/mudstone in equal proportions

Type V: Minor limestone inter-layered with claystone/mudstone

For stratigraphic Types II, III, and V, the second method of determining RocFall parameters was used. The data were obtained from five sites of known rockfall landing sites, rockfall weights, and slope cross-sections. For Types I and IV, enough field data were not available to determine the required parameters and, therefore, the most reasonable parameters from Types II, III, and IV were used. Table 5.26 summarizes RocFall parameters used for the analysis.

RocFall Analysis

Average dimensions of rockfalls, as measured in the field, and density values of rock, determined in the laboratory, were used to obtain the average rockfall weights of 122 lbs (55.5 kg) for limestone and 2978 lbs (1353.6 kg) for sandstone. One hundred rockfalls were used for

Table 5.26: Parameters used for RocFall analysis of slopes comprised of types I, II, and III stratigraphic assemblages.

Site	Stratigraphy	Rockfall Lithology	Rn* (Slope Material/Catchment Ditch)	Rt** (Slope Material/Catchment Ditch)	Slope Roughness in Terms of Standard Deviation	Friction Angle (Slope/Catchment ditch)	Mode of Rockfall Movement
	Type I	Sandstone	053/0.32	0.99/0.8	0	10/30	Mainly rolling
BEL-70-1,JEF-CR77-0.6	Type II.	Sandstone	0.32/0.32	0.82/0.8	0	30/30	Mainly sliding
LAW-52-11	Type III	Sandstone	0.53/0.32	0..99/.82	1	30/30	Mainly sliding
	Type IV	Limestone	0.53/0.32	0.99/.82	1	10/30	Mainly rolling
WAS-77-15, MUS-70-25	Type V.	Limestone	0.32/0.32	0.8-0.82/0.8-0.82	0	10/30	Mainly rolling

each RocFall analysis and percentages of rockfalls held on the bench or retained in the catchment

ditch were recorded. The rockfall seeder was placed on the highest position of the slope in order

to consider the worst case scenario with the longest trajectory of a rockfall. The frequency

distribution histograms of rockfalls retained on the bench or the catchment ditch are shown in

Figure 5.36.

Two types of analysis were conducted using the RocFall software:

1. The purpose of the first analysis was to evaluate the effectiveness of catchment ditch

   design for slopes of varying heights (20 ft/6.1m, 40 ft/12.2 m, 60 ft/18.3m, 80 ft/24.4m,

   100 ft/30.5m), angles (1.5H:1V, 0.25H:1V, 1H:1V, 0.5H:1V) and stratigraphic conditions

   (Types I, II, III, IV, V). Rt, Rn, friction angle, and roughness values (in terms of standard

   deviation) obtained for the five types of stratigraphic assemblages were used for the

   analysis. A total of 200 RocFall analyses were performed for different combinations of

   slope height, slope angle, and stratigraphy.

   Two ditch designs were chosen for the analysis, both with a 10 ft (3 m) wide flat

   bottom but one having a foreslope angle of 3H:1V and the other with a foreslope angle of

   6H:1V. The foreslope in both cases starts at the end of the 10 ft (3 m) wide flat bottom.

   Figure 5.37 shows the basic elements of ditch design used for the analysis (the commonly

   used design in Ohio). The total width of the ditch with 3H:1V foreslope was taken as 13

   ft (3.9 m) and the total width of the ditch with 6H:1V foreslope was taken as 16 ft (4.8

   m). Based on the chosen ditch geometries, both ditches are 1 ft (0.3 m) deep. In the

   following sections, these two ditch designs will be referred to as "GB 3 design option 2-

   a" and "GB 3 design option 2-b", respectively (based on GB 3 Figure 3, option 2). The

   relatively narrow ditch widths were chosen to investigate if narrow ditches, in

Horizontal Location of Rock End-points
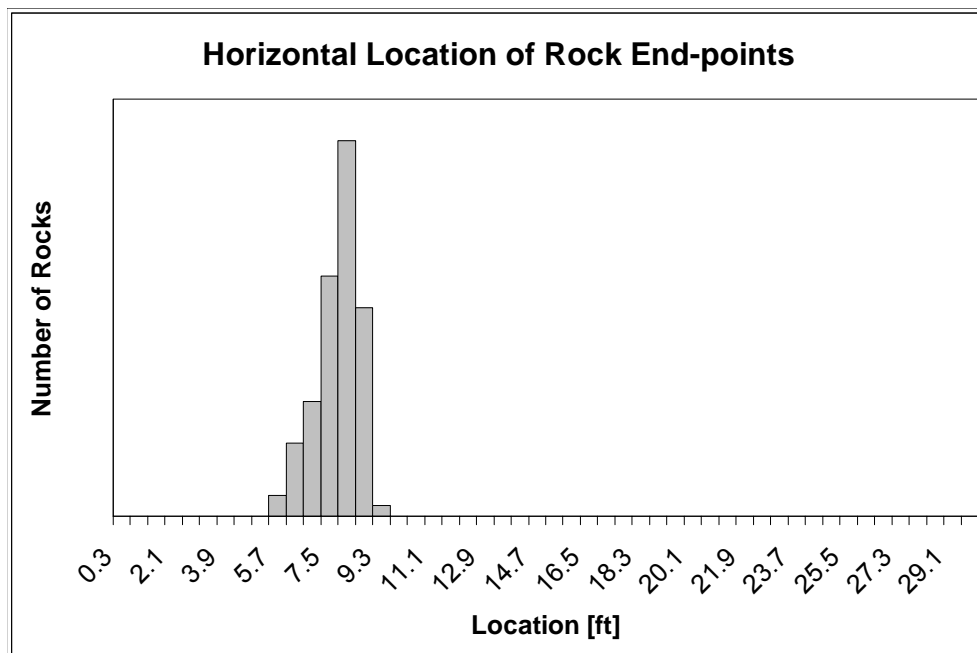
Figure 5.36: An example of distribution of rockfalls along a horizontal axis across the catchment ditch, starting from the toe of a slope. For a bench, the horizontal axis starts from the inner edge of the bench.
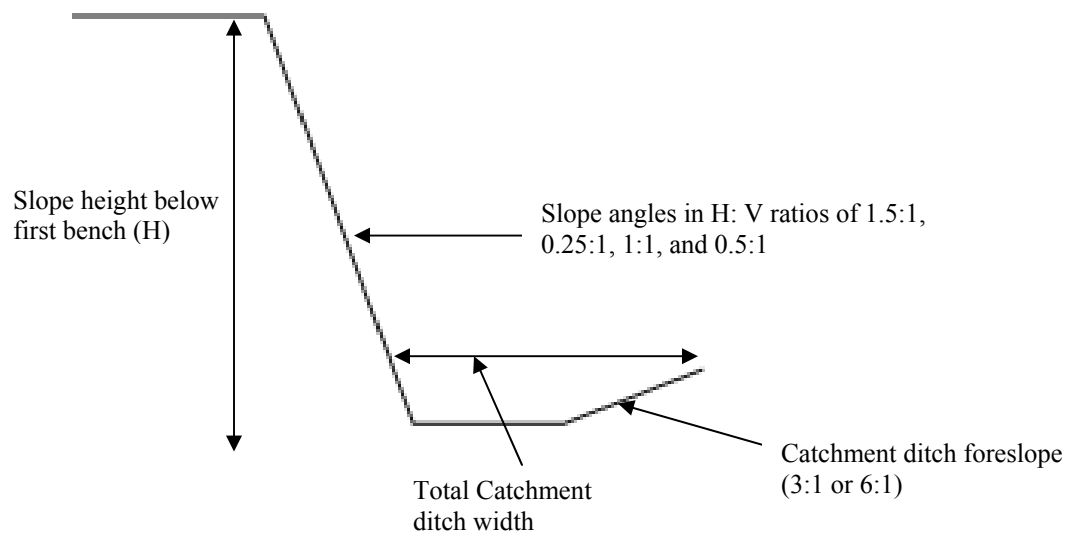
Figure 5.37: Elements of catchment ditch design.
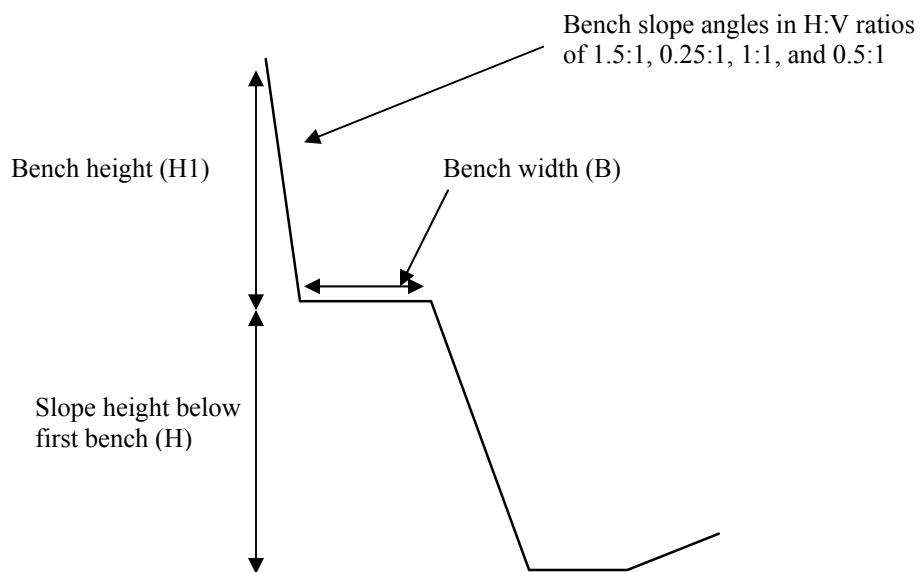
Figure 5.38: Elements of bench design.

conjunction with barriers, can be effective in containing rockfalls where use of wider

ditches may not be feasible because of space restrictions. It should be noted that ditch

widths for the 26 project sites range from 7 ft (2.1 m) to 70 ft (21.2 m), with an average

of 24 ft (7.3 m). Davis and Shakoor (2005) measured 101 ditches in various ODOT

districts and found ditch widths ranging from 2 ft (0.6 m) to 33 ft (10 m), with an average

of 18 ft (5.5 m). Table 1.4 from GB 3 (Table C in GB 3) recommends ditch widths

ranging from 10 ft (3 m) to > 40 ft (12 m), based on slope angle and slope height. The

table is based on a combination of sources including other state DOT standards, FHWA-

cosponsored research, and ODOT research.

2. The purpose of the second analysis was to evaluate the effectiveness of bench design

(Figure 5.38) by varying bench height (H1 = 20 ft/6.1 m , 40 ft/12.2 m), bench width as a

function of H1 (B = H1, B = 1/2(H1), B = 1/4(H1)), bench slope angle (1.5H:1V,

0.25H:1V, 1H:1V, 0.5H:1V), and bench stratigraphy. A total of 120 RocFall runs were

completed for different combinations of bench height, bench width, bench slope angle, and

bench stratigraphy.

<u>Effectiveness of Catchment Ditches</u>

Tables 5.27 and 5.28 summarize the results of RocFall analysis for the two catchment

ditch designs, described above, for varying combinations of slope angle, slope height, and

stratigraphic condition. A catchment ditch that contains at least 95 % of rockfalls is considered

effective. The results show that both ditch designs are more effective for slopes cut at 0.25H:1V,

and less effective for slopes cut at 0.5H:1V, 1H:1V, and 1.5H:1V, especially for stratigraphic

Types I, II, IV, and V. Comparing both ditch designs, the GB 3 design option 2-b ditch is more

effective than the GB 3 design option 2-a ditch.

Table 5.27: Percentage of rockfalls retained in catchment ditch with 3:1 foreslope. Maximum bounce height (ft) of rockfalls on the edges of catchment ditches retaining < 95 % rockfalls is provided in parenthesis.

Slope Strat.	Slope Height Below First Bench, H (ft)	Percent Rockfalls Retained (Bounce Height) Slope Angle (in H:V Ratios)				Corresponding Stratigraphic Types Used in Chapter 7
		0.25:1	0.5:1	1:01	1.5:1	
Type I	100	0 (4.5)	0 (6.4)	0 (3.3)	0 (1.7)	Competent Design Unit
	80	0 (0.9)	0 (5.1)	0 (2.7)	0 (1.1)	
	60	100	0 (2.5)	0 (1.6)	0 (0.4)	
	40	100	0 (0.3)	0 (0.3)	0 (0.4)	
	20	100	100	99	100	
Type II	100	0 (1.5)	0 (5.1)	0 (1.9)	48 (0.4)	Type A
	80	0 (0)	0 (2.6)	0 (0.6)	66 (0)	
	60	100	0 (0.5)	0 (0.4)	96 (0)	
	40	100	5 (0.2)	75	100	
	20	100	100	100	100	
Type III	100	0 (6.9)	0 (5.5)	0 (1.9)	35 (0.5)	Type B, Case 1
	80	25 (4.6)	5 (3.6)	0 (1.2)	55 (0.1)	
	60	40 (3.1)	11 (2.3)	1 (0.6)	88 (0)	
	40	50 (0.8)	18 (0.5)	45 (0.3)	100	
	20	97	92 (0.1)	100	100	
Type IV	100	20 (7.7)	6 (7.2)	0 (6.1)	0 (4.6)	Type C, Case 1
	80	31 (5.7)	4 (5.4)	0 (4.7)	0 (2.9)	
	60	28 (3.3)	5 (3.1)	0 (2.4)	0 (2.1)	
	40	45 (0.3)	2 (1.0)	0 (0.7)	0 (2.1)	
	20	97 (0.3)	79 (0.2)	77 (0.1)	95	
Type V	100	0 (4.0)	0 (6.8)	0 (3.3)	0 (1.6)	Type C, Case 2
	80	0 (0.9)	0 (4.8)	0 (2.8)	0 (1.1)	
	60	100	0 (2.4)	0 (1.6)	0 (0.5)	
	40	100	0 (0.4)	0 (0.4)	0 (0.4)	
	20	100	100	96	100	

Table 5.28: Percentage of rockfalls retained in catchment ditch with 6:1 foreslope. Maximum bounce height (ft) of rockfalls on the edges of catchment ditches retaining < 95 % rockfalls is provided in parenthesis.

Slope Strat.	Slope Height Below First Bench, H (ft)	Percent Rockfalls Retained (Bounce Height) Slope Angle (in H:V Ratios)				Corresponding Stratigraphic Types Used in Chapter 7
		0.25:1	0.5:1	1:01	1.5:1	
Type I	100	0 (0.7)	0 (6.1)	0 (3.6)	0 (1.8)	Competent Design Unit
	80	11 (0)	0 (3.9)	0 (2.6)	0 (0.9)	
	60	100	1 (0.4)	0 (1.0)	0 (0.2)	
	40	100	37 (0.6)	1 (0.2)	1 (0.1)	
	20	100	100	100	100	
Type II	100	0 (0.2)	0 (0.7)	0 (0.3)	75 (0.02)	Type A
	80	100	0 (0.6)	0 (0.3)	93 (0)	
	60	100	0 (0.3)	70 (0.04)	99	
	40	100	100	100	100	
	20	100	100	100	100	
Type III	100	30 (6.8)	5 (5.5)	0 (2.1)	64 (0.5)	Type B, Case 1
	80	35 (4.6)	15 (3.6)	5 (1.2)	89 (0.1)	
	60	45 (3.1)	20 (2.3)	15 (0.6)	87 (0)	
	40	55 (0.8)	57 (0.5)	85 (0.3)	100	
	20	100	100	100	100	
Type IV	100	29 (6.9)	5 (7.1)	0 (6.5)	0 (4.2)	Type C, Case 1
	80	31 (4.5)	1 (4.5)	0 (5.4)	0 (2.3)	
	60	39 (1.9)	11 (4.7)	0 (2.1)	0 (2.0)	
	40	60 (0.5)	35 (1.7)	9 (1.0)	0 (0.2)	
	20	100	99	100	100	
Type V	100	0 (1.2)	0 (2.2)	0 (3.5)	0 (1.5)	Type C, Case 2
	80	100	0 (3.9)	0 (2.5)	0 (1.2)	
	60	100	0 (0.4)	0 (0.9)	0 (0.2)	
	40	100	0 (0)	0 (0.2)	0 (0.1)	
	20	100	100	100	100	

Tables 5.27 and 5.28 also provide the maximum bounce heights at the edges of catchment ditches that retain < 95 % rockfalls. In Chapter 7, the bounce heights are used to select heights of barrier walls or catch fences for ditches that retain < 95 % rockfalls. For both ditch designs, the 0.5H:1V slope and Types III and IV stratigraphic configurations result in the maximum number of cases where the rockfall bounce height exceeds 4.2 ft (1.3 m), the height of ODOT's commonly used barrier (D-50 wall). Overall, the GB 3 design option 2-b ditch results in fewer cases of bounce height exceeding 4.2 ft (1.3 m) than the GB 3 design option 2-a ditch.

The bounce height information from Tables 5.27 and 5.28 was used to select the worst case situations where a D-50 wall will not be adequate to contain all rockfalls (i.e. the bounce height is > 50 inches/1.3 m). For these worst case situations, RocFall analysis was redone to select minimum ditch widths that would retain at least 95 % of rockfalls without the use of a rockfall barrier. In order to accomplish this objective, the total ditch widths for both design options (GB 3 design options 2-a and 2-b) were incrementally increased to 20 ft (6m), 30 ft (9.1 m), 40 ft (12 m), and 45 ft (13.6 m). In all cases, the foreslope started at the end of the 10 ft (3 m) wide flat bottom and extended toward the roadway at a constant angle of 3H:1V or 6H:1V. This resulted in ditch depths ranging from 3.3-11.6 ft (1.0-3.5 m) for GB 3 design option 2-a ditches (widths: 20-45 ft/6-13.6 m), and 1.7-5.9 ft (0.5-1.8 m) for GB 3 design option 2-b ditches (widths: 20-45 ft/6-13.6 m). These ditch dimensions encompass, to a large extent, the ditch dimension range used in Table 1.4 as well as the ditch dimensions observed in the field.

For competent rock (Type I stratigraphy), the worst case situation (maximum bounce height) occurs when the slope angle is 0.5H:1V or 0.25H:1V and the slope height is 100 ft (30 m). RocFall analysis indicates that ditch widths of 30 ft (9.1 m) and 20 ft (6 m), respectively, will be required for 0.5H:1V and 0.25H:1V slopes for both GB 3 design option 2-a and GB 3 design

option 2-b catchment ditches, if no barriers are used. Therefore, if the ditch width is less than 30 ft (6 m) for a 0.5H:1V slope and less than 20 ft (9 m) for a 0.25H:1V slope, and the slope height is 100 ft (30 m) or greater, rockfall barriers should be used in accordance with the results provided in Tables 5.27 and 5.28.

Similar to competent rock, RocFall analysis was conducted on Type IV of inter-layered stratigraphy to determine the minimum ditch width that would retain at least 95 % rockfalls without a barrier. Type IV stratigraphy was chosen for this analysis because it represents the worst case scenario with respect to bounce heights among all inter-layered stratigraphic variations. Four slope angles were chosen for the analysis: 1.5H:1V, 1H:1V, 0.5H:1V, and 0.25H:1V. The results indicated the following ditch widths for GB 3 design option 2-a ditch: 1.5H:1V slope - 45 ft (13.6 m); 1H:1V slope – 40 ft (12 m); 0.5H:1V slope – 35 ft (10.7 m); 0.25H:1V slope – 40 ft (12 m). For GB 3 design option 2-b ditch, the required widths are: 1.5H:1V – 35 ft (10.7 m); 1H:1V – 45 ft (13.6 m); 0.5H:1V – 45 ft (13.6 m); 0.25H:1V – 35 ft (10.7 m). Thus, ditches as wide as 35-45 ft (10.6-13.5 m) may be required for inter-layered design units if no barriers are used.

A comparison of ditch dimensions given by RocFall analysis, when no barrier is used, with the ditch dimensions recommended in Table 1.4 indicates that, in most cases, RocFall analysis suggests wider ditches both for competent and inter-layered rock units. This is because the ditch dimensions in Table 1.4 are mostly based on Option 1 ditch configuration (foreslope starting from the slope toe – see Figure 1.16) whereas this study used Option 2 configuration.

Effectiveness of Benches

The effectiveness of benches is measured by the percentage of rockfalls caught on the newly constructed benches. It should be noted that, in this research, the effectiveness of

catchment ditches is evaluated independent of the effectiveness of benches. Also, the benches deteriorate with time and their ability to retain rockfalls decreases. The bench effectiveness, as evaluated here, should be taken as the ability of a bench to prevent rockfalls from bouncing. Benches of different heights and slope angles were considered in relation to the five types of stratigraphic variations. The results are shown in Table 5.29. Benches retaining > 95 % of rockfalls that fall on them are regarded as effective.

5.3.4.4 Stable Angle for Undercutting Rock Units

One of the important questions that needs to be addressed in regards to undercutting-induced slope failures is whether the undercutting rock units tend to reach a stable angle beyond which further undercutting does not occur. Angles of undercutting rock units that appeared stable, as indicated by the presence of vegetation, were measured for seven sites (Appendix 15). These angles show a normal distribution with an average value of 38 degrees (Figure 5.39), which may be considered as the final stable angle of undercutting rock units.

5.3.5 Comparison of Methods

The Franklin shale rating indicates average upper and lower slope angles values of 39 and 21 degrees, respectively. Based on these recommended values, the existing slope angles are too steep and, hence, unstable. GB 3 recommends upper angles of 63-76 degrees and lower angles of 45-63 degrees, which are higher than the existing slope angles for the majority of the design units, suggesting that the slopes are stable at their existing angles. The average stable angle of undercutting units of 38 degrees is less than the existing slope angles for 11 of the 14 design units.

Table 5.29: Percentage of rockfalls retained on as constructed benches (Note: the effective of catchment ditches is evaluated independent of the effectiveness of benches).

Slope Strat.	Bench Height, H1(ft)	Bench Width (B)	Percent Rockfalls Retained on Newly Constructed Benches Bench Slope Angle (in H:V Ratios)		Corresponding Stratigraphic Types Used in Chapter 7
			0.25:1	0.5:1	
Type I	40	B=H1	100	100	Competent Design Unit
	40	B=1/2(H1)	100	100	
	40	B=1/4(H1)	0	0	
	20	B=H1	100	100	
	20	B=1/2(H1)	100	11	
	20	B=1/4(H1)	0	0	
Type II	40	B=H1	100	100	Type A
	40	B=1/2(H1)	100	100	
	40	B=1/4(H1)	0	0	
	20	B=H1	100	100	
	20	B=1/2(H1)	100	100	
	20	B=1/4(H1)	0	0	
Type III	40	B=H1	100	98	Type B, Case 1
	40	B=1/2(H1)	64	45	
	40	B=1/4(H1)	25	9	
	20	B=H1	100	81	
	20	B=1/2(H1)	65	29	
	20	B=1/4(H1)	25	16	
Type IV	40	B=H1	99	97	Type C, Case 1
	40	B=1/2(H1)	59	20	
	40	B=1/4(H1)	52	9	
	20	B=H1	90	77	
	20	B=1/2(H1)	44	25	
	20	B=1/4(H1)	25	15	
Type V	40	B=H1	100	100	Type C, Case 2
	40	B=1/2(H1)	100	0	
	40	B=1/4(H1)	0	0	
	20	B=H1	100	100	
	20	B=1/2(H1)	100	0	
	20	B=1/4(H1)	0	0	
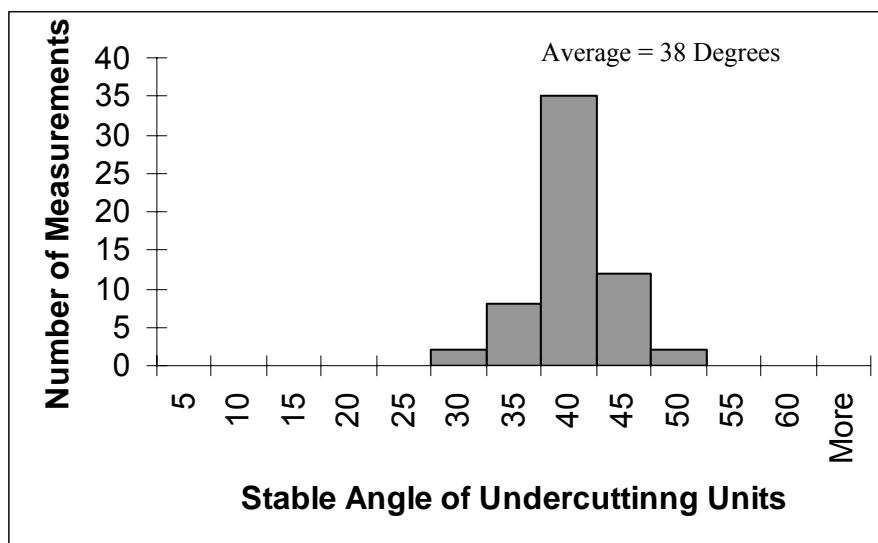
Figure 5.39: Frequency distribution of stable slope angles for the undercutting rock units.

CHAPTER 6

DISCUSSION AND SLOPE DESIGN CONSIDERATIONS

This chapter discusses the results of slope stability analyses presented in Chapter 5 and highlights the important slope design considerations for the three design units: competent, incompetent, and inter-layered. These slope design considerations provide the rationale for cut slope design recommendations outlined in Chapter 7.

6.1 Competent Design Units

6.1.1 Discussion of Stability Analysis Results

Slope stability problems associated with competent rock units are the failures promoted by unfavorably oriented discontinuity planes. Kinematic analysis, using RockPack and DIPS software, indicated that plane and wedge failures are rare among the study sites because of the steep nature of discontinuities. Ten of the 12 sites, containing competent rock units, showed no plane or wedge failures at their present slope angles. RockPack and DIPS software resulted in average stable slope angles of 79 and 81 degrees, respectively. The stable slope angles for the two sites that showed the potential for plane or wedge failures were found to be 61 and 64 degrees, respectively. These kinematic analysis results are in agreement with field observations which showed that only a small number of discontinuities, or their intersections, that could lead to potential plane or wedge failures, daylighted on the slope faces. However, field observations and kinematic analysis both identified Type B toppling as the common mode of failure due to the ubiquity of steeply dipping intersecting planes and the presence of weak, 0.5 ft-2.0 ft (0.15 m-0.6 m) thick, layers within competent rock units. Type B toppling failure is common close to the ends of cut slopes where discontinuities are closely spaced. Existing methods are not capable of

determining slope angles that would minimize the occurrence of Type B failure. The use of

cartoon models is the only approach that was considered reasonable for identifying appropriate

slope angles that would reduce the potential for Type B toppling failure.

The consistently steep orientations of discontinuity sets (orthogonal and valley stress

relief joints) and their intersections, as shown in Figures 4.8 and 4.11, is attributed to the tectonic

history of sedimentary sequences in which the cut slopes are made. According to Pluijm and

Marshak (2004), orthogonal joints are common in continental interiors and foreland basins,

bordering major orogenic belts, to which Ohio's sedimentary sequences belong. These sediments

are undeformed, maintaining their horizontal bedding and sub-vertical orthogonal joints.

The fact that the sedimentary sequences of Ohio are not deformed and, hence, not closely

jointed explains the results of SLIDE program which indicated that none of the study sites

consisting of competent rock units had factor of safety values less than 1.5 against global

rotational failure. Field observations corroborate these results.

GB 3 recommends an upper angle of 76 degrees (0.25H: 1V) and lower angle of 63

degrees (0.5H:1V) for competent rock units. The upper angle appears to be adequate to prevent

plane or wedge failures. The lower angle can minimize the potential for Type B toppling.

6.1.2 Slope Design Considerations for Competent Design Units

Slope design for competent design units includes cut slope angles, stabilization

techniques, and catchment ditch design. The design should be based on the following

considerations:

1. Slope angles should be chosen to minimize the potential for Type B toppling and any

    other discontinuity related failures. The cartoon models, described in Chapter 5, indicated

    that a 1H:1V slope would result in the least number of toppling failures. However, a

0.5H:1V slope would be more feasible and would also reduce the potential for Type B toppling failure. Any failures that may occur can be contained in properly designed catchment ditches, as discussed in Chapter 5. Zones of close joint spacing around the ends of the slope would require special attention (use of gentler slope or wire mesh).

2. Slopes may be cut at 0.25H:1V. The use of a steeper slope may result in more failures but the trajectories of the failures will be nearly vertical. For a 0.25H:1V slope, without a rockfall barrier, RocFall analysis showed that the two catchment ditch designs discussed in Chapter 5 (GB 3 design option 2-a and GB 3 design option 2-b) are effective (contain at least 95% of rockfalls) as long as the slope height is less than 60 ft (18 m) (Tables 5.27 and 5.28). These catchment ditch designs were also found effective for other slope angles (1.5H:1V, 1H:1V and 0.5H:1V) for heights not exceeding 20 ft (6 m) (Tables 5.27 and 5.28). However, if a 4.2 ft (1.3 m) high barrier (e.g., D-50 wall) is provided next to a GB 3 design option 2-b catchment ditch, the ditch will contain 95 % rockfalls for all analyzed slopes except a 100 ft (30.3 m) high slope cut at 0.5H:1V (Table 5.28). The barrier should be able to withstand rockfall impact and ditches should be cleaned periodically to reduce the likelihood of rockfalls bouncing off of previous rockfalls.

3. Thinly bedded, closely jointed, poorly cemented, friable sandstone units, which may range in thickness from 0.5 ft to 10 ft (0.15 m to 3 m) and which tend to weather faster than the other competent rock units, should be treated as red-flag items within the overall competent design unit. Personnel in charge of core logging should ensure that these weak sandstone units are properly identified and recorded on the borehole logs. The presence of these weak sandstone layers usually promotes type B toppling. However, if such a sandstone happens to be >5 ft (1.5 m) thick, it will require a 1H:1V slope angle and

provision of a bench if it underlies a massive, competent sandstone. Specifically, if the core log description includes the term "friable" or the strength descriptor is very weak, weak, or slightly strong, then a density test will be performed on the core sample. If the density is less than 140 pcf (2.24 Mg/m^3), a slake durability test will be performed. If the second-cycle slake durability index (Id_2) is less than 85 %, the unit will be identified as a special case and cut at 1H:1V.

4. Depending on slope height, slope angle, and whether or not a rockfall barrier is used, benches may be provided to improve stability and control rockfall trajectories. For example, RocFall analysis indicates that for the narrow ditches used (GB 3 design options 2-a and 2-b) and in the absence of a rockfall barrier, a bench would be needed if the slope height exceeds 60 ft (18 m) for a 0.25H:1V slope and 20 ft (6 m) for a 0.5H:1V slope. Based on Rocfall analysis, a bench with a width B = 1/2 H1, but not exceeding 15 ft (4.5 m), should be an effective design (Figure 5.37).

5. Problems associated with soil-rock contact should be addressed to avoid soil failure. Failure of overburden soil was observed at ATH-33-14 site. GB 3 recommendation of a 2H:1V slope for the overburden soil and a 10 ft (3 m) wide bench along the soil-rock contact appears to be adequate.

6.2 Incompetent Design Units

6.2.1 Discussion of Stability Analysis Results

The main slope problems associated with incompetent rock units are raveling and mudflows. Mudflows are uncommon and were observed only at two sites (ADA-32-12 and CLE-275-5) comprised of claystone/mudstone units, with a few layers of limestone, whereas raveling

was observed at all seven sites comprised of incompetent rock units. Both mudflows and raveling are related to surface weathering and require only minor maintenance.

The average maximum natural slope angles for red claystones/mudstones (redbeds), gray claystones/mudstones, and shales were found to be 12, 11, and 22 degrees, respectively. The average talus angles for these rock units were 26, 38, and 38 degrees, respectively. Skempton (1964) and Bjerrum (1967) also found the natural slope angles for clay-shale slopes, several thousand years old, to be as low as 8–10 degrees. The relatively higher values of talus angle, compared to natural slope angle, represents the younger age of cut slopes. Over time, the cut slopes in incompetent rock are expected to weather down to their natural slope angles of 10-12 degrees. For the purposes of cut slope design, within the anticipated service life of five to six decades, the average talus angle can be used as a reasonable guideline for cut slope angle.

In addition to weathering-related degradation, water is an important agent of erosion of slopes comprised of incompetent rock units. Even where slope angles are gentle, surface water degrades cut slopes through gully erosion. Gully erosion is very common in claystone/mudstone units but not in shales. The red claystones/mudstones are more prone to gully erosion compared to the gray claystone/mudstone units.

A global or deep-seated rotational failure in incompetent rock units could cause the closure of a roadway, leading to expensive maintenance (Franklin, 1983). Although, during the course of this study, evidence of a global failure was not observed at any of the project sites or the additional sites consisting of incompetent rock units, the Franklin shale rating system and the GSI methods were used to check the potential for global (rotational) failure. Based on the upper angle values obtained from Franklin shale rating system, the study sites comprised of incompetent rock units are stable to marginally stable. The lower angle values given by the shale

rating system indicate that only two of the study sites are stable. Unfavorably oriented discontinuities were not observed at the study sites and, therefore, the use of the lower angle will be too conservative. GSI based analysis showed that all sites, except one, have factor of safety values greater than 1.5 under dry conditions. For saturated conditions, one site has a factor of safety equal to 1 and two sites have values less than 1. Although it is unlikely that cut slopes in incompetent rocks will get completely saturated because of their low permeability, relatively unfractured nature, and deep water table, the results of Franklin shale rating and GSI analyses suggest that flatter slope angles need to be used for those slopes found to be marginally stable or unstable.

GB 3 recommends a special design for three of the seven study sites comprised of incompetent rock units because of the nature of geologic formations present and their low unconfined compressive strength values. For the rest of the study sites upper angles of 0.25H:1V and lower angles of 0.5H:1V or 1H:1V are recommended. These angles appear to be too high to prevent weathering related problems or a global failure. A possible explanation for higher angles given by GB 3 methodology could be that GB 3 recommendations are partly based on RQD values which can be high even for weak rocks.

6.2.2 Slope Design Considerations for Incompetent Design Units

Slope design for incompetent design units includes cut slopes angle, drainage control, and stabilization techniques. The main objective of selecting appropriate cut slope angles for incompetent rock units should be to minimize the natural degradation of slopes by weathering and erosion processes. This can be accomplished by the following considerations:

1. The weathering of slopes in incompetent rocks is greatly influenced by their durability as indicated by the second-cycle slake durability index (Id_2) values. Thus, the slope design

for incompetent rock units needs to be based on Id_2 values. Figure 6.1 shows the

relationship between Id_2 values and slope angles suggested by the Franklin shale rating

system (Table 5.11). This figure provides a very useful guide for selecting appropriate

slope angles for the incompetent design units. The relationship shown in Figure 6.1 is

based on 43 data points, including data from the seven study sites comprised of

incompetent rock units (shown in bold). The remaining 36 data points are based on a

previous study by Sarman (1991) who tested shale, claystone, and mudstone samples

from across the United States to investigate their swelling potential, with seven of his

samples coming from Ohio, four from Pennsylvania, and one from West Virginia. The

relationship between Id_2 and slope angle (Figure 6.1) shows two distinct trends with the

change occurring at an Id_2 value of about 80 %. This is because the shale rating system

uses Id_2 and plasticity index (PI) values for rating when Id_2 is < 80 %, and Id_2 and point

load index (Is_{50}) values when Id_2 is > 80 %. This distinction also accounts for soil-like

versus rock-like behavior of incompetent rocks, depending upon their Id_2 values. Based

on Figure 6.1, the following slope angles appear to be appropriate for incompetent design

units: Id_2 < 20 % - flatter than 2H:1V; Id_2 = 20-60 % - 2H:1V; Id_2 = 60-85 % - 1.5H:1V;

Id_2 = 85-95 % - 1H:1V; Id_2 > 95 % - 0.5H:1V. The slope angles based on Figure 6.1 are

also in agreement with the talus angles observed in this study (25-40 degrees) as long as

the Id_2 values are less than 85 %. Use of angles suggested by Figure 6.1 would allow the

raveled material to stay on the slope face, protecting it from further weathering.

2. Selection of slope angles for redbeds, which usually have Id_2 values less than 20 % and

    are characterized by their very weak and highly erodible nature, should be addressed on

    case-by-case basis.
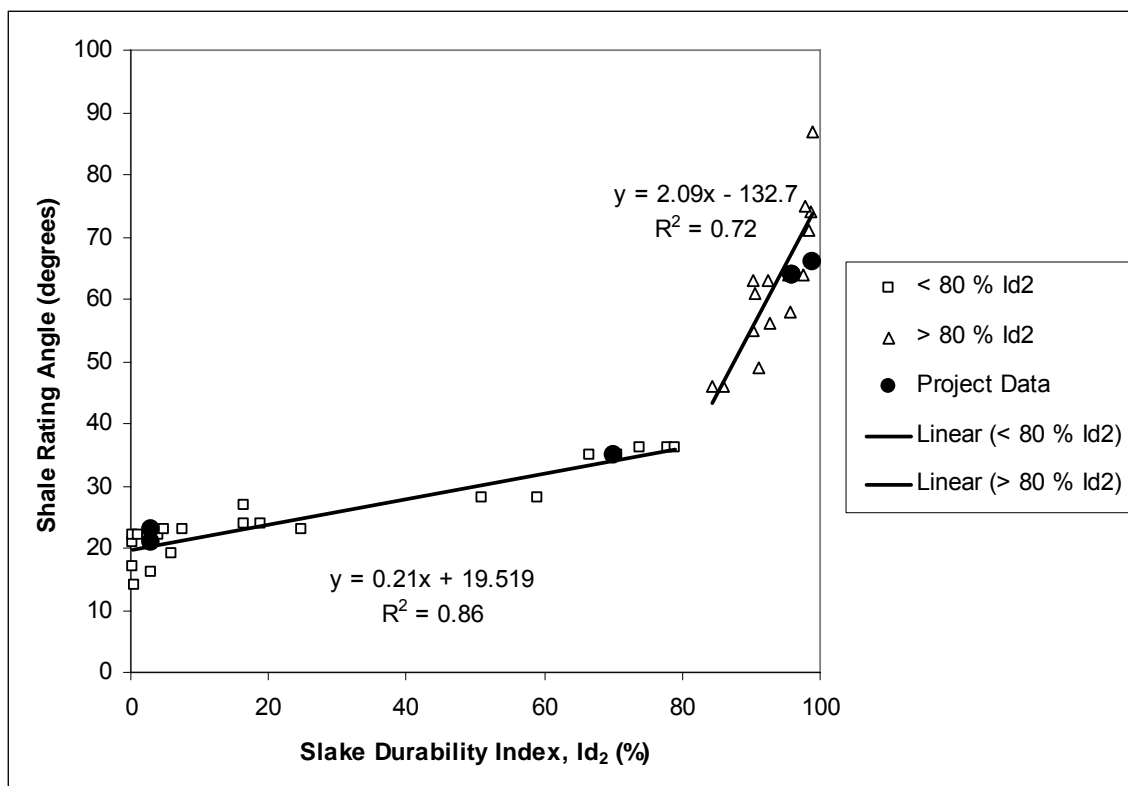
Figure 6.1: Relationship between slake durability index and shale rating slope angle for incompetent rock units. The data points from the seven study sites are shown in bold. The remaining data are from Sarman (1991).

3. Use of erosion control matting over slope face may be considered to hold raveled material and allow vegetation growth, especially where slopes flatter than 2H:1V are used. This was done at JEF-7-14, one of the 113 preliminary sites (Figure 6.2). At this site, the lower shale unit has been draped with a jute mat that has held weathered material and promoted vegetation growth.

4. Option of providing a backslope drain (a ditch behind the crest of the cut slope) may be considered to reduce surface water erosion. A backslope drain was provided at GUE-22-6 during its rehabilitation work (Figure 6.3). Backslope drains can be seen on cut slopes in shale all along the Pennsylvania Turnpike. Most of these shale slopes do not show active raveling and are covered with grass. For high slopes, provision of mid-slope drains may be necessary.

5. Catchment ditches should be wide enough to accommodate raveled material, that may not be held on the slopes, and any rockfalls resulting from the presence of minor competent rock units.

6.3 Inter-layered Competent and Incompetent Design Units

6.3.1 Discussion of Stability and Statistical Analyses Results

Four different analysis approaches were used for inter-layered competent and incompetent rock units. The first analysis focused on investigating the potential for global failure due to low rock mass strength. Fourteen inter-layered design units were analyzed using the SLIDE software and only two sites resulted in factor of safety values less than 1.5. It should be noted that the GSI values used for the analysis were obtained from a chart developed for flysh (deformed sedimentary sequences) by Marinos and Hoek (2000). The GSI values for

Figure 6.2: Vegetation growth over incompetent rock unit facilitated by placement of jute matting (JEF-7-14 site).

Figure 6.3: Back slope drain lined with rip rap and underlain by an impermeable geofabric at the rehabilitated GUE-22-6 site. Note that the back slope drain is connected with toe drain.

undeformed inter-layered units of the study sites are expected to be higher than those used in the analysis and, therefore, the calculated factor of safety values could be lower than the actual values. This problem of underestimating GSI values for undeformed sedimentary rocks using the flysh GSI chart was noted by Hoek et al. (2005) who suggest that GSI values as high as 75 be used for tunneling through undeformed inter-layered rocks. However, the new GSI values suggested by Hoek et al. (2005), for cut slopes in undeformed inter-layered rock units, were not found to be any higher than the GSI values for flysh deposits.

The absence of a global failure in the inter-layered design units, as indicated by the SLIDE analysis and field observations, may be attributed to:

i)   The discontinuous nature of joints within the competent rock units is not conducive to the propagation of a global rotational failure.

ii) The high permeability of competent units helps relieve pore pressure along potential failure surfaces.

iii) The competent rock units lend greater support to the slope relative to the much weaker incompetent rock units.

The second analysis was aimed at identifying factors affecting the generation of rockfalls due to differential weathering. Undercut sandstone and non-fossiliferous limestone units were included in the analysis. Sites containing Ordovician fossiliferous limestone units could not be included due to the absence of pre-split blasthole markings and original design plans that were needed to determine the total amount of undercutting. As discussed in Chapter 5, multivariate regression analysis identified relative position of undercut unit, joint spacing of undercut unit, slake durability of undercutting unit, and original slope angle of undercutting unit as factors explaining 61 % of the variation in the total amount of undercutting, in decreasing order. The

unexplained 39 % of the variation could be attributed to erosion due to groundwater seepage and

surface water runoff that keep removing weathered material from underneath an undercut unit

(Figures 6.4 and 6.5). The exact amounts of groundwater seepage and surface runoff could not be

estimated reliably and, therefore, were not included in the multivariate analysis.

An important factor behind the process of undercutting is the vertical infiltration of

groundwater through fractures in a competent unit until it encounters an incompetent rock unit

whereupon it flows laterally, following the contact between competent and incompetent rock

units. Ultimately, the water seeps out on the slope face and erodes the weathered material below

the competent unit, promoting undercutting. Competent units closer to the crest of the cut slope

release the largest amounts of infiltrating groundwater to the slope face, thereby experiencing the

largest amount of undercutting. Also undercut units with closer joint spacing have higher

permeability and, hence, cause larger amounts of groundwater seepage on the slope face. The

effect of the presence of joints on promoting undercutting was also noted by Shakoor and Rogers

(1992). Therefore, determining joint spacing within competent units and channelizing seeping

water should be important considerations prior to design of cut slopes prone to undercutting.

RQD from vertical holes is not a reliable estimator of joint spacing in Ohio where major

discontinuities (orthogonal joints and valley stress relief joints) are nearly vertical. In case of

vertical joints, empirical correlations between joint spacing and bedding thickness, established

by previous researchers (Bogdanov, 1947; Sowers, 1970; McQuillan, 1973; Nelson, 2001), may

be useful in predicting joint spacing from bedding thickness (Figure 6.6). However, a good

correlation between bedding thickness and joint spacing was not observed in this study. For the

purposes of design of cut slopes in Ohio, the relationships between lithology and joint spacing,

given in Chapter 4, can be used. Limestones uniformly exhibit closer joint spacing (average 16

Figure 6.4: Groundwater flowing out of joint planes, promoting undercutting (BEL-7-10 site).

Figure 6.5: Surface runoff over a slope face promoting undercutting (ATH-50-23 site).
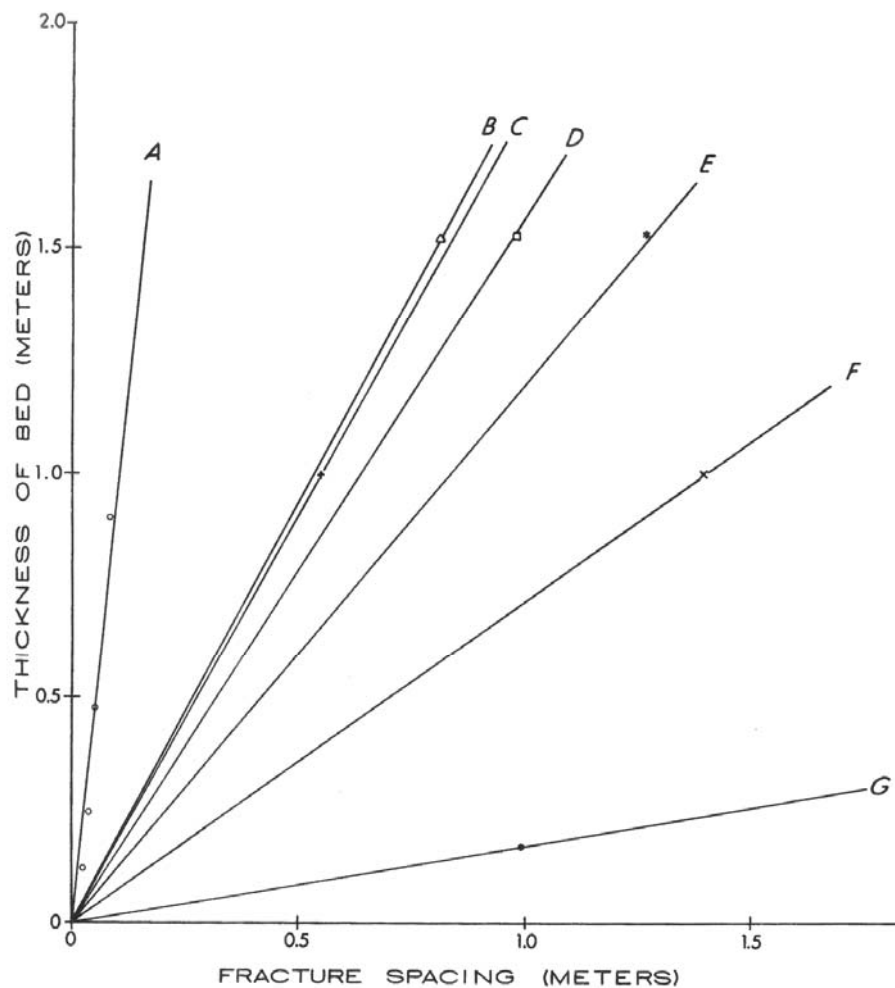
Figure 6.6: Relationship between bedding thickness and fracture spacing by: (A) Nelson, (2004), (B, D, E) Mcquillan (1973), (C, F) Bogdanov (1947), and (G) Sowers (1970).

inches/40 cm) than sandstones (average 34 inches/86 cm).

As discussed in Chapter 5, amount of recession of the competent rock units and fate of rockfalls are important aspects of undercutting induced failures. Non-fossiliferous limestone units have higher rate of recession than sandstones and, therefore, are likely to produce more frequent rockfalls. This is further supported by the numerous rockfalls held in catchment ditches of cut slopes, consisting of non-fossiliferous limestones, at WAS-77-15 and BEL-7-10 sites. WAS-77-15 site requires frequent ditch cleaning and BEL-7-10 has a concrete barrier to contain the numerous limestone rockfalls. On the other hand, cut slopes consisting of actively undercut sandstone units, such as JEF-CR77-0.38, generate much fewer rockfalls

Rockfalls from non-fossiliferous limestones are usually cubical (similar to "circular" in CRSP) and reach the catchment ditches by rolling down the slopes. Fossiliferous limestones and some sandstones, due to their low bedding thickness to joint spacing ratios, produce flat rockfalls (similar to "discoidal" in CRSP) that, in most cases, stay on slope faces. However, HAM-126-12 (containing fossiliferous limestone) and BEL-70-22 (containing sandstone) sites produce flat rockfalls that tend to have longer trajectories when they land on their sides on a steep slope (steeper than 1H:1V), traveling as a rolling discs.

The third analysis focused on determining if the process of undercutting stabilizes after a given time and if further undercutting is either greatly reduced or stops altogether. In other words, whether undercutting is linearly related to time and continues to occur at a constant rate or whether it stabilizes after a given time, exhibiting a non-linear relationship with time. This relationship could not be established from the undercutting data collected during the narrow time span of the present study. Therefore, selected sites in West Virginia, which exhibit similar geology as seen in Ohio and where total amount of undercutting was measured in 1992 by

Shakoor and Rodgers (1992), were revisited in 2008 to measure the amount of undercutting.

According to the data obtained, hardly any undercutting has occurred since the previous

measurements in 1992, indicating a non-linear undercutting-time relationship. This finding is

also supported by a recent study by Neiman (2009), which states that undercutting does not

progress continuously and stabilizes when the weathered material covers the undercutting units.

The final angle that the undercutting rock unit reaches is the angle of repose or the talus angle.

The average talus angle measured at the study sites is 38 degrees. It is reasonable to assume that

if slopes subject to undercutting are cut close to 38 degrees, minimum undercutting will take

place. This could be the reason for the higher amount of undercutting of

sandstone by the thicker part of shale, compared to the thinner part, at the JEF-CR77-0.38 site

(originally cut vertical). This variation in the amount of undercutting, caused by the same

undercutting unit, is explained in Figure 6.7 which shows that as the shale reaches its final stable

angle of ~ 38 degrees, the horizontal undercut distance is greater for thicker portion of the

undercutting unit. It also partly explains the lower amount of undercutting experienced by

competent units located in lower parts of slopes, underlain by thinner undercutting units. The

above discussion suggests dividing slope stratigraphy into distinct sub-design units, with

independent slope angles, in situations where incompetent rock units exhibit significant

variations in thicknesses across the slope length.

The purpose of the fourth analysis conducted for inter-layered design units was to

investigate how slope height, slope angle, and stratigraphy affect the effectiveness of benches of

various widths as well as the two catchment ditch designs recommended in GB 3. Both analyzed

ditches have 10 ft (3 m) wide flat bottoms and either a 3H:1V or 6H:1V foreslope angle. The

results show that a slope angle of 0.25H:1V is the best for rockfalls to be caught in a catchment
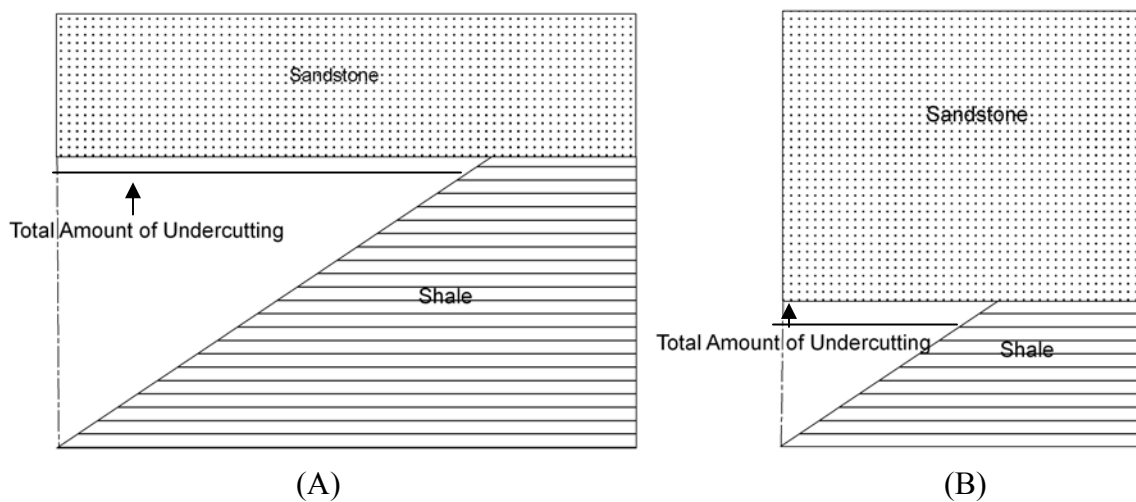
Figure 6.7: Variation of the total amount of undercutting with varying thickness of the undercutting shale unit, once the undercutting shale reaches an angle of ~ 38 degrees. The sandstone in (A) is underlain by shale that is twice as thick as the shale in (B) and experiences twice the amount of undercutting than the sandstone in (B).

ditch or for a bench not to act as a launching pad. This is because rockfalls generated from near vertical cuts can fall straight into a catchment ditch or on a bench.

6.3.2 Slope Design Considerations for Inter-layered Design Units

Slope design for inter-layered competent and incompetent design units includes selection of cut slope angles, selection of stabilization techniques, provision of benches, and provision of catchment ditches. The main concept behind cut slope design for inter-layered rocks is to identify the factors that promote undercutting-induced failures and implement measures that counteract the role of these factors. Based on this concept, the following design considerations appear to be relevant:

1. The potential for discontinuity dependent, undercutting-induced, failures within the competent rock units should be minimized. Such failures are common in thick (> 3 ft/1 m) sandstone or limestone units underlain by shale or claystone/mudstone.

2. The amount of weathering of incompetent rock units should be reduced. Cutting slopes at angles recommended previously for incompetent units will reduce the amount of undercutting.

3. Use of erosion control matting should be considered for holding weathered material on the slope face and allowing vegetation growth.

4. The rate of undercutting should be reduced by placing a bench on top of the undercutting rock unit. Benches may also be necessary for high cut slopes to account for stratigraphic variations within the inter-layered design unit. Bench widths should be chosen so that benches do not act as launching pads to direct rockfalls beyond catchment ditches.

5. The influence of factors that contribute to total amount of undercutting and amount of recession should be minimized. Undercut rock units that outcrop in the upper portion of a cut slope and those that have closer joint spacing may require artificial stabilization.

6. Cut slope angles for inter-layered design units containing thin to medium thick competent rock units may be selected on the basis of weighted average slake durability index values. Figure 6.8 shows the relationship between weighted slake durability index values and the slope angles suggested by the shale rating system. Based on Figure 6.8, the following slope angles may be used for initial design: weighted Id_2 < 30 % - 2H:1V or flatter; weighted Id_2 = 30-60 % - 2H:1V; Id_2 = 60-85 % - 1.5H:1V; Id_2 = 85-95 % - 1H:1V; Id_2 > 95 % - 0.5H:1V. For weighted Id_2 values of up to 85 %, the above noted angles also conform to the observed range of talus angles (25-40 degrees). However, these angles will require adjustments based on previous experience with inter-layered design units.

7. The amount of surface water runoff and groundwater seepage should be reduced by providing backslope and midslope (if necessary) drains.

8. Methods for keeping weathered material in place should be considered.

9. Maximum effectiveness of catchment ditches, as indicated by rockfall simulation analysis, should be achieved. In cases where a catchment ditch is not effective i.e. retains less than 95 % rockfalls for the chosen width, use of a wider ditch or a rockfall barrier (D-50 wall or a rockfall catch fence) should be considered based on the rockfall bounce heights provided in Tables 5.27 and 5.28. This aspect of catchment ditch design is discussed in detail in Chapter 5. The D-50 wall and catch fence should be capable of withstanding rockfall impact and catchment ditches should be cleaned periodically.
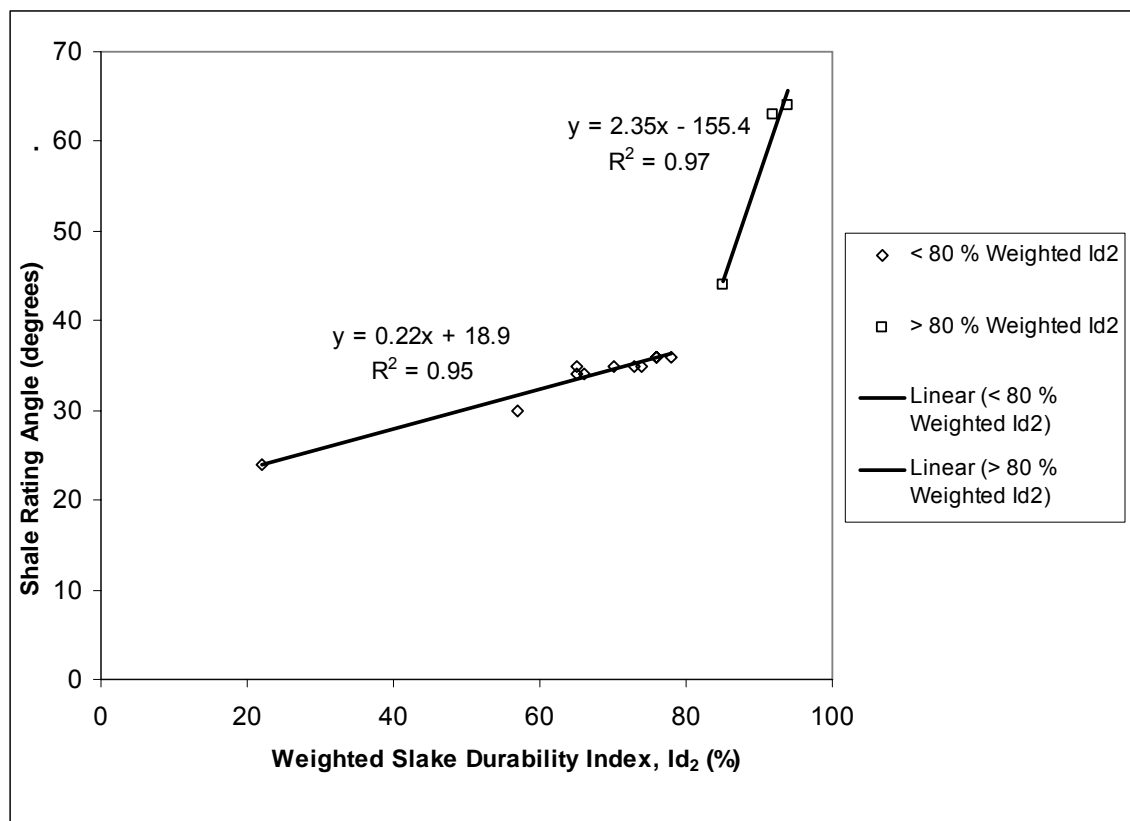
Figure 6.8: Relationship between weighted slake durability index and shale rating slope angle for inter-layered rock units.

CHAPTER 7

CUT SLOPE DESIGN RECOMMENDATIONS

This chapter summarizes various stabilization methods and recommends specific slope designs for different design units based on stability analysis results presented in Chapter 5 and discussion of these results presented in Chapter 6.

7.1 Stabilization Methods

Since slope stabilization is an important aspect of cut slope design, it is appropriate to provide a summary of stabilization methods before discussing specific slope designs for the three design units. The three broad categories of commonly used slope stabilization methods are: (i) reinforcement (rock bolts/rock anchors, dowels, tied-back retaining walls, shotcrete, buttresses, drainage), (ii) rock removal (regrading, trimming, scaling), and (iii) protection measures (ditches, wire-mesh nets, barriers/catch fences) (Wyllie and Mah, 2004). The choice of a given stabilization method depends on site geology, construction constraints, and cost considerations. A detailed cost analysis of various stabilization options must be performed before selecting a particular method or combination of methods. Furthermore, past experience about the success of various methods for particular geologic conditions should be used as a guide for selecting stabilization methods for a new site. Stabilization methods that are relevant to cut slopes in Ohio include rock anchors, shotcrete, erosion control mats, buttresses, drainage, rockfall barriers, and removal of loose rock blocks.

7.1.1 Rock Anchors

Rock anchors are usually installed where unfavorably oriented discontinuities promote plane or wedge failures, toppling, and large-size rockfalls.. Rock anchors can be bars (bolts) or cables, tensioned or untensioned (Figure 7.1). Tensioned rock anchors, installed across potential failure surfaces, are anchored in sound rock beyond the failure surface using resins, cement grouts, and mechanical devises, and tightened at the slope face end using reaction plates. The tensile force in the rock anchor, induced by the reaction plate, produces a compression in the surrounding rock mass which, in turn, increases the resisting force (shear strength) and decrease the driving force along the failure surface. For optimum results and cost savings, the angle between the anchor and the failure surface should be equal to the friction angle along the failure surface (Wyllie and Norrish, 1996). The requirements of a permanent, tensioned rock anchor are: (i) proper anchoring of the distal end of the anchor in the drill hole, (ii) application and maintenance of anchor tension without creep and loss of load over time, (iii) field testing of the anchor, and (iv) protection of anchor assembly against corrosion for the design life of the project. Details of these requirements can be found in Wyllie and Norrish (1996) and Wyllie and Mah (2004). Untensioned rock anchors are used for reinforcing a cut slope before an excavation is made. They are installed from behind the crest of a planned slope cut (Figure 7.1), are fully grouted, and prevent loss of interlock due to relaxation of rock upon excavation.

Figures 7.2 and 7.3 show examples of rock anchors applications from Pennsylvania where the stratigraphy is very similar to that in Ohio. It should be pointed out, however, that the use of rock anchors as a stabilization measure is more feasible in situations where competent rock units contain well developed, relatively widely spaced joints and where failures pose a serious threat to traffic as may be the case with high cuts in urban areas.
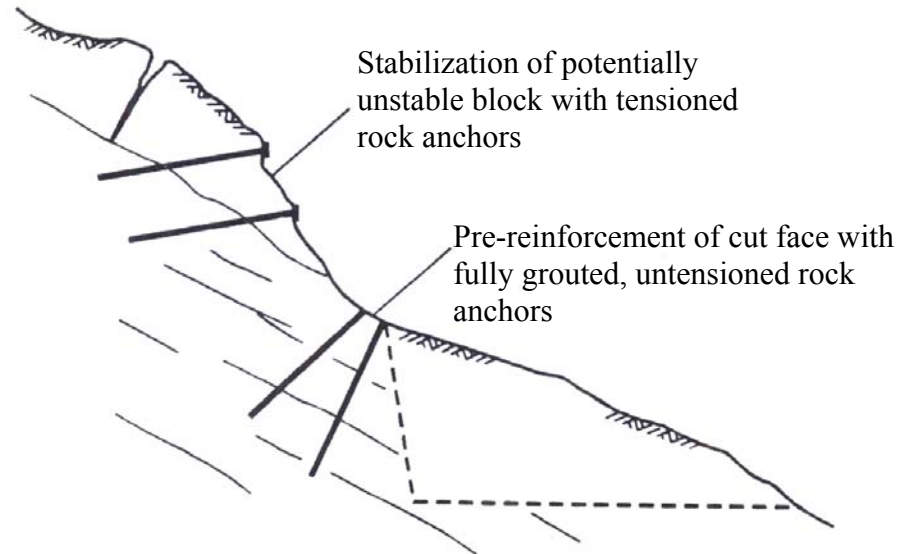
Figure 7.1: (a) Tensioned rock bolts to prevent sliding of a loosened rock block and (b) fully grouted, untensioned rock bolts (dowels) installed prior to excavation for reinforcement (after Wyllie and Mah, 2004).

Figure 7.2: Example of rock anchors application from the Duquesne Bluffs site, Pittsburgh Parkway, Pennsylvania. The rock anchors at this site are used to stabilize a relatively thick unit of sandstone that is underlain by a claystone layer. The claystone layer has been shotcreted to prevent undercutting of the sandstone. A catch fence with friction brakes is provided as a rockfall barrier.
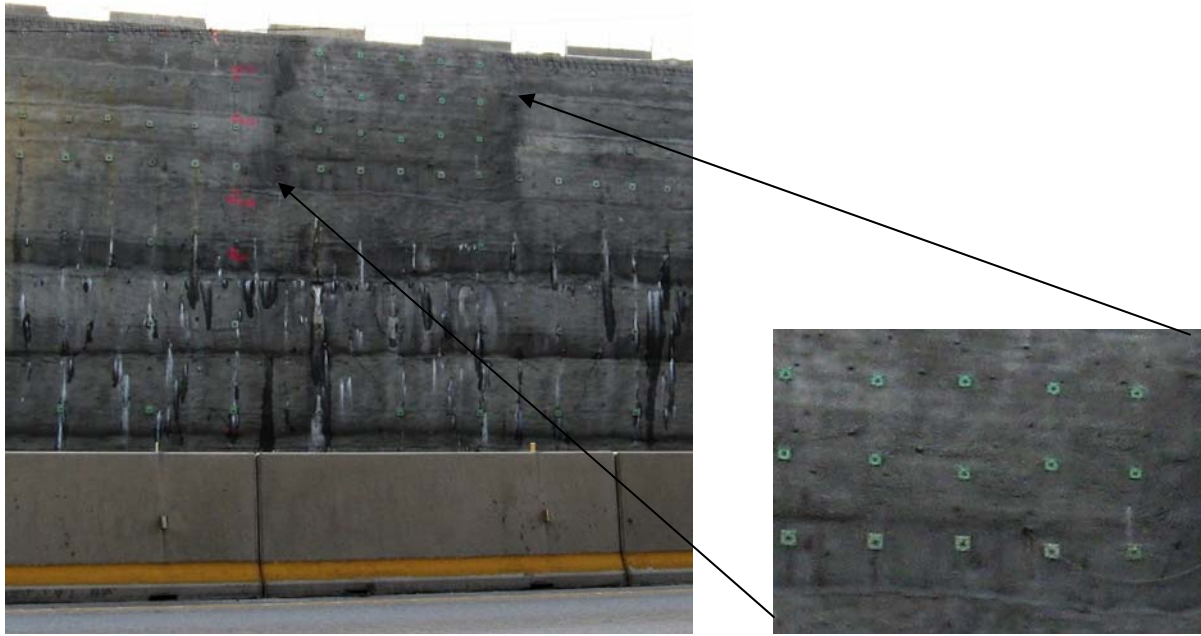
Figure 7.3; Example of closely spaced rock anchors (nails) from a road cut along Interstate 76, outside of Pittsburgh, Pennsylvania. In addition to providing support to the rock mass, the anchors in this case help holding the shotcrete in place.

An important consideration in choosing rock anchors as a stabilization option is their high cost of installation compared to other stabilization measures. The cost is usually site specific and depends on such factors as required anchor length, anchor load, anchor spacing, total number of anchors needed, and location of anchor installation on slope face.

7.1.2 Shotcrete

Shotcrete is a thin, 2-4 inches (50-100 mm) thick, layer of fine aggregate mortar that is pneumatically applied to cover closely jointed or weak degradable rocks (Wyllie and Mah, 2004). Shotcrete can hold small rocks on slope face, preventing them from falling. It can also protect weak layers from weathering, minimizing their potential for undercutting the overlying competent layers. The shotcrete mixture basically consists of aggregate (2.5-10 mm size stone and sand), cement, and some admixtures (superplasticizers) that are added for high early strength and quick setting (Wyllie and Mah, 2004). Ultrafine silica powder (silica fume) can be added to minimize rebound, increase layer thickness, and increase long term strength. Shotcrete can be used either as a wet or a dry mix. The wet mix is delivered by concrete–mixing trucks that use water to mix cement and aggregate. In case of a dry mix, aggregate material of required gradations is mixed, poured into the hopper of a pump, passed through a pre-dampener to add moisture, then pumped on to the slope face. The dry mix is advantageous where small quantities are used at a time or where the site of application is inaccessible.

For long term performance, shotcrete is reinforced by welded wire mesh, steel or polypropylene fibers, and anchors (nails). Reinforcement reduces spalling, cracking, and other forms of deterioration (Wyllie and Mah, 2004). Complete details of shotcrete specifications can be found in a special publication by the American Concrete Institute (ACI, 1995).

Figures 7.3, 7.4, and 7.5 provide examples of shotcrete applications from cut slopes in

Figure 7.4: An example of shotcrete application from Route 28, Pittsburgh, Pennsylvania. The redbeds at this site have been shotcreted to protect them from weathering and to minimize their potential for undercutting the overlying competent unit. Notice the closely spaced drain holes at the base of the shotcreted layer and the provision of a catch fence for additional protection.

Figure 7.5: Shotcreting of claystone layer at the Duquesne Bluffs site, Pittsburgh Parkway, Pennsylvania. Notice the jack hammer marks on the face of upper upper sandstone layer resulting from scaling.

Pennsylvania. Provision of drainage is an essential requirement for successful application of shotcrete. Without proper drainage, shotcrete is likely to fail soon after placement. Figure 7.4 shows the closely spaced drain holes at the base of the shotcreted layer.

It needs to be pointed out that ODOT's experience with shotcrete application in Ohio has been less than positive. However, if properly applied, shotcrete may be considered as viable option for minimizing undercutting. The shotcrete in Figure 7.5, covering a 10 ft (3 m) thick claystone layer, is more than 25 years old but is still intact because of the provision of drainage.

7.1.3 Erosion Control Mats

Erosion control mats are being increasingly used to minimize weathering, keep weathered material in place, and allow vegetation to grow. Mats can be temporary and biodegradable (Maccaferri; www.maccaferri-northamerica.com/Biomac.aspx) or they can be permanent (Wolbert and Master, Inc; www.wolbertandmaster.com/ecmatting.htm#). Figure 7.6 shows a close up view of a biodegradable jute mat. Figures 6.2 and 6.3 show applications of matting in promoting vegetation at the JEF-7-14 and GUE-22-6 sites. Figure 7.7 illustrates another large-scale application of erosion control matting. Matting may be considered as one of the options for stabilizing gentle slopes (2H:1V or gentler) comprised of very low durability rocks, such as redbeds. ODOT's past experience with use of erosion control mats will be valuable in selecting situations (slope angle, rock type, pH value, nutrient content, etc.) where this stabilization measure may be most effective.

7.1.4 Buttresses/Backstowing

Buttresses are concrete infillings used under unstable openings, such as mine openings, to provide support (Wyllie and Mah, 2004). The bottom of a buttress should be founded on sound

Figure 7.6: An example of a biodegradable jute mat (source: www.forestry-suppliers.com/product_pages).

Figure7.7: Field application of erosion control matting (source: www.sderosion.com/blankets.htm).

rock and the top part should be in contact with the underside of an opening. In order to achieve a direct contact in the top part, the concrete should be poured from a hole drilled from the slope surface into the opening that requires the support.

An alternate method of stabilizing mine openings is the backstowing method. In this method, once the ventilation has occurred and any fallen roof rock near the entrance of the opening has been removed, # 4-sized washed river gravel is pneumatically injected to a minimum of 20 ft (6 m) into the opening. The method requires that the stone be placed around any mine pillars encountered within the backstowed area and that the density of the placed stone be approximately 75-95 percent of the rock density.

7.1.5 Drainage

Water is one of the most important factors contributing to slope instability. Provision of surface drains and horizontal drains can reduce water pressure by limiting surface infiltration and providing outlet for water behind the slope face. Figure 7.8-A and 7.8-B show various types of surface drains (backslope drain, contact zone drain, bench drain). Figures 6.3 and 7.9 show examples of back drains, one lined with rip rap and the other with concrete. Surface drains should be interconnected and ultimately discharge into the storm drain system (Wyllie and Mah, 2004). Surface drains can reduce surface erosion as well as undercutting by collecting groundwater seeping out along the contacts between competent and incompetent rock units. In addition to surface drains, horizontal drains, extending into the slope at approximately 5° and placed at 10-30 ft (3-10 m) spacing, may be installed to relieve water pressure build up along discontinuity planes (Wyllie and Mah, 2004). An example of horizontal drains can be seen in Figure 7.10. For long cuts (> 1500 ft/455 m), the option of using downslope drains, connecting lateral drains with the toe drain, may be considered. All drains, except the toe drain, should be
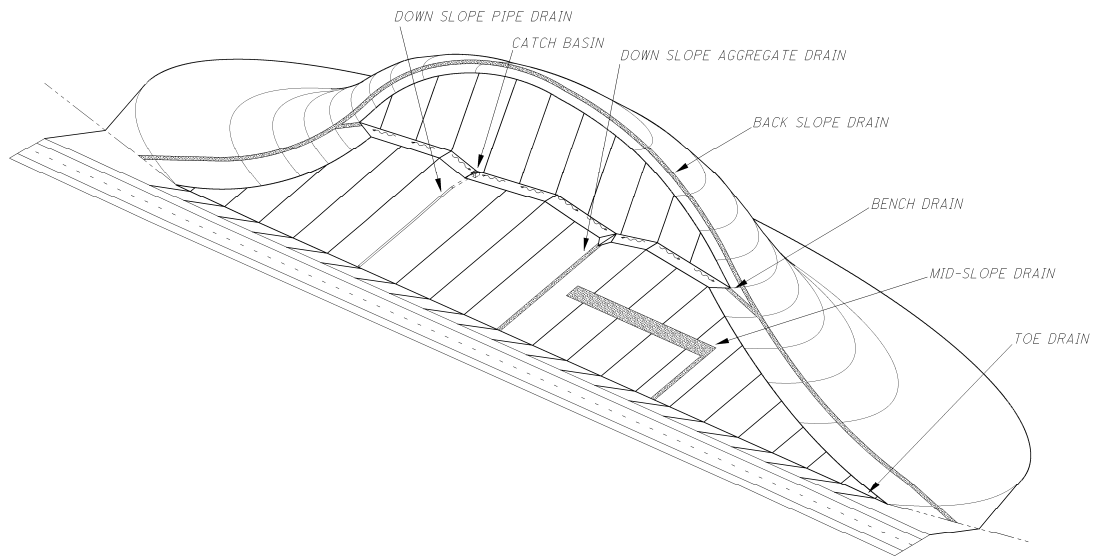
Figure 7.8-A: Different types of drains on a cut slope.

Figure 7.8-B: Field application of various types of surface drains.

Figure 7.9: An example of a back drain lined with concrete.

Figure 7.10: An example of horizontal drains.

lined with concrete or with rip rap underlain by a geofabric. The extent of drainage facilities required at a site will depend on rock type, permeability of rock, and slope dimensions.

7.1.6 Rockfall Barriers

Barriers are placed along the roadway side of a catchment ditch to enhance the ability of a ditch to retain rockfalls. They are especially effective where the slopes are flatter and the falling rocks roll down the slope face, roll up the ditch foreslope, and are ultimately trapped by the barrier. Barriers can be either rigid or flexible and should be capable of absorbing the impact energy of rockfalls without damage. Portable concrete barriers (PCB), cast-in-place concrete barriers (CCB), gabions, geofabric- reinforced soil barriers, and fences are the most widely used barriers (Wyllie and Mah, 2004). PCB and CCB are placed along the edges of catchment ditches. Figures 7.3 and 7.4 show the use of PCB and Figure 7.11 shows an example of CCB. These two types of barriers are widely used in Ohio. Gabions are rock-filled wire mesh baskets and are advantageous on hill sides or where foundations are irregular. Geofabric-soil barriers consist of soil layers reinforced by a geofabric. Rockfall catch fences (Figures 7.2 and 7.4) are made of non-rigid components that are able to absorb rockfall energy. Latest designs incorporate friction brakes for added flexibility. Friction brakes are loops of wire that are activated upon impact and help dissipate energy (Figure 7.2). Companies such as Geobrugg Corporation, Maccaferri, Inc., and Isofer Industries are the major manufactures of rockfall catch fences.

7.1.7 Wire Mesh Nets

A wire mesh net is usually placed over a slope consisting of a highly jointed rock mass. It is an effective method of controlling rockfall trajectories and preventing them from bouncing. The net is anchored only on the top end and freely hangs over the slope. Rockfalls caught behind

Figure 7.11: An example of a cast-in-place barrier (ODOT D-50 wall).

Figure 7.12: Use of wire mesh net in controlling rockfall trajectories at the ASD-97-4.11 site. The figure also shows use of a PCB.

the net roll down within the space between the slope face and the net, entering the catchment ditch with minimum energy (Wyllie and Mah, 2004). Wire mesh nets are particularly useful where wide catchment ditches are not feasible. Figure 7.12 from ASD-97-4.11 site shows the application of wire mesh net as well as the use of a PCB.

7.1.8 Removal of Loose Rock Blocks

Overhangs and loose rock blocks on a slope need to be removed to avoid future rockfall hazard. Removal methods generally consist of trim blasting to minimize the effect of blasting on slope material (Wyllie and Mah, 2004) or scaling, which is removing loose rock blocks by using crow bars, bladders, and jack hammers (Wyllie and Mah, 2004). Figure 7.13 provides an example of scaling from a site in Jackson County, Ohio whereas Figure 7.5 shows scaled sandstone face with jack hammer marks.

7.2 Cut Slope Design Recommendations

7.2.1 Competent Design Units

Two specific design options, as indicated by RocFall analysis (Tables 5.27 and 5.28), can be used for competent design units:

1. Cut the slope at 0.5H:1V and provide a catchment ditch with either GB 3 design option 2-a or GB 3 design option 2-b (Figure 7.14). These two catchment ditch designs were found to be effective in retaining 95 % of the rockfalls for varying slope angles and slope heights, either with or without the use of a rockfall barrier. If a GB 3 design option 2-a ditch is used for a 0.5H:1V slope, a rockfall barrier will not be needed as long as the slope height is less than 20 ft (6m). If the slope height is between 20 ft and 60 ft (6 m and 18 m), a D-50 wall will be required. If the slope height is between 60 and 100 ft (18

Figure 7.13: Scaling operation at a site along Route 35, Jackson County, Ohio.
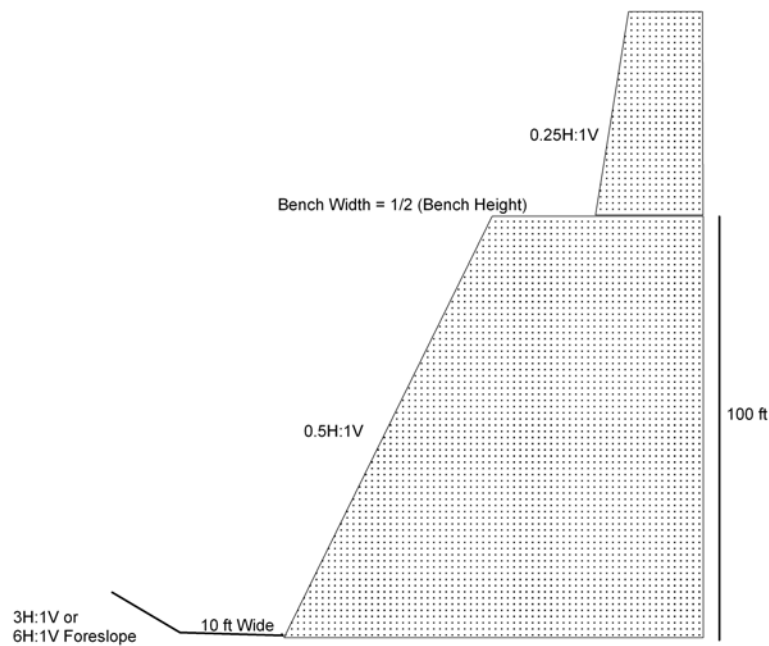
Figure 7.14: Recommended slope design for competent design units, option 1. The bench height shown in the figure is for situations where a 10 ft (3 m) high catch fence is used as a rockfall barrier.

m and 30 m), a 10 ft (3m) high catch fence will be needed. A bench will be required if the slope height exceeds 100 ft (30 m). The bench can be placed at 60 ft height if a D-50 wall is used or at 100 ft (30 m) height if a catch fence is used. The bench width should be B = ½ H1 (Figure 5.37), but not exceeding 15 ft (4.5 m). The barrier height and bench location recommendations stated above are only valid for GB 3 design option 2-a ditch (Table 5.27). For GB 3 design option 2-b ditch, Table 5.28 can be used to obtain barrier heights and bench locations.

Pre-split holes should follow the designed slope contours to ensure uniform slope angle and bench width. Zones of close joint spacing, especially near the ends of the cut slope, should be either flattened using a 1H:1V slope or stabilized using wire mesh net.

2. If the competent design unit consists only of sandstone, the option of cutting the slope at a steeper angle of 0.25H:1V and providing a wider catchment ditch with GB 3 option 2-b design may be considered (Figure 7.15). If this option is used, no barrier will be needed for slope heights less than 60 ft (18 m). If the slope height is between 60 ft and 100 ft (18 m and 30 m), provide a D-50 wall along the catchment ditch. A bench will be required if the slope height exceeds 100 ft (30 m). The bench can be placed at 60 ft (18 m) height if no barrier is used and at 100 ft (30 m) height if a D-50 wall is used. The option of using rock anchors to reduce the potential for discontinuity controlled failures, especially type B toppling, or use of wire mesh net to control failure trajectories may be considered.

It should be noted that the design options described above are based on the two types of ditches used in RocFall analysis (GB 3 design option 2-a, and design option 2-b ditches). Because of the relatively narrow ditch widths used, rockfall barriers are required
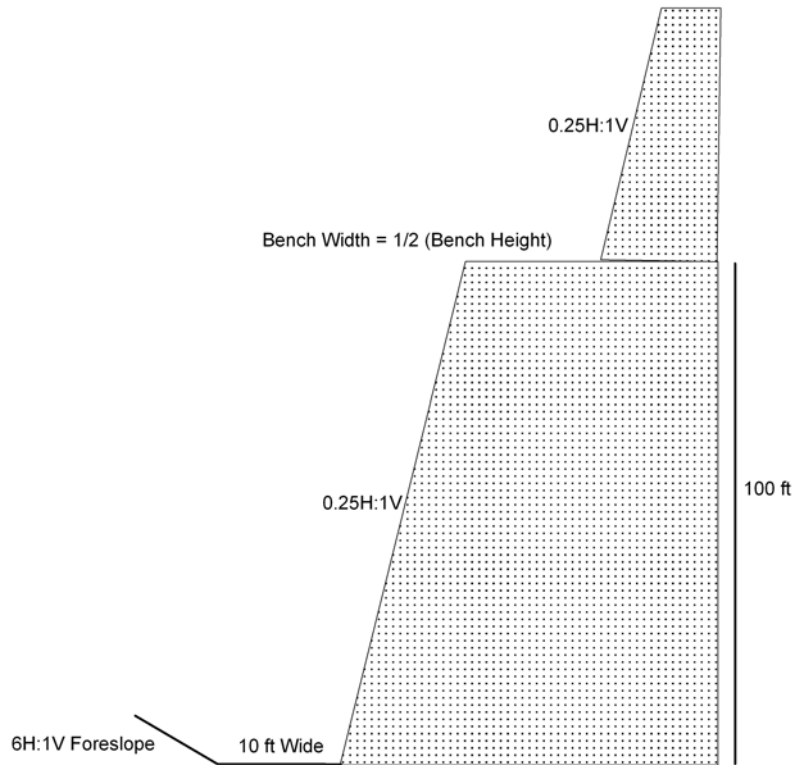
Figure 7.15: Recommended slope design for competent design units (sandstones only), option 2. The bench height shown in the figure is for situations where a D-50 wall is used as a rockfall barrier.

if the cut slopes exceed certain heights. If a rockfall barrier is not used, a 20 ft (6 m) wide ditch can be used for a 0.25H:1V slope and a 30 ft (9.1 m) wide ditch for a 0.5H:1V slope, as suggested by RocFall analysis. Both ditches should have either a 3H:1V or 6H:1V foreslope angle. Another option would be to use Table 1.4 to select ditch width. As pointed out previously, Table 1.4 is based on considerable research.

7.2.2 Incompetent Design Units

A two-step approach is recommended for design of cut slopes in incompetent rock:

1. Slope angles for incompetent design units can be selected using second-cycle slake durability index (Id_2) and Figure 6.1 as follows: Id_2 < 20 % - flatter than 2H:1V; Id_2 = 20-60 % - 2H:1V; Id_2 = 60-85 % - 1.5H:1V; Id_2 = 85-95 % - 1H:1V; Id_2 > 95 % - 0.5H:1V. Backslope drains, lined with rip rap and underlain by an impermeable geofabric (Figure 7.16), should be provided to reduce surface runoff. The backslope drains should be connected with the toe drains. For long slope cuts (> 1500 ft/455 m), the option of providing downslope drains, connecting backslope drain to the toe drain, may be considered. For high but gentle (< 1H:1V) cut slopes (e.g. slopes in redbeds), a midslope drain, lined with rip rap and connected with the backslope drain, may be necessary. In addition to provision of drainage, use of erosion control matting may be considered for incompetent rocks with Id_2 values < 85 %. A catchment ditch (GB 3 options 1 or 2), should be provided for all slopes comprised of incompetent rock (Figure 7.16).

2. Redbeds, characterized by very low durability (Id_2 usually < 20 %), should be treated as a special units and addressed on a case-by-case basis. Past experience of slope performance in redbeds should be considered in selecting the final slope angle.
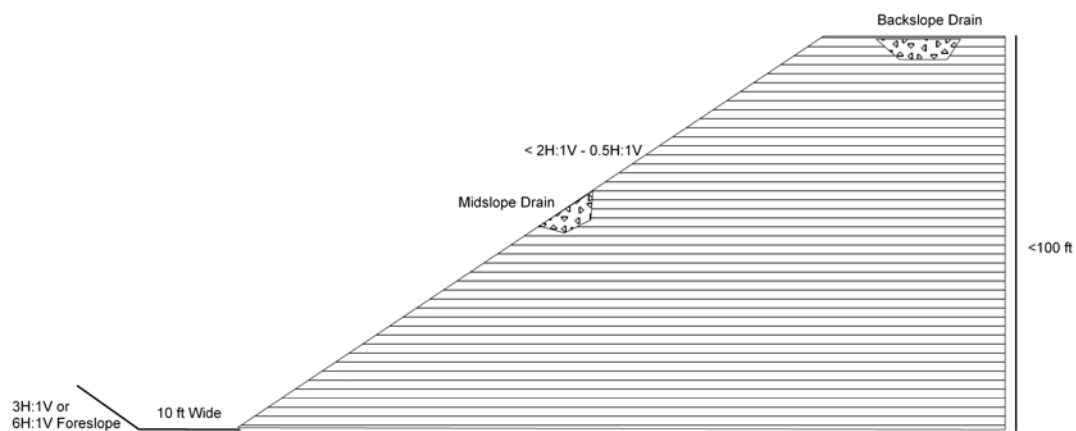
Figure 7.16: Recommended slope design for incompetent design units.

7.2.3 Inter-layered Competent and Incompetent Design Units

Inter-layered competent and incompetent design units exhibit significant stratigraphic variations which should be accounted for in cut slope design. Four stratigraphic configurations, designated as Type A through Type D, were recognized during this study and are defined below:

i) Type A - Thick (>3 ft/1 m) sandstone or limestone units underlain by shale or claystone/mudstone units (Figure 7.17).

ii) Type B - Thin to medium thick (< 3 ft/1 m) sandstone units inter-layered with shale or claystone/mudstone units in variable proportions. Two cases of Type B stratigraphy exist. Case 1 is where sandstone to shale or claystone/mudstone ratio is > 0.5 (Figure 7.18) and case 2 is where this ratio is < 0.5 (Figure 7.19). Case 1 is much less common than case 2.

iii) Type C - Non-marine limestone (1-3 ft/0.3-1 m) units inter-layered with claystone/mudstone units in variable proportions. Type C stratigraphy also can be divided into two distinct cases, with case 1 having limestone to claystone/mudstone ratio > 0.5 (Figure 7.20) and case 2 with this ratio being < 0.5 (Figure 7.21).

iv) Type D – Thin (2-3 inches/5-8 cm) fossiliferous limestone units inter-layered with claystone/mudstone units in variable proportions (Figure 7.22).

Recommended Slope Design for Type A Stratigraphy

Type A stratigraphy results in discoidal as well as cubical rockfalls due to undercutting and presence of discontinuities in the incompetent units. Design should focus on reducing the failures promoted by discontinuities within the competent rock units or controlling the trajectories of such failures, especially Type B toppling failure, minimizing excessive degradation of the incompetent units, and providing properly designed benches and catchment

Figure 7.17: An example of Type A stratigraphy (COL-7-3).

Figure 7.18: An example of Type B stratigraphy - case 1 (upper portion of cut slope) (LAW-52-12).

Figure 7.19: An example of Type B stratigraphy - case 2 (BEL-70-22).

Figure 7.20: An example of Type C stratigraphy - case 1 (BEL-470 Interchange).

Figure 7.21: An example of Type C stratigraphy - Case 2 (WAS-77-15).

Figure 7.22: An example of Type D stratigraphy.

ditches. The following slope design options, based on Figure 6.1 and RocFall analysis, are recommended for Type A stratigraphy:

1. Cut the competent rock unit (both limestone and sandstone) at 0.5H:1V (Figure 7.23) to decrease the potential for Type B toppling and other discontinuity-related failures. Cut the incompetent rock unit at varying angles ($< 2H:1V-0.5$ H:1V), based on Id_2 values (Figure 6.1), to minimize excessive degradation and recession. Provide a bench along the contact between competent and incompetent rock units (Figure 7.24) with a width equal to the thickness of the competent rock unit (B = H1), but not exceeding 15 ft (4.5 m). The cut slope should follow the contour of the contact so that the cut face would have a more rounded shape with a uniform bench width. Install a bench drain along the contact between the competent and incompetent rock units to collect seeping water, and a backslope drain behind the slope crest to reduce runoff on slope face. The lateral drains (bench, backslope) should be connected to the toe drain. Long (> 1500 ft/455 m) cut slopes may require downslope drains. All drains, except the toe drain, should be lined with rip rap underlain by an impermeable geofabric. A catchment ditch, meeting GB 3 design options 2-a or 2-b specifications, should be provided (Figure 7.23). If the incompetent rock unit is 80-100 ft (25-30 m) thick, place a D-50 wall along the edge of the catchment ditch. If a D-50 wall is not used, provide a wider (35-45 ft/10.6-13.5 m) catchment ditch, as suggested by RocFall analysis (Section 5.3.4.3), or use Table 1.4.

2. If the competent unit in Type A stratigraphy consists only of sandstone, a 0.25H:1V slope may be used (Figure 7.25). There will be a greater potential for type B toppling and other discontinuity-related failures in this case which may be controlled by provision of a wire mesh net, a D-50 wall, or a wider catchment ditch as described in option 1.
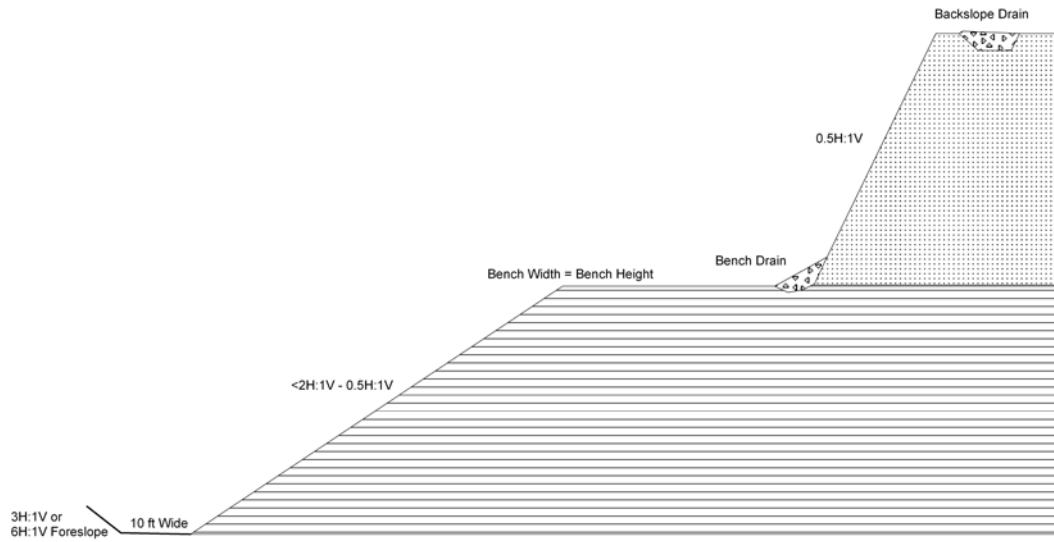
Figure 7.23: Recommended slope design for Type A stratigraphic configuration of inter-layered design units, option 1.

Figure 7.24: Provision of a bench along the contact between competent and incompetent units of Type A stratigraphy (JEF-7-14).

Recommended Slope Design for Type B Stratigraphy

Type B stratigraphy results in discoidal to cubical rockfalls. The design approach for this type of stratigraphy should be to cut the slope at a uniform gentle angle, using Figure 6.8 as a guide, and provide adequate ditches and barriers to contain the rockfalls. Based on Figure 6.8, the following slope angles may be used: weighted $Id_2 < 30$ % - 2H:1V or flatter; weighted $Id_2 = 30\text{-}60$ % - 2H:1V; weighted $Id_2 = 60\text{–}85$ % - 1.5H:1V; weighted $Id_2 = 85\text{-}95$ % - 1H:1V; weighted $Id_2 > 95$ % 0.5H:1V. Due to smaller thickness of the sandstone units, use of multiple benches will be impractical in this case.

The following slope design options are recommended for case 1 of Type B stratigraphy:

1. If the weighted Id_2 is < 85 %, cut the slope at a uniform angle as indicated by Figure 6.8, but not exceeding 1.5H:1V (Figure 7.26). For a 1.5H:1V slope, a catchment ditch, designed in accordance with GB 3 design option 2-b, should be adequate as long as the slope height is less than 40 ft (12 m). For slopes between 40 ft and 100 ft (12 m and 30 m) height, a D-50 wall will be required along the catchment ditch (Table 5.28). If the slope height exceeds 100 ft (30 m), a bench (width B = H1; not exceeding 15 ft/4.5m) should be placed at 100 ft (30 m) height on top of the incompetent rock unit (Figure 7.26). The slope above the bench should be cut at a steeper angle, preferably at 0.25H:1V. This requirement, based on RocFall output, ensures that rockfalls from upper slope will not bounce from the bench below. A lateral drain should be placed on bench and should be connected with backslope drain and with toe drain. Drains should be lined with rip rap underlain by an impermeable geofabric. The above recommendations pertaining to bench location, barrier height, and drainage are also applicable to slopes gentler than 1.5 H:1V. If a barrier is not used, the ditch width should be 35-45 ft (10.6-
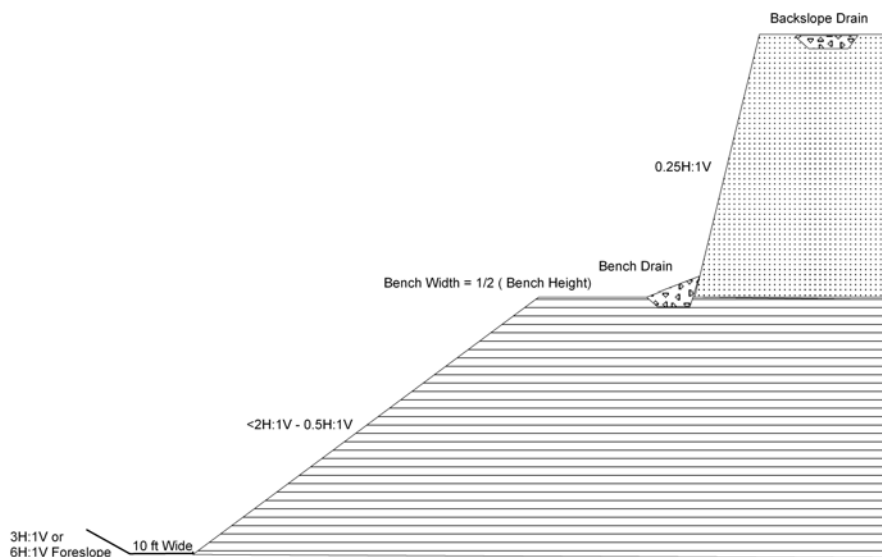
Figure 7.25: Recommended slope design for Type A stratigraphic configuration of inter-layered design units, option 2.
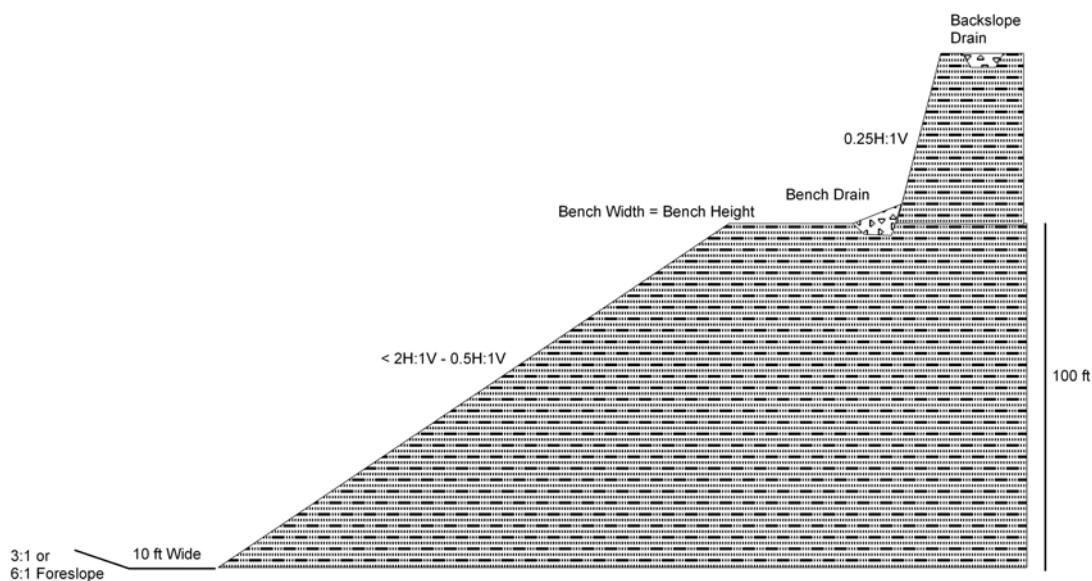
Figure 7.26: Recommended slope design for Type B stratigraphic configuration of inter-layered design units, case 1, option 1. The bench height shown in the figure is for a situation where a D-50 wall is used.

13.5 m), as indicated by RocFall analysis, or Table 1.4 should be used to select appropriate ditch width.

If the weighted Id_2 value is > 85 %, cut the slope at 1H:1V or steeper, using Figure 6.8. The rest of the design will be the same as described above except that a 10 ft (3 m) high rockfall catch fence will be required. If a fence is not used, design the ditch as stated in option 1.

2. A second option, indicated by RocFall analysis, is to cut the slope at 0.25H:1V (Figure 7.27) to keep the rockfall trajectories closer to vertical. Catchment ditch should follow GB 3 design option 2-b. If the slope height is 20-60 ft (6-18 m), provide a D-50 wall. If the height is 60-100 ft (18-30 m), a 10 ft (3 m) high catch fence will be needed. If the barrier option is not used, provide a wider catchment ditch as in option 1. For slopes higher than 100 ft (30 m), a bench will be needed at 100 ft (30 m) height (Figure 7.27). The slope above the bench may also be cut at 0.25H:1V. Drainage design should be the same as for option 1.

The recommended slope design for case 2 of Type B stratigraphy is to cut the slope at an appropriate angle using Figure 6.8. The maximum slope angle should not exceed 1.5H:1V (Figure 7.28) to keep the discoidal rockfalls on the slope face. If the slope is higher than 40 ft (12 m), a 10 ft high rockfall catch fence should be provided for the catchment ditch. Catchment ditch and drainage design should be the same as for case 1.

If a different design unit is present under Type B stratigraphic sequence, in either option 1 or option 2, a bench should be placed between the two design units. The bench should be designed with a width equal to H1.
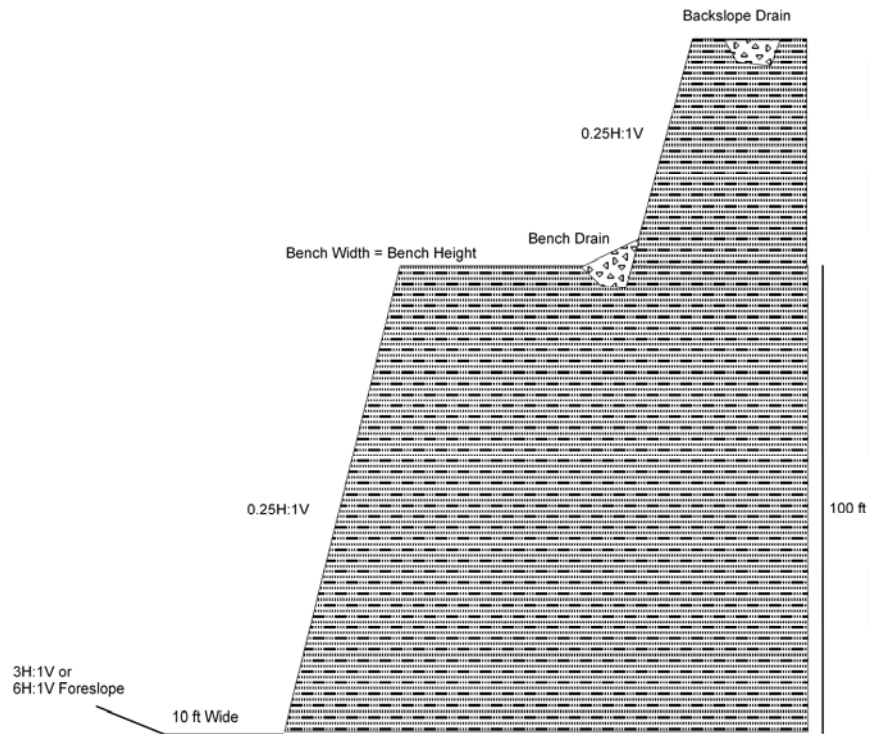
Figure 7.27: Recommended slope design for Type B stratigraphic configuration of inter-layered design units, case 1, option 2. The bench height shown in the figure is for situations where a 10 ft (3 m)height fence is used.
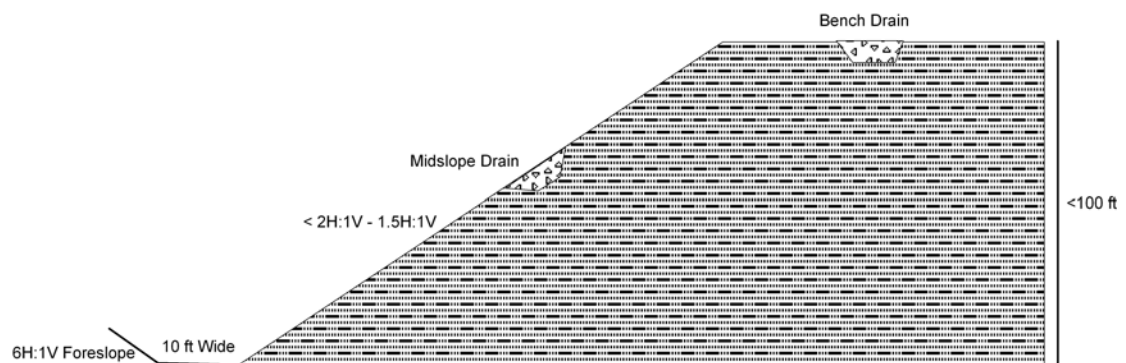
Figure 7.28: Recommended slope design for Type B stratigraphic configuration of inter-layered design units, case 2.

Recommended Slope Design for Type C Stratigraphy

Type C stratigraphy results in frequent cubical rockfalls. Two cases can be considered depending on the proportion of limestone.

Case 1: The ratio of limestone to shale or claystone/mudstone is > 0.5. Examples of this case include BEL-7-10 and BEL-470-7 sites. Coal seams are common within this stratigraphy and should be protected from weathering when exposed in cut slopes. Placing benches on top of coal seams may not prevent undercutting. In this subclass, the incompetent rock units are not thick enough to be designed independently. Two approaches can be used for case 1.

1. Cut the slope using Figure 6.8 and provide a catchment ditch having GB 3 design option 2-b. Provide a D-50 wall or a 10 ft (3 m) high catch fence depending on the bounce heights of rockfalls for varying slope angles, as given in Table 5.28. If barriers are not uses, provide a 35- 45 ft (10.6-13.5 m) wide catchment ditch or use Table 1.4 to select ditch width. Drainage provisions should be similar to Type B stratigraphy.

2. The second approach, based on RocFall analysis, is to cut the slope at 0.25H:1V to keep the rockfall trajectories close to vertical (Figure 7.29). Provide a GB 3 design option 2-b catchment ditch. For slope heights falling between 20 ft and 60 ft (6 m and 18 m), provide a D-50 wall. For heights between 60 ft and 100 ft (18 m and 30 m), use a 10 ft (3 m) high rockfall catch fence. For slope heights exceeding 100 ft (30 m), provide a bench on top of incompetent rock unit, with width B = H1 (not exceeding 15 ft/4.5 m), at 60 ft (18 m) height if a D-50 wall is used and at 100 ft (30 m) height if a fence is used (Figure 7.29). If a D-50 wall or a fence is not used, provide a wider (35-45 ft/10.6-13.5 m) catchment ditch in accordance with RocFall analysis (Section 5.3.4.3) or use Table 1.4 to select ditch width. Reinforced shotcrete option may be considered to protect thicker (> 5
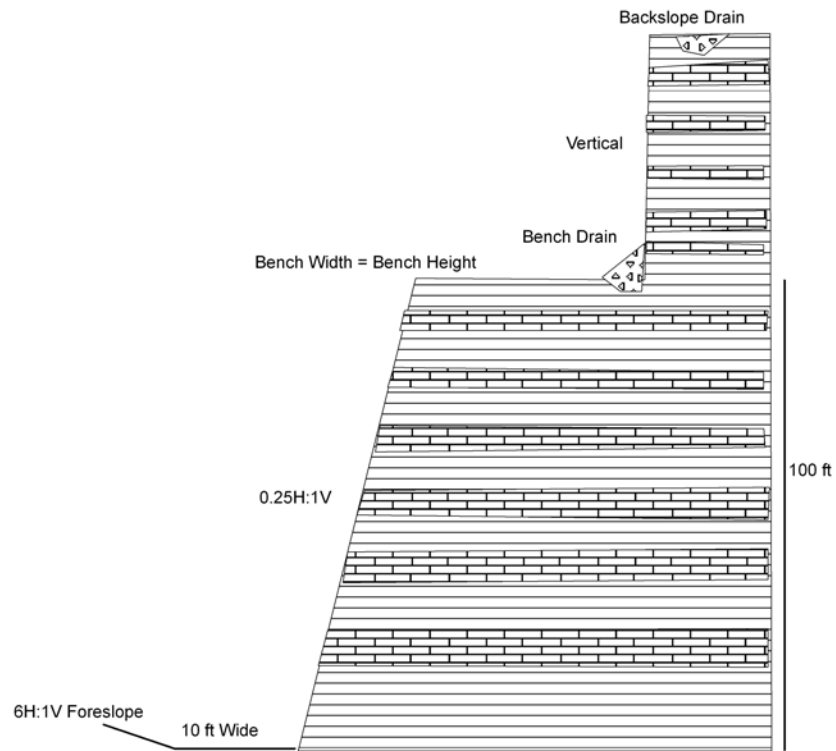
Figure 7.29: Recommended slope design for Type C stratigraphic configuration of inter-layered design units, case 1. The bench height shown in the figure is for a situation where a 10 ft (3 m) high fence is used.

ft/1.5 m) units of incompetent rock. Coal mine entries may require stabilization by

backstowing method. Drainage design should be the same as case 1.

Case 2: The ratio of limestone to claystones/mudstones (redbeds in most cases) is < 0.5.

Examples of this subclass include ATH-50-22, MUS-70-25, and WAS-77-15 sites. Due to

small thicknesses and close joint spacing of limestone units, mechanical means of stabilizing

limestone units will be impractical. Shotcreting of the thick claystone/mudstone units,

undercutting the limestones, will also be impractical. Therefore, the design approach in this case

should focus on reducing the degradation of the thick incompetent units by using gentler slopes

or small benches. The following slope design options are proposed for case 2 of Type C

stratigraphy:

Cut the slope at 2H:1V or flatter (Figure 7.30), using Figure 6.8 as a guide. If feasible,

erosion control matting may be used to hold weathered material on the slope face. A

backslope drain, connected to the toe drain, should be provided. For long slopes, the

option of providing downslope drains, connecting the backslope drain to the toe drain,

may be considered. A midslope drain, lined with rip rap and connected to the backslope

drain, may be necessary for high cut slopes. A catchment ditch, meeting GB 3 design

option 2-b requirements, should be provided. Alternatively, Table 1.4 can be used to

design catchment ditch.

1. Cut the slope at an overall angle ranging from < 2H:1V-0.5H:1V and provide small

   benches (3-5 ft/1-1.5 m high), with widths being equal H1, for zones containing limestone

   units (Figure 7.31). The benches should be placed on top of shale units. Provision of

   small benches will prevent rockfalls from rolling down the slope, gaining momentum.

   Provision of bench drains (Figure 7.31) will reduce surface runoff. Additional drainage
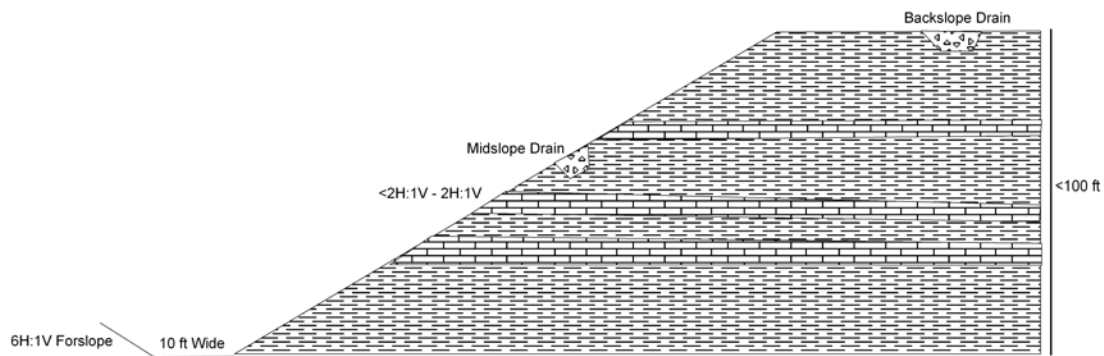
Figure 7.30: Recommended slope design for Type C stratigraphic configuration of inter-layered design units, case2, option 1.
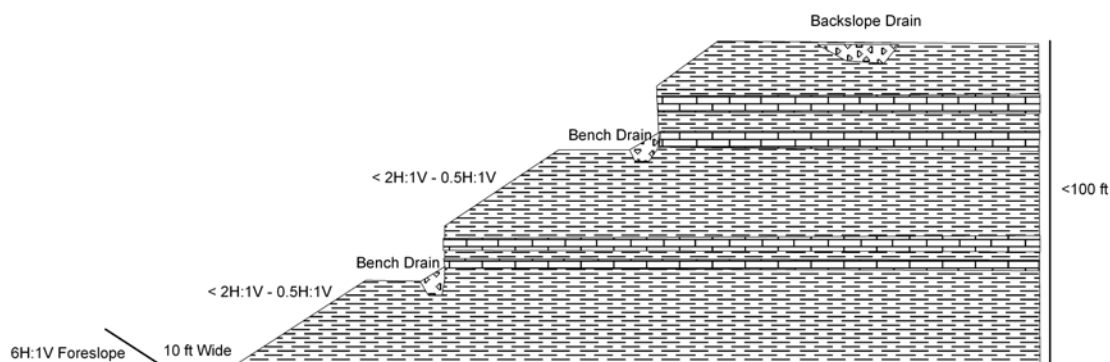
Figure 7.31: Recommended slope design for Type C stratigraphic configuration of inter-layered design units, case 2, option 2.
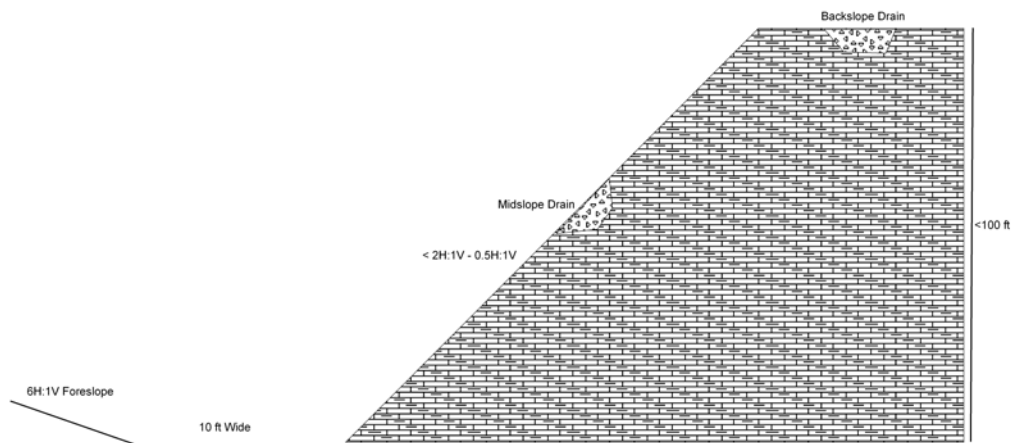
Figure 7.32: Recommended slope design for Type D stratigraphic configuration of inter-layered design units.

and catchment ditch design should be the same as option 1.

If a different design unit is present under Type C stratigraphic sequence, in either case 1 or 2, a bench should be placed between the two design units. The bench should be designed with a width equal to H1.

Recommended Slope Design for Type D Stratigraphy

Type D stratigraphy is especially prone to releasing flat-shaped rockfalls that can have long trajectories in case of steep slopes. Field observations showed that toppling and other types of undercutting-induced failures can occur where limestone proportion is high, as at HAM-126-12 site. The following slope design is recommended for Type D stratigraphy:

Use Figure 6.8 to select cut slope angle, not exceeding 1H:1V. Provide a catchment ditch meeting GB 3 design option 2-b requirements (Figure 7.32). If the slope is higher than 40 ft (12 m), a D-50 wall or a catch fence should be provided for the catchment ditch. The alternative of using a wider catchment ditch will not be feasible in this case because of the long rockfall trajectories. Drainage design should be the same as for Type C stratigraphy.

Many cut slopes may include more than one of the above-described stratigraphic variations (A through D). In such cases, benches should be provided where one stratigraphic sub-class changes into another.

7.2.4 Cut Slope Design Action Plan

Tables 7.1 through 7.5 summarize slope design criteria discussed above. These tables provide the action plan for designing cut slopes in Ohio.

7.3 Slope Monitoring

The main cause of slope instability in Ohio is weathering and erosion of incompetent rock units. The primary discontinuity dependent failure, Type B toppling, is also promoted by weathering. Slope failures due to low rock mass strength were not observed during this study. Therefore, monitoring for evaluating future performance of cut slopes should focus on documenting surficial changes. Photographs and LIDAR scans are excellent tools for monitoring temporal changes occurring on the slope surfaces. Photographs taken annually and LIDAR scans taken every 3-4 years should be adequate. Information from these imageries can be used to verify and refine the findings of this study. Information about incidents of rockfalls making their way into the roadway should be collected with respect to time, size, and final landing position of rockfalls.

Table 7.1: Slope design recommendations for competent and incompetent design units.

Design Unit	Lithology		Slope Angle	Bench Design (B=H1)	Catchment Ditch Design	Drainage Design*	Required Stabilization
Competent Design Unit	Sandstone or limestone	Option 1	0.5H:1V	Bench required for slopes exceeding 100 ft (30 m) height. Bench can be placed at 60 ft (18 m) height with a D-50 wall present or at 100 ft (30 m) height if a 10 ft (3 m) high rockfall catch fence is used. If no barrier is used, the bench should be placed at 100 ft (30 m) height.	i) GB 3 design options 2-a or 2-b. A D-50 wall required for slope heights between 20-60 ft (6-18 m) and a 10 ft (3 m) high rockfall catch fence required for slope heights between 60-100 ft (18-30 m). ii) If no barrier is used, provide a 30 ft (9.1 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		Flatten zones of close jointing (ends of slope) to 1H:1V or use wire mesh nets.
	Sandstone	Option 2	0.25H:1V	Bench required for slopes exceeding 100 ft (30 m) height. Bench can be placed at 60 ft (18 m) height if no barrier is used, or at 100 ft (30 m) height if a D-50 wall is used. If no barrier is used, the bench should be placed at 100 ft (30 m) height.	i) GB 3 design option 2-b. A D-50 wall required for slope heights between 60-100 ft (18-30 m). ii) If no barrier is used, provide a 20 ft (6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		Stabilization needs (rock anchors or wire mesh nets) to be evaluated on case-by-case basis.
Incompetent Design Unit	Claystones, mudstones, redbeds, shales	N/A	$Id_2 < 20$ % - flatter than 2H:1V; $Id_2 =$ 20-60 % - 2H:1V; $Id_2 =$ 60-85 % - 1.5H:1V; $Id_2 =$ 85-95 % - 1H:1V; $Id_2 >$ 95 % - 0.5H:1V.	Bench required at 100 ft (30 m) height.	GB 3 design options 2-a or 2-b or Table 1.4	Backslope drain connected with toe drain	Erosion control matting may be used in special cases such as slopes in redbeds.

*Drains should be lined with rip rap underlain by geofabric

Table 7.2: Slope design recommendations for Type A stratigraphy of inter-layered design units.

Design Unit	Stratigraphy Type	Lithology	Slope Angle	Bench Design (B=H1)	Catchment Ditch Design	Drainage Design*	Required Stabilization
Inter-layered design Unit	Type A	Sandstone or Limestone	0.5H:1V for sandstone or limestone; 2H:1V or flatter to 1H:1V for incompetent rock unit depending on Id_2 (Figure 6.1).	Bench (not exceeding 15 ft/4.5 m) should be placed on top of incompetent rock unit.	(i) GB 3 design option 2-b. D-50 wall required if thickness of incompetent rock unit is 80-100 ft (24-30 m). (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width .	Backslope drain connected with toe drain.	Flatten the sandstone slope near the end of the cut or use rock anchors/ wire mesh net, if needed.
		Sandstone	Sandstone at 0.25H:1V; 2H:1V or flatter to 1H:1V for incompetent rock unit depending on Id_2 (Figure 6.1).				

*Drains should be lined with rip rap underlain by geofabric

Table 7.3: Slope design recommendations for Type B stratigraphy of inter-layered design units.

Design Unit	Stratigraphy Type		Slope Angle	Bench Design (B=H1)	Catchment Ditch Design	Drainage Design*	Required Stabilization
Inter-layered design unit	Type B, Case 1	Option 1	2H:1V or flatter to 0.5H:1V (Figure 6.8)	Bench required at 100 ft (30 m) height for slopes exceeding 100 ft (30 m) height.	(i) GB 3 design option 2-b. For 1.5H:1V or flatter slopes, no barrier required for heights < 40 ft (12 m) and a D-50 wall required for 40–100 ft (12–30 m) heights. For 1 H:1V slopes, no barrier required for heights < 20 ft (6 m) and a D-50 wall required for 20–100 ft (6–30 m) heights. For 0.5H:1V, no barrier required for heights < 20 ft (6 m), a D-50 wall required for 20–80 ft (6–24 m) heights, and a 10 ft (3 m) fence required 80–100 ft (24–30 m) heights. (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width	Backslope drain connected with toe drain	Sandstone units in the upper parts will most likely require stabilization
		Option 2	0.25H:1V (RocFall analysis)		(i) GB 3 option 2 design. No barrier needed for heights less than 20 ft (6m). Provide a D-50 wall for slope heights 20–60 ft (6–8 m) and a 10 ft (3 m) fence for heights 60–100 ft (18–30 m). (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		
Inter-layered design unit	Type B, Case 2		2H:1V or flatter to 1.5H:1V (Figure 6.8)		(i) GB 3 option 2 design. Provide a 10 ft high (3 m) catch fence if slope height is greater than 40 ft (12 m) (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		

*Drains can be lined with rip rap underlain by geofabric; ** Bench should be designed with B = H1 and 0.25H:1V bench slope angle

Table 7.4: Design recommendations for Type C stratigraphy of inter-layered design units.

Design Unit	Stratigraphy Type			Slope Angle	Bench Design (B=H1)	Catchment Ditch Design*	Drainage Design**	Required Stabilization
Inter-layered design unit	Type C	Case 1		(i) 2H:1V or flatter to 0.5H:1V (Figure 6.8) (ii) 0.25H:1V (RocFall analysis).	(i) For slopes designed using Figure 6.8 place a bench at 100 ft (30 m) height. (ii) For 0.25H:1V slope, provide a bench at 60 ft (24 m) height if a D-50 wall is used and at 100 ft (30 m) height if a 10 ft (3 m) high fence is used. If no barrier is used, the bench should be placed at 100 ft (30 m) height.	(i) GB 3 design option 2-b. (a) For slopes of variable heights (Figure 6.8), use bounce height (Table 5.28) to select barrier design. (b) For 0.25H:1V slope, no barrier is required for heights up to 20 ft (6m). Provide a D-50 wall if the slope is 20-60 ft (6-18 m) high and a 10 ft (3 m) fence if the slope height is 60-100 ft (18 -30 m) (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width	Backslope drain connected with toe drain	For 0.25H:1V slopes, option of shotcreting the incompetent rook units (> 5 ft/ 1.5 m) in the upper part of the slope should be considered. Unmined coal seams may also require shotcreting. Coal mine openings should be stabilized using backstowing.
		Case 2	Option 1	2H:1V or flatter to 0.5H:1V (Figure 6.8)	Bench required at 100 ft (30m) height	(i) GB 3 design option 2-b (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		
			Option 2	2H:1V or flatter to 0.5H:1V (Figure 6.8)	Place short (3-5 ft/1-1.5 m) vertical benches where there are limestone layers.	(i)GB 3 design option 2-b. If short benches are not provided, use a D-50 wall for slope heights greater than 20 ft (6m). (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch, as indicated by RocFall analysis, or use Table 1.4 to select ditch width		

* A ditch width between 35 and 45 ft (10.6 – 13.6 m) required if no barrier is used   ** Drains can be lined with rip rap underlain by geofabric

Table 7.5: Design criteria for Type D inter-layered design units.

Design Unit	Stratigraphy Type	Slope Angle	Bench Design	Catchment Ditch Design	Drainage Design*	Required Stabilization
Inter-layered design unit	Type D	2H:1V or flatter to 1H:1V (Figure 6.8)	Bench required at 100 ft (30m) height	(i) GB 3 design option 2-b. Provide a D-50 wall or a fence if slope height is greater than 40 ft (12 m). (ii) If no barrier is used, provide a 35–45 ft (10.6-13.6 m) wide ditch or use Table 1.4 to select ditch width	Backslope drain connected with toe drain	To be decided on case-by-case basis

* Drains can be lined with rip rap underlain by geofabric

CHAPTER 8

CONCLUSIONS, RECOMMENDATIONS, AND IMPLEMENTATION

8.1 Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. Slope stability problems in Ohio are closely related to stratigraphy which consists of stronger, durable, competent rocks (limestones, sandstones, siltstones) alternating with weaker, nondurable, incompetent rocks (shales, claystones, mudstones). This type of stratigraphy is highly prone to differential weathering which results in undercutting of competent rock units by incompetent rock units. The undercutting, in turn, leads to a variety of slope failures such as rockfalls, toppling failures, plane failures, and wedge failures.

2. For the purpose of designing cut slopes in Ohio, the stratigraphy can be divided into three distinctly different design units: (i) competent design unit consisting of > 90 % of competent rock with the incompetent material (< 10 %) occurring evenly as thin layers; (ii) incompetent design unit: consisting of > 90 % of incompetent rocks wit the competent material (< 10 %) occurring evenly as thin layers; and (iii) inter-layered design unit: consisting of inter-layered competent and incompetent rock units, each ranging in proportion from more than 10 % to 90 %.

3. Slope stability problems affecting the competent design units are the failures caused by unfavorable orientation of discontinuities, with Type B toppling being the most common form of failure. Because of the steep nature of discontinuities in competent design units, plane and wedge failures are uncommon unless promoted by undercutting. Two cut slope design options are proposed for competent design units: (i) cut the slope at 0.5H:1V and

provide either a GB 3 design option 2-a ditch (13 ft/3.9 m wide with a 10 ft/3 m wide flat bottom and 3H:1V foreslope) or GB 3 design option 2-b ditch (16 ft/4.8 m wide with a 10 ft/3 m wide flat bottom and 6H:1V foreslope); and (ii) if the competent unit consists only of sandstone, cut the slope at 0.25H:1V and provide a GB 3 design option 2-b catchment ditch. Both design options require provision of rockfall barriers for varying slope heights and provision of benches at 100 ft (30 m) height. If barriers are not used, 35-45 ft (10.6-13.5 m) wide ditches, based on RocFall analysis, can be used or Table 1.4 can be used to select ditch width required to contain 95 % of rockfalls.. Friable sandstones (density < 140 pcf/2.24 Mg/m^3) should be treated as a special case of competent design units and should be cut at 1H:1V slope.

4. Slope stability problems affecting the incompetent design units are raveling, gully erosion, and occasional development of a deep-seated rotational failure. The Franklin shale rating system, based on plasticity index, slake durability index, and point load strength index, suggests stable angles against rotational failures. In this study a relationship was developed between second-cycle slake durability index and stable slope angle suggested by shale rating (Figure 6.1). Based on this relationship, the following slope angles are proposed for cut slopes in incompetent design units: Id_2 < 20 % - flatter than 2H:1V; Id_2 = 20-60 % - 2H:1V; Id_2 = 60-85 % - 1.5H:1V; Id_2 = 85-95 % - 1H:1V; Id_2 > 95 % - 0.5H:1V. Properly designed catchment ditches, meeting GB 3 design options 2-a and 2-b, or based on Table 1.4, should be provided. Provision of an adequate drainage system should be an integral part of cut slope design in incompetent rocks. In order to minimize erosion and promote vegetation, use of matting may be considered. Redbeds should be treated on case-by-case basis.

5. Slope stability problems affecting the inter-layered design units are primarily undercutting-induced failures (plane failure, wedge failure, Type B toppling failure). Regardless of the mode of failure, all undercutting-induced failures end up as rockfalls. Cut slope design for inter-layered design units is more complex than the other two design units and must take into account the variations in stratigraphy. Four stratigraphic variations, designated as A through D, are recognized within the inter-layered design units as follows: Type A - thick (>3 ft/1 m) sandstone or limestone underlain by shale or claystone/mudstone; Type B - thin to medium thick (< 3 ft/1 m) sandstone units inter-layered with shale or claystone/mudstone units in variable proportions; Type C - non-marine limestone (1-3 ft/0.3-1 m) units inter-layered with claystone/mudstone units in variable proportions; and Type D – thin (2-3 inches/5-8 cm) Ordovician fossiliferous limestone units inter-layered with claystone/mudstone units in variable proportions. A separate cut slope design is recommended for each of the stratigraphic variations listed above. The cut slope design for Type A stratigraphy combines design principles for competent and incompetent rocks, with the provision of a bench (< 15 ft/4.5 m) along the contact between the two rock types. For stratigraphic variations B, C, and D, the relationship between weighted slake durability index and slope angle, given by shale rating, is proposed as follows: weighted Id_2 < 30 % - 2H:1V or flatter; weighted Id_2 = 30-60 % - 2H:1V; Id_2 = 60-85 % - 1.5H:1V; Id_2 = 85-95 % - 1H:1V; Id_2 > 95 % - 0.5H:1V. Three options of catchment ditch design can be used: (i) GB 3 design options 2-a and 2-b (based on rockfall analysis) in conjunction with rockfall barriers; (ii) 35-45 ft (10.6-13.5 m) wide ditches (based on RocFall analysis) without barriers; and (iii) use of Table 1.4 to select ditch widths if no barriers are used. For all stratigraphic variations of inter-layered

design units, benches (< 15 ft/4.5 m) are suggested at 100 ft (30 m) height, and an

adequate drainage system is recommended to minimize undercutting.

8.2 Recommendations

1. Option of using selected remediation measures such as rock anchors, wire mesh nets,

    shotcrete, and erosion control mats should be considered to improve stability of cut

    slopes on a case-by-case basis.

2. A major problem in evaluating the process of undercutting, and associated failures, is the

    absence of undercutting data collected regularly over the service period of a cut slope.

    Temporal data regarding undercutting should be collected regularly, using LiDAR scans,

    for better understanding of the progression of undercutting with time and its effect on

    slope instability. Future studies should focus on this aspect of data collection.

3. Additional research should be conducted to estimate the quantities of surface water and

    groundwater flows within the cut slope area so that the effect of these parameters on the

    rate of undercutting can be quantified.

8.3 Implementation

Appendix 16 is the draft version of the ODOT Rock Slope Design Manual. This manual

is based on the results of this research as well as additional resources. Note that due to its status

as a required deliverable for this project, it has been included as an Appendix at the request of

the Sponsor, even though it was authored independently of this research report. An updated

version of this manual along with a revised Geotechnical Bulletin 3 can be obtained from

Administrator, ODOT Office of Geotechnical Engineering beginning in October 2010.

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APPENDICES

APPENDIX 1

PHOTOGRAPHS OF THE STUDY SITES

APPENDIX 1-A

PHOTOGRAPHS OF THE 26 PROJECT SITES

Figure 1A-1: Overview of ADA-32-12.5 site (observed slope problems: mudflows).

Figure 1A-2: Overview of ADA-41-15.4 site (observed slope problems: undercutting of competent rock units).

Figure 1A-3: Overview of ATH-33-14.6 site (observed slope problems: none).

Figure 1A-4: Overview of ATH-50-22.9 site (observed slope problems: gullying and undercutting of competent rock units; rockfalls).
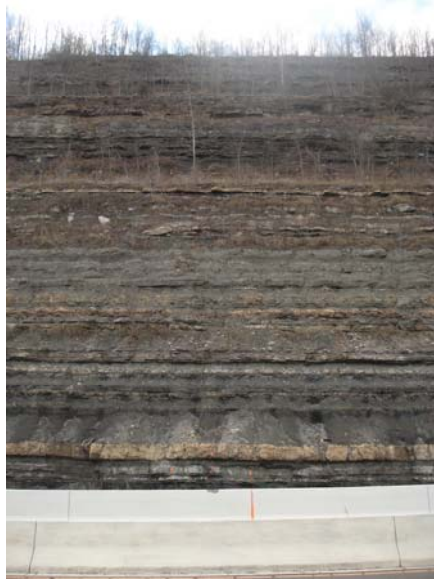
Figure 1A-5: Overview of BEL-7-10 site (observed slope problems: undercutting of competent rock units; rockfalls).

Figure 1A-6: Overview of BEL-70-22.1 site (observed slope problems: undercutting of competent rock units; rockfalls).

Figure 1A-7: Overview of BEL-470-6 site (observed slope problems: undercutting of competent rock units).

Figure 1A-8: Overview of CLA-4-8.9 site (observed slope problems: toppling due to steep lines intersection of discontinuity planes).

Figure 1A-9: Overview of CLA-68-6.9 site (observed slope problems: no slope problem observed).

Figure 1A-10: Overview of CLE-275-5.2 site (observed slope problems: mudflows and undercutting of competent rock units).

Figure 1A-11: Overview of COL-7-5 site (observed slope problems: plane failure).

Figure 1A-12: Overview of FRA-270-25 site (observed slope problems: ravelling of an incompetent rock unit).

Figure 1A-13: Overview of GUE-22-6 site (observed slope problems: possible rotational failure in the upper half of the slope).

Figure 1A-14: Overview of GUE-77-8.2 site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1A-15: Overview of HAM-74-6.4 site (observed slope problems: undercutting of competent rock units and raveling of incompetent units).

Figure 1A-16: Overview of HAM-126-12.8 site (observed slope problems: undercutting of competent rock units and raveling of incompetent units).

Figure 1A-17: Overview of Photograph of JEF-CR77-0.38 site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1A-18: Overview of LAW-52-11.8 site (observed slope problems: undercutting of thick competent rock units).

Figure 1A-19. : Overview of LAW-52-12.8 site (observed slope problems: undercutting of thick competent rock units).

Figure 1A-20: Overview of LIC-16-28.47 site (observed slope problems: plane failure).

Figure 1A-21: Overview of MEG-33-6 site (observed slope problems: undercutting of a competent rock unit).

Figure 1A-22: Overview of MEG-33-15 site (observed slope problems: minor undercutting of a competent rock unit and gullying of incompetent rock units).

Figure 1A-23: Overview of MUS-70-11 site (observed slope problems: undercutting of thick competent rock units).

Figure 1A-24: Overview of RIC-30-12.5 site (observed slope problems: toppling due to steep line of intersection of discontinuity planes).

Figure 1A-25: Overview of STA-30-27.3 site (observed slope problems: undercutting of an incompetent rock unit and raveling of an incompetent unit).

Figure 1A-26: Overview of WAS-7-18.2 site (observed slope problems: undercutting of a thick competent rock unit).

APPENDIX 1-B

PHOTOGRAPHS OF THE ADDITIONAL 23 SITES

Figure 1B-1: Overview ATH-33-26 site (observed slope problems: minor gullying).

Figure 1B-2: Overview ATH-50-28 site (observed slope problems: minor gullying).

Figure 1B-3: Overview BEL-70-1.58 site (observed slope problems: undercutting of a competent rock unit).

Figure 1B-4. BEL-7-24 (photo not available).

Figure 1B-5: Overview COL-7-3 site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1B-6: Overview COL-30-30 site (observed slope problems: ravelling of an incompetent rock unit).

Figure 1B-7: Overview COL-11-16 site (observed slope problems: ravelling of an incompetent rock unit).

Figure 1B-8: Overview GUE-70-12.9 site (observed slope problems: ravelling of an incompetent rock unit).

Figure 1B-9: Overview GUE-77-21 site (observed slope problems: ravelling of incompetent rock unit).

Figure 1B-10: Overview HAM-74-8.9 site (observed slope problems: mudflows in incompetent rock units and undercutting of competent rock units).

Figure 1B-11: Overview HAM-74-12.4 site (observed slope problems: ravelling of incompetent rock units and undercutting of competent rock units).

Figure 1B-12: Overview HAM-74-16.6 site (observed slope problems: ravelling of incompetent rock units and undercutting of competent rock units).

Figure 1B-13: HAM-275-1.4 ((photo not available).

Figure 1B-14: Overview JEF-22-8(N-Facing) site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1B-15: Overview JEF-22-8 (S-Facing) site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1B-16: Overview JEF-7-6 site (observed slope problems: undercutting of thick competent rock units).

Figure 1B-17: Overview JEF-7-23 site (observed slope problems: undercutting of thick competent rock units).

Figure 1B-18: Overview MUS-70-25 site (observed slope problems: undercutting of thick competent rock unit).

Figure 1B-19: Overview TUS-77-3 site (observed slope problems: undercutting of a thick competent rock unit).

Figure 1B-20: Overview WAS-77-15(799*) site (observed slope problems: undercutting of competent units and raveling of incompetent rock units).

*feet marker for sites that fall within the same mile marker

Figure 1B-21: Overview WAS-77-15 (801*) site (observed slope problems: undercutting of competent units and raveling of incompetent rock units).

Figure 1B-22: Overview WAS-77-15(810*) site (observed slope problems: undercutting of competent units and raveling of incompetent rock units).
*feet marker for sites that fall within the same mile marker

Figure 1B-23: Overview WAS-77-15(908*) site (observed slope problems: undercutting of a competent rock unit and raveling of an incompetent rock unit).

*feet marker for sites that fall within the same mile marker

APPENDIX 2

DATA COLLECTION FORMS

General Site Information

Site No. _____

Site Identification _____ Name _____

Photo no. _____

Date _____

District _____

Road Direction _____

Aspect of Road Cut _____

Latitude of Starting Point _____ Long. of starting point _____

Length of Road cut _____

Height of Road Cut _____

Slope Geometry _____
 (1) uniform slope angle, (2) varying slope angle (3) benched slope
Vegetation on Slope Face _____
(1) no vegetation ,(2) sparse 20% vegetation , (3) moderate (40%) vegetation, (4) completely vegetated
Blasting Information _____
(1) presplit, (2) production blasted, (3) excavated
Date of Construction _____

Hydrogeological Information _____
(1) no flow, (2) damp, (3) wet, (4) dripping, (5) flowing

_____

_____

Hydrological Information _____
(1) no gullying, (2) slight gullying, (3) moderate gullying, (4) extreme gullying

_____

_____

Geology and Slope Problems
Geological Group
(1) sst, (2) shale,shale with minor sst/sst (3) sst underlain by shale (4) sst interlayered with shale/siltstone (5) thinly bedded limestone with shale (6) limestone
Type of Slope Failure _____
(1) undercutting induced, (2) raveling , (3) rockfalls, (4) plane failures (5) wedge failure (6) rotational slides, (7) flows

_____

_____

_____

_____

Slope Performance _____
(1) good, (2) moderate, (3) poor

_____

Design Suggestions

_____

_____

_____

_____

_____

Catchment Ditch Data Form, Hardness Scale

Site identification _____

Block Size

Station	X1	X 2	Z	X3	Condition	A	B	C

Surface roughness   **Block Size**

1. Rough
2. Smooth   A = Long Axis
3. Polished   B = Short Axis
4. Slickensided   C = Thickness

Geological Sketch

Cell	Rt	Rn	Surface roughness

Hardness input code	Field ID	Normal Coef(Rn)	Tangential coef.(Rt)	Surface roughness
S1	Easily penetrated several inches by fist	0.1	0.5	
S2	Easily penetrated several inches by thumb	0.1	0.55	
S3	Can be penetrated several inches by thumb with moderate effort	0.15	0.65	
S4	Readily indented by thumb but penetrated only with great effort	0.15	0.75	
S5	Readily indented by thumbnail	0.2	0.8-0.85	
S6	Indented with difficulty by thumbnail	0.2	0.9	
R0	Indented by thumbnail	0.15	0.7	
R1	Crumbles under firm blows with point of geological pick, can be peeled with a pocket knife	0.15	0.75	
R2	Can be peeled by a pocket knife with difficulty, shallow indentation made by firm blow of geological pick	0.2	0.8	
R3	Cannot be scraped or peeled with pocket knife, specimen can be fractured with single firm blow of a hammer end of geological pick	0.25	0.85	
R4	Specimen required more than one blow with hammer end of geological pick to fracture it	0.25-0.30	0.95-1.0	
R5	Specimen required many blows with hammer end of geological pick to fracture it	0.25-0.30	0.95-1.0	
R6	Specimen can only be chipped with geological pick	0.25-0.30	0.95-1.0	

Nature of Discontinuities Form

Site Identification _____

Type of Survey   Line survey (1), window mapping (2), Random measurement (3)

Traverse dir. (V/H)	Location of beginning of the traverse	Height of beginning of traverse	Lithology	Lithology on strat col.	Chainage	Type of disc.		Dip	Dip dir	Aperture	Continuity	Water flow	Discontinuity set parameter		
													Set no.	Spacing	Aperture

Lithology
0. Limestone
1. Sandstone
2. Siltstone
3. Mudstone
4. Claystone
5. Silt Shale
6. Mud Shale
7. Clay Shale
8. Interbedded
9. Buried

Type of disc.
1. Bedding
2. Tectonic joint
3. Stress relief joint

Spacing
1. Extremely close spacing (<2cm, <0.8in)
2. Very close spacing (2-6cm, 0.8-2.4in)
3. Close spacing (6-20cm), 2.4-8in)
4. Moderate spacing (20-60cm,, 8in-2ft)
5. Wide spacing (60cm-2m, 2-6.6ft)
6. Very wide spacing (2m-6m, 6.6-20ft)
7. Extremely wide spacing (>6m, >20ft)

Continuity
1. Very low persistence   < 1 m   < 3.3 ft
2. Low persistence   1 - 3 m   3.3 - 10 ft
3. Medium persistence   3 - 10 m   10 ft - 33 ft
4. High persistence   10 - 20 m   33 - 66 ft
5. Very high persistence   > 20 m   > 66 ft

Aperture Width
1. Very Tight (<0.1 mm, <0.004in)
2. Tight (0.1-0.25 mm, 0.004-0.01in)
3. Partly open (0.25-0.5 mm, 0.01-0.02in)
4. Open (0.5-2.5 mm, 0.02-0.1 in)

5. Moderately wide (2.5mm-1cm, 0.1-0.4in)
6. Wide (> 1cm, >0.4in))
7. Very wide (1-10 cm, 0.4-4in)
8. Extremely wide (10-100 cm, 4in-3.3t))
9. Cavernous (> 1 m, >3.3ft)

Rock Mass Characterization Form

Site identification _____

Height from	Height to	Location of starting pt.	Location of end point	Whole rock						Discontinuity characterization					Unconfined compressive strength			RQD				
				Lithology	Lithology on strat.col.	Ground water condition	Grain Size	Fabric	State of weathering	Disc. set no.	Gen.dip	Gen.dip dir	Spacing for disc.set	Discontinuity condition	Assessed	Measured	SDI	x	y	z	RQD	GSI

Compressive Strength

	Mpa	Psf
S1 Very soft clay	< 0.025	500 psf
S2 Soft Clay	0.025-0.05	500-1,000 psf
S3 Firm clay	0.05-0.10	1,000-2,000 psf
S4 Stiff clay	0.10-0.25	2,000-5,000 psf
S5 Very stiff clay	0.25-0.50	5,000-10,000 psf
S6 Hard clay	>0.50	>10,000 psf
R0 Extremely weak rock	0.25-1.0	36 - 145 psi
R1 Very weak rock	1.0-5.0	145 - 725 psi
R2 Weak rock	5.0-25	725 - 3,625 psi
R3 Medium strong rock	25-50	3,625 - 7,250 psi
R4 Strong rock	50-100	7,250 - 14,500 psi
R5 Very strong rock	100-250	14,500 - 36,250 psi
R6 Extremely strong rock	>250	> 36,250 psi

State of Weathering
1. Fresh
2. Slightly
3. Moderately
4. Highly
5. Completely
6. Residual soil

Lithology
0. Limestone
1. Sandstone
2. Siltstone
3. Mudstone
4. Claystone
5. Silt Shale
6. Mud Shale
7. Clay Shale
8. Interbedded
9. Buried

Groundwater Condition
1. No inflow -or- 0 ratio -or- completely dry.
2. < 10 L/min -or- < 10 ratio -or- damp.
3. 10-25 L/min inflow -or- 0.1-0.2 ratio -or- wet.
4. 22-125 L/min inflow -or- 0.2-0.5 ratio -or- dripping.
5. > 125 L/min inflow -or- > 0.5 ratio -or- flowing.

Color
1. Pink
2. Red
3. Yellow
4. Brown
5. Olive
6. Green
7. Blue
8. White
9. Grey
10. Black

Fabric
1. Blocky
2. Tabular
3. Columnar
4. Shattered
5. massive
6. Fissile

Grain Size
1. Very coarse (>60 mm)
2. Coarse (2 - 60 mm)
3. Medium (60 μm - 2 mm)
4. Fine (2 - 60 μm)
5. Very Fine (<2 μm)

Discontinuity Condition
1. Very rough surfaces, not continuous, no separation, and unweathered rock walls.
2. Slightly rough surfaces, separation < 1 mm, and slightly weathered walls.
3. Slightly rough surface, separation < 1 mm, and highly weathered walls.
4. Slickenslided surfaces -or- gouge (infilling), 1-5 mm thick -or- separation 1-5 mm and continuous.
5. Soft gouge > 5 mm -or- separation > 5 mm and continuous

115 - 3.3(Jv) ;

Sampling Form

Site identification _____

Sample no	Station	Sampling Height	Lithology	Result	
				SDI	Point Load

Undercutting Characterization Form

Site identification _____

Photo no. _____

Station	Beginning Station (line survey)	Pre-split marks present	Chainage (line survey)	Lithology	Undercut Unit				Undercutting Unit				Amt. of undercutting (in.)	Depth of gullying
					Lithology on strat. Column	Lithology	Joint set present	Spacing of Joint set present	Lithology on strat. Column	Lithology	Joint set present	Spacing of Joint set present		

Lithology   0. Limestone   4. Claystone   8.Interbedded
1. Sandstone   5. Silt Shale   9. Buried
2. Siltstone   6. Mud Shale
3. Mudstone   7. Clay Shale

APPENDIX 3

GEOMETRICAL DATA
(SLOPE ANGLE, SLOPE HEIGHT, AND SLOPE ASPECT DATA)

Table 3-1: Slope angle, slope height, and slope aspect data for the 26 selected sites.

Site	Design Unit	Rock Type	Slope Angle (degrees)	Slope Height (ft)	Slope Aspect (degrees)
ADA-32-12	Competent	Limestone	75	102	195
	Incompetent	Grey mudstone/claystone	27		
ADA-41-15	Competent	Limestone	60	21	130
	Inter-Layered	Limestone Inter-layered with grey mudstone/claystone	43		
ATH-33-14	Competent	Sandstone	79	100	50
ATH-50-23	Inter-Layered	Limestone and sandstone inter-layered with mudstone/claystone (redbeds)	33	143	270
BEL-7-10	Competent	Limestone	50	169	90
	Inter-Layered	Limestone inter-layered with green mudstone/claystone	53		
	Inter-Layered	Sandstone/siltstone inter-layered with shale			
BEL-70-22	Inter-Layered	Minor sandstone and limestone inter-layered with shale	42	61	0
BEL-470-6	Competent	Limestone	65	83	350
	Inter-Layered	Limestone inter-layered with green mudstone/claystone	50		
CLA-4-8	Competent	Limestone	69	26	330
CLA-68-7	Competent	Limestone	73	30	260
CLE-275	Incompetent	Grey mudstone/claystone with minor limestone	38	58	270
COL-7-5	Competent	Sandstone	75	350	175
	Incompetent	Shale	57		
FRA-270-23	Incompetent	Shale	35	45	180
GUE-22-6	Competent	Siltsone	45	56	335
	Incompetent	Shale	80		

Table 3-1 (contd.).

Site	Design Unit	Rock Type	Slope Angle (degrees)	Slope Height (ft)	Slope Aspect (degrees)
GUE-77-8	Competent	Sandstone	59	87	280
	Incompetent	Mudstone/claystone (redbed) with minor sandstone			
HAM-74-6	Inter-Layered	Limestone inter-layered with grey mudstone/claystone	36	57	220
HAM-126-12	Inter-Layered	Limestone inter-layered with grey mudstone/claystone	45	53	12
JEF-CR77-.38	Competent	Sandstone	76	70	15
	Incompetent	Shale	27		
LAW-52-11	Competent	Sandstone	58	160	215
	Incompetent	Shale	58		
	Inter-Layered	Sandstone inter-layered with shale	70		
LAW-52-12	Inter-Layered	Sandstone inter-layered with shale	58	133	226
	Competent	Sandstone	75		
LIC-16-28	Competent	Sandstone	69	81	170
MEG-33-6	Inter-Layered	Mudstone/claystone (redbed) with minor sandstone	40	76	250
MEG-33-15	Inter-Layered	Mudstone/claystone (redbed) with minor sandstone	42	54	20
MUS-70-11	Competent	Sandstone	75	50	180
	Incompetent	Shale	40		
RIC-30-12	Competent	Sandstone	79	38	0
STA-30-27	Inter-Layered	Shale with minor siltstone	71	36	185
WAS-7-18	Competent	Sandstone	80	85	130
	Incompetent	Mudstone/claystone (redbed) with minor sandstone	45		

APPENDIX 4

STRATIGRAPHC CROSS-SECTIONS

Figure 4-1: Stratigraphic cross-section for ADA-32-12.5.

Site: ADA-41-15.4

Competent Design Unit (90 % competent, 10 % incompetent)
Limestone with minor inter-layers of grey claystone/ mudstone:
Limestone: grey, very strong, thinly bedded, slightly jointed, contains fossils
Limestone average unconfined compressive strength = 22710 psi
(outcrop sample no. 7)

Limestone average slake durability index = 99 %
(outcrop sample no. 7)

RQD = 46 % (core depth 14-50 ft)

Inter-layered Design Unit (60 % competent, 40 % incompetent)
Claystone/ mudstone inter-layered with limestone:
Claystone/ mudstone: grey, very weak
Limestone: grey, strong, thinly bedded, slightly
jointed, and contains fossils
Limestone average unconfined compressive
strength = 14829 psi
(outcrop sample nos. 1, 4, 6)
Grey claystone/ mudstone average
unconfined compressive strength = 1029 psi
(outcrop sample nos. 2, 3, 5)
Weighted unconfined compressive strength = 9309 psi

Limestone average slake durability index = 99 %
(outcrop sample nos. 1, 4, 6)
Grey claystone/ mudstone average slake
durability index = 18 %
(outcrop sample nos. 2, 3, 5)
Weighted slake durability index =66 %

RQD = 46 % (core depth 14-50 ft)

Elevation = 733 ft

Representative core depth = 14-50 ft*

Drowning Creek Formation (Lower Silurian)

1 in : 5 ft

Feet
0   5   10

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs because of lateral stratigraphic variations

Figure 4-2: Stratigraphic cross-section for ADA-41-15.4.

Site: ATH-33-14.6

Competent Design Unit
Sandstone: yellowish grey, slightly strong, thickly bedded
slightly jointed to not jointed
Average unconfined compressive strength = 2579 psi
(outcrop sample nos. 1, 2, 3, 4, 5)

Average slake durability index = 78 %
(outcrop sample nos. 1, 2, 3, 4, 5)

RQD = 78 % (core depth 44-148 ft)

Soil

Representative core depth = 44-148ft*

Conemaugh Group (Upper Pennsylvanian)

Elevation = 915 ft

1 in : 20 ft

Feet
0   5   10   20

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-3: Stratigraphic cross-section for ATH-33-14.6.

Site: ATH-50-22.9

Inter-layered Design Unit (50 % competent, 50 % incompetent)
Claystone/ mudstone (redbeds) inter-layered with mainly limestone with minor sandstone
Claystone/ mudstone (redbeds): red, weak
Limestone: yellowish grey, strong, thinly bedded, moderately jointed
Sandstone: green, strong, medium bedding, moderately jointed
Limestone average unconfined compressive strength = 10634 psi
(outcrop sample nos. 2, 4, 6)
Sandstone average unconfined compressive strength = 5919 psi
(outcrop sample nos. 9, 10)
Claystone/ mudstone (redbeds) average unconfined compressive strength = 812 psi
(outcrop sample nos. 1, 3, 5, 11, 8)
Weighted unconfined compressive strength = 4957 psi

Limestone average slake durability index = 99 %
(outcrop sample nos. 2, 4, 6)
Sandstone average slake durability index = 96 %
(outcrop sample nos. 9, 10)
Claystone/ mudstone (redbeds) average sake durability index = 33 %
(outcrop sample nos. 1, 3, 5, 11, 8)
Weighted slake durability index = 65 %

RQD = 0 % (outcrop estimate)

Conemaugh Group (Upper Pennsylvanian)

1 in : 40 ft

30   15   0   30 Feet

Figure 4-4: Stratigraphic cross-section for ATH-50-22.9.

Figure 4-5: Stratigraphic cross-section for BEL-470-6.

Site: BEL-70-22.1

Inter-layered Design Unit (30 % competent, 70 % incompetent)
Claystone/mudstone inter-layered with minor sandstone and limestone:
Claystone/mudstone: dark grey, very weak
Sandstone: grey, very strong, thinly bedded, slightly jointed, micaceous
Sandstone average unconfined compressive strength = 16011 psi
(outcrop sample nos. 2, 4, 4A, 4B)
Limestone average unconfined compressive strength = 13249 psi
(core sample nos. 9, 10)
Claystone/mudstone average unconfined compressive strength =1398 psi
(outcrop sample nos. 1, 3, 3A, 3B)
Weighted unconfined compressive strength = 5368 psi
Sandstone average slake durability index = 96 %
(outcrop sample nos. 2, 4, 4A, 4B)

Limestone average slake durability index = 86 %
(core sample nos. 9)
Claystone/mudstone average slake durability index = 54 %
(outcrop sample nos. 1, 3, 3A, 3B)
Weighted slake durability index = 65 %

RQD = 73 % (core depth 81-140 ft)

Sandstone

Limestone

Shale

Sandstone

Representative core depth = 81- 140 ft*

Dunkard Group (Lower Permian - Upper Pennsyvanian)

Elevation = 1140 ft

1 in : 10 ft

0   5   10   20 Feet

* Thickness of cross section may not exactly match the corresponding thickness on drill core due to stratigraphic
variations

Figure 4-6: Stratigraphic cross-section for BEL-70-22.1.

Site: BEL-7-10

Inter-layered Design Unit (30 % competent, 70 % incompetent)
Sandstone inter-layered with shale and claystone/mudstone
Sandstone: greenish grey, very strong, thickly bedded, intact
Shale and claystone/mudstone: dark green to green, slightly strong
Sandstone average unconfined compressive strength = 16804 psi
(core sample nos. 20, 25)
Shale average unconfined compressive strength = 3380 psi
(core sample nos. 21, 22, 23, 24, 26)
Weighted unconfined compressive strength = 7407 psi

Sandstone average slake durability index = 99 %
(core sample nos. 20, 25)
Shale and claystone/mudstone average slake durability index = 89 %
(core sample nos. 21, 22, 23, 24, 26)
Weighted slake durability index = 92 %

RQD = 94 % (core depth 146-194 ft)

Coal

Representative core depth = 146-245 ft*
Monongahela Group (Upper Pennsylvanian)

Inter-layered Design Unit (47 % competent, 53 % incompetent)
Limestone inter-layered with green shale and claystone/mudstone
Limestone: dark grey, very strong, medium bedded, slightly jointed
Shale and claystone/mudstone: green, slightly strong
Limestone average unconfined compressive strength = 21249 psi
(core sample nos. 28, 30)
Shale and claystone/mudstone average unconfined compressive strength = 2920 psi
(core sample nos. 27, 29, 31)
Weighted unconfined compressive strength = 11535 psi

Limestone average slake durability index = 99 %
(core sample nos. 28, 30)
Shale and claystone/mudstone average slake durability index = 59 %
(core sample nos. 27, 29, 31)
Weighted slake durability index = 78 %

RQD = 79 % (core depth 194-245 ft)

Shale
Coal

0   25   50   100 Feet

1 in : 50 ft

Elevation = 700 ft

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-7: Stratigraphic cross-section for BEL-7-10.

Figure 4-8: Stratigraphic cross-section for CLA-4-8.9.

Site: CLA-68-6.9

Competent Design Unit
Limestone: dark yellow, strong, thinly bedded
Average unconfined compressive
strength = 11460 psi (outcrop sample nos. 1-3)

Average slake durability index = 99 %
(outcrop sample nos. 1-3)

RQD = 78 % (core depth 10-52 ft)

Representative core depth = 10-52 ft*

Cedarville, Springfiled and Euphemia Dolomite (Upper and lower Silurian)

Elevation = 940 ft

1 in : 5 ft

Feet

0   2.5   5   10

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-9: Stratigraphic cross-section for CLA-68-6.9.

Site: CLE-275-5.2

Inter-layered Design Unit (20 % competent, 80 % incompetent)
Grey claystone/mudstone with minor limestone
Claystone /mudstone: grey, very weak
Limestone: grey, very strong, thinly bedded, slightly jointed
Grey claystone/mudstone average unconfined compressive strength = 632 psi
(outcrop sample nos. 1, 3, 4, 6, 7, 9)
Limestone average unconfined compressive strength = 19085 psi
(outcrop sample nos. 2, 5, 8)
Weighted unconfined compressive strength = 3400 psi

Grey claystone/mudstone average slake durability index = 50 %
(outcrop sample nos. 1, 3, 4, 6, 7, 9)
Limestone average slake durability index = 99 %
(outcrop sample nos. 2, 5, 8)
Weighted slake durability index = 57 %

RQD = 28% (core depth 17-70 ft)
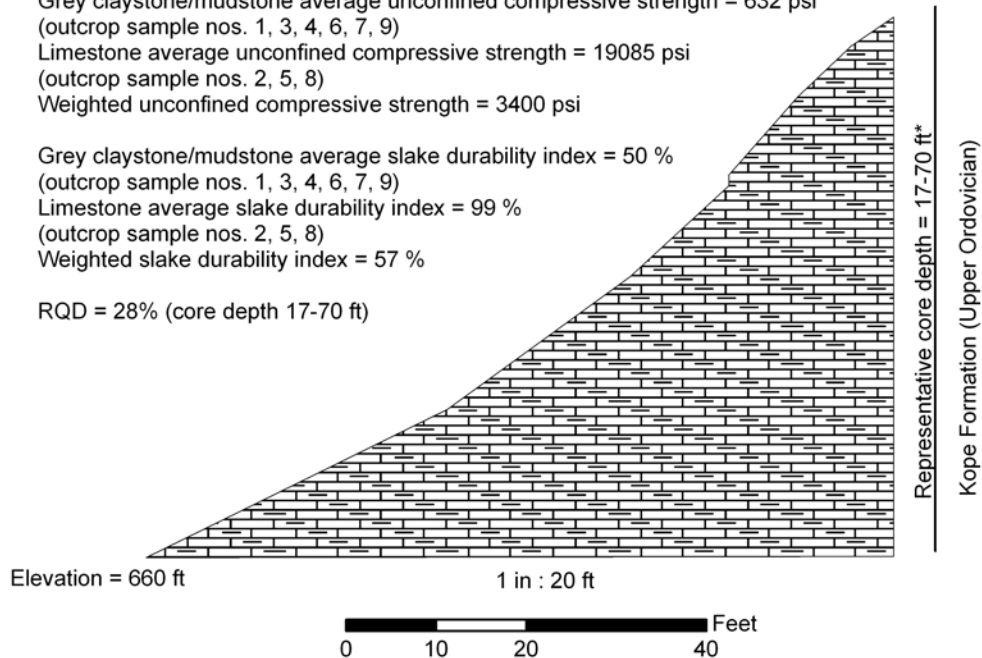
Representative core depth = 17-70 ft*

Kope Formation (Upper Ordovician)

Elevation = 660 ft

1 in : 20 ft

Feet
0   10   20   40

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs because of lateral stratigraphic variations

Figure 4-10: Stratigraphic cross-section for CLE-275-5.2.
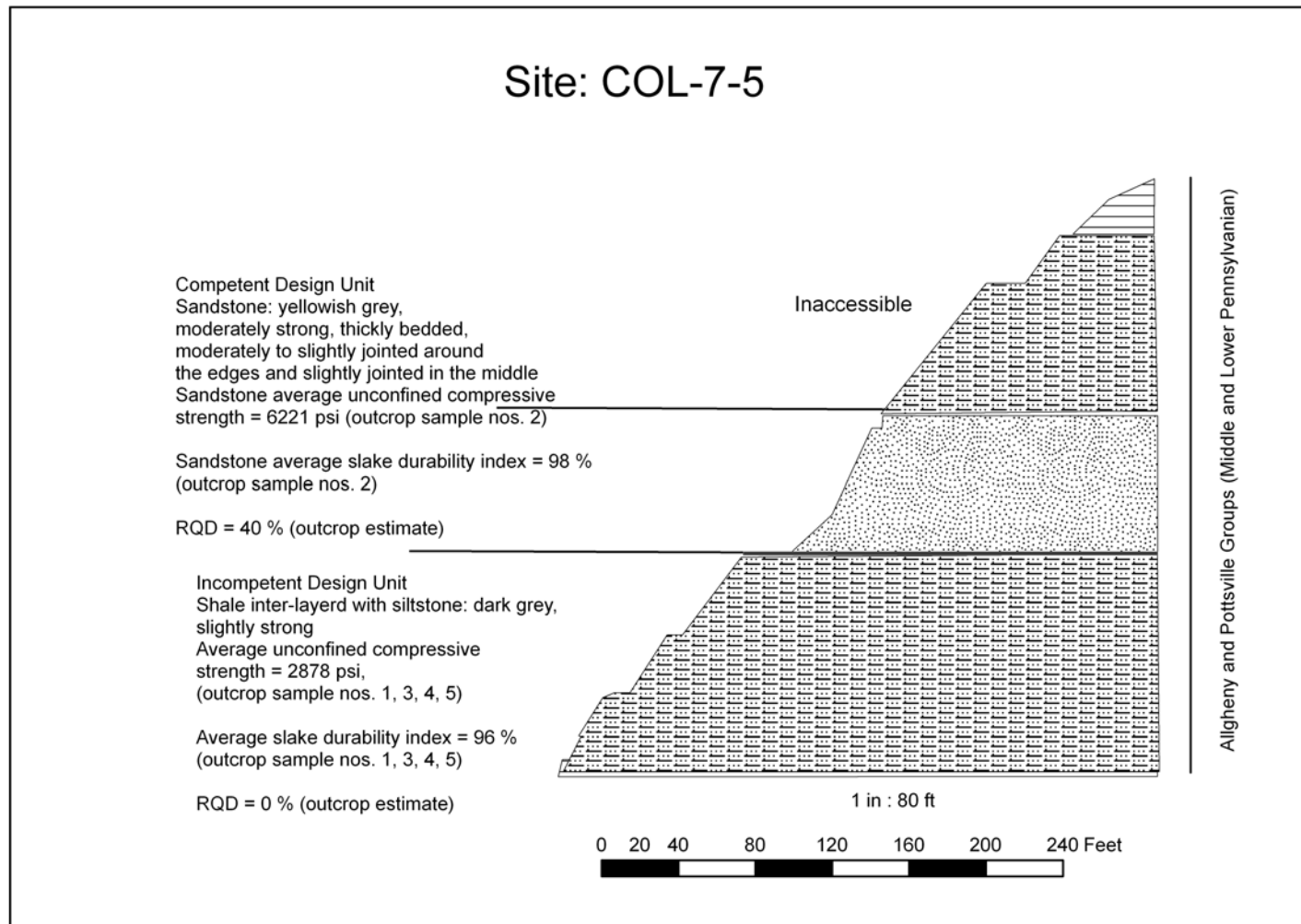
Figure 4-11: Stratigraphic cross-section for COL-7-5.

Site: FRA-270-23.5

Incompetent Design Unit
Shale: yellowish grey, slightly strong,
moderately jointed
Average unconfined
compressive strength = 3854 psi
(outcrop sample no. 1)

Average slake durability index = 99 %
(outcrop sample no. 1)

RQD = 0 % (outcrop estimate)

Ohio Shale (Upper Devonian)

1 in : 10 ft

0   5   10   20 Feet
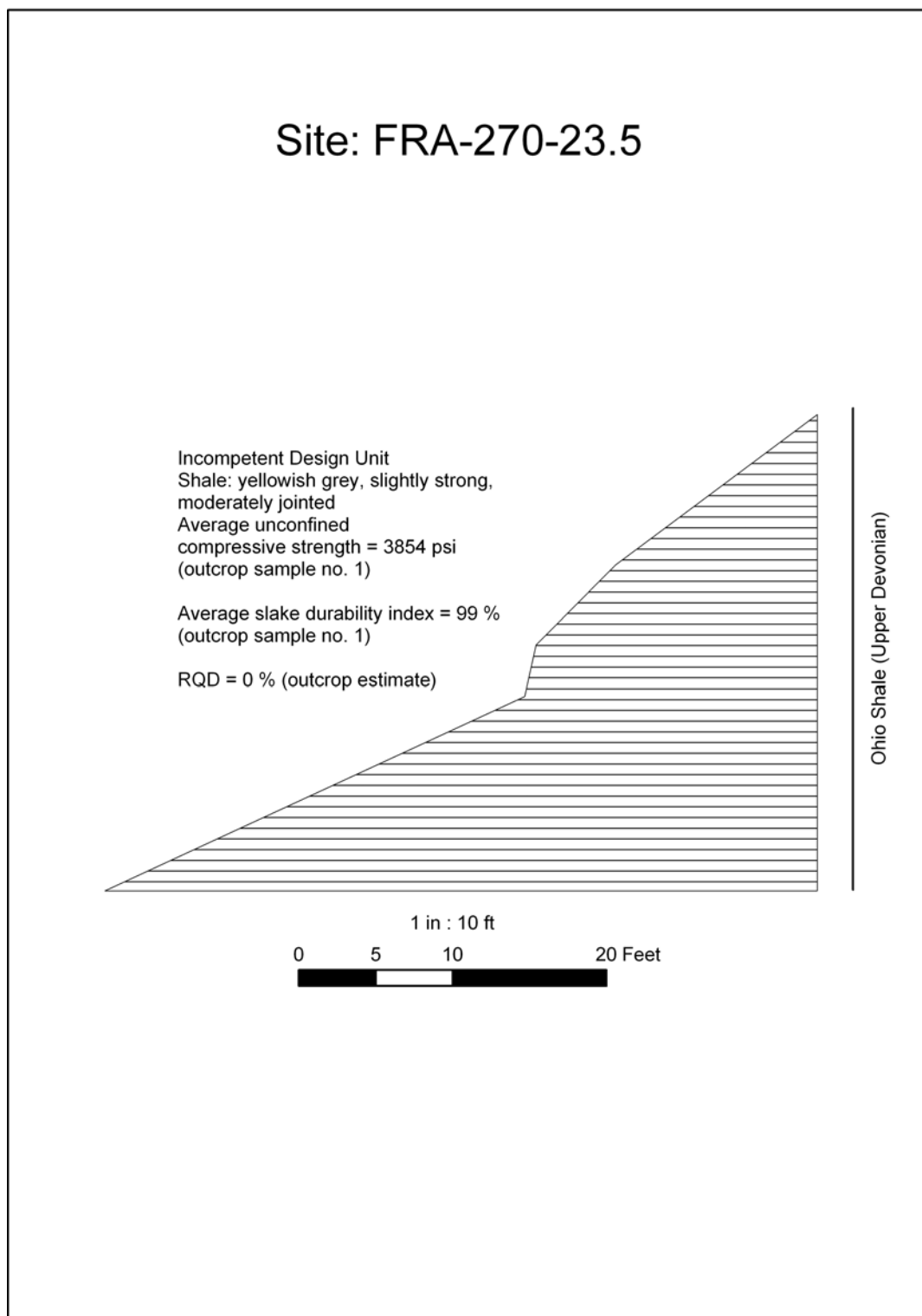
Figure 4-12: Stratigraphic cross-section for FRA-270-23.5.
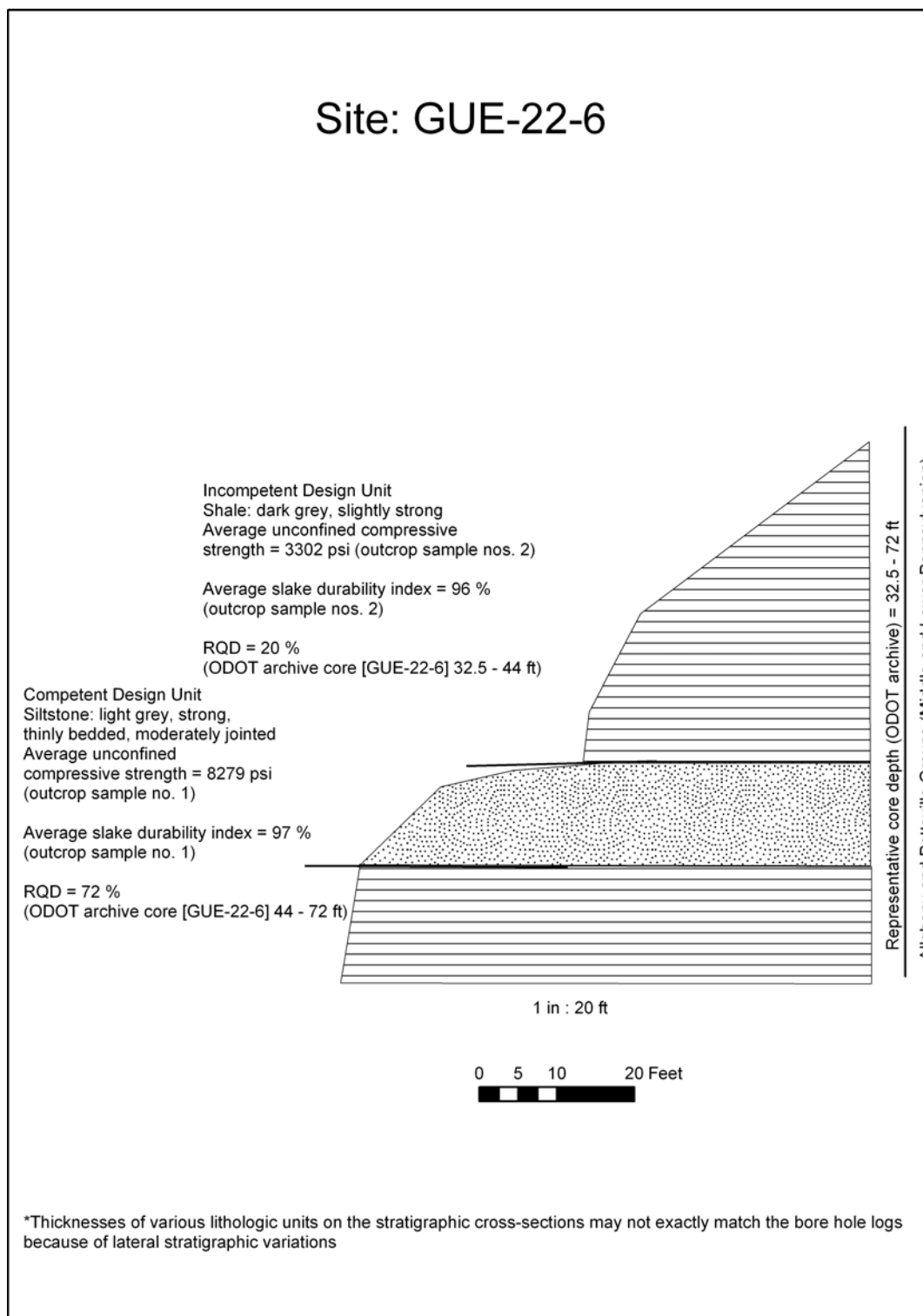
Figure 4-13: Stratigraphic cross-section for GUE-22-6.
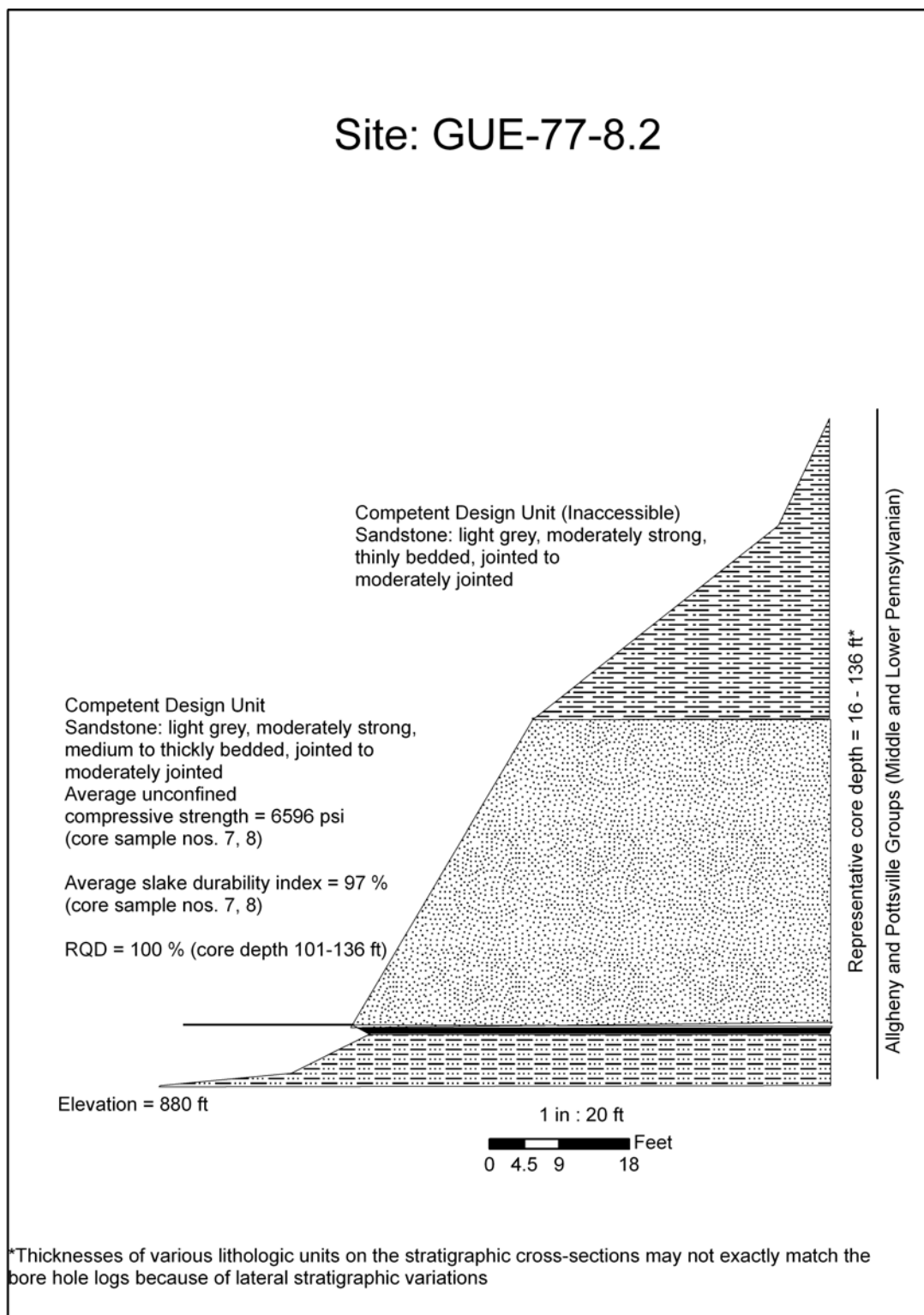
Figure 4-14: Stratigraphic cross-section for GUE-77-8.2.

Site: HAM-126-12.8

Inter-layered Design Unit (62 % competent, 38 %incompetent)
Limestone inter-layered with grey claystone/mudstone
Limestone: grey, very strong, thinly bedded,
moderately to slightly jointed
Claystone/ mudstone: grey, weak
Limestone average unconfined compressive
strength = 16381 psi (core sample nos. 1A, 2A, 3A, 4A)
Grey claystone/ mudstone average
unconfined compressive strength= 1293 psi
(core sample nos. 1, 2, 3, 4)
Weighted unconfined compressive strength =10648 psi

Limestone average slake durability index = 97 %
(core sample nos. 1A, 2A, 3A, 4A)
Grey claystone/ mudstone average slake
durability index = 34 % (core sample nos. 1, 2, 3, 4)
Weighted slake durability index = 73 %

RQD = 56 % (core depth 15-100 ft)

Representative core depth = 15-100 ft*

Grant Lake Formation (Upper Ordovician)

Elevation = 740ft

1 in : 20 ft

Feet

0   10   20   40

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-15: Stratigraphic cross-section for HAM-126-12.8.

Figure 4-16: Stratigraphic cross-section for HAM-74-6.4.

Figure 4-17: Stratigraphic cross-section for JEF-CR77-0.38.

LAW-52-11.8

Inter-layered Design Unit (15 % competent, 85 % incompetent)
Shale and claystone/mudstone inter-layered with sandstone
Sandstone: grey, strong, medium bedded, slightly jointed
to intact
Shale and claystone/mudstone: grey, weak
Sandstone average unconfined compressive strength = 12122 psi
(core sample nos. 5, 7, 12, 15)
Shale and claystone/mudstone average unconfined c
ompressive strength = 1565 psi
(core sample nos. 2, 3, 4, 6, 8, 9, 10, 11, 13, 14)
Weighted unconfined compressive strength = 3149 psi

Sandstone average slake durability index = 96 %,
(core sample nos. 5, 7, 12, 15)
Shale and claystone/mudstone average slake durability index = 83 %
(core sample nos. 2, 3, 4, 6, 8, 9, 10, 11, 13, 14)
Weighted slake durability index = 85 %

RQD = 85 % (core depth 26-118 ft)

Competent Design Unit
Sandstone: light brownish grey,
thickly bedded, not jointed
Average unconfined compressive strength = 3764 psi
(outcrop sample nos. 6, 9)

Average slake durability index = 90 %
(outcrop sample nos. 6, 9)

RQD = 100 % (core depth 118-159 ft)

Inter-layered Design Unit (57 % competent, 43 % incompetent)
Sandstone with minor limestone inter-layered with shale and claystone/mudstone
Sandstone: grey, strong, medium bedded, slightly jointed
to intact
Limesone: grey, strong, intact
Shale and claystone/mudstone: grey, weak
Sandstone average unconfined compressive strength = 7367 psi
(outcrop sample nos. 2, 3, 4, 7)
Limestone average unconfined compressive strength = 20745 psi
(outcrop sample nos. 8)
Shale and claystone/mudstone average unconfined compressive strength = 955 psi
(outcrop sample nos. 1, 5, 10)
Weighted unconfined compressive strength = 6135 psi

Sandstone average slake durability index = 97 %,
(outcrop sample nos. 2, 3, 4, 7)
Limesone average slake durability index = 99%
(outcrop sample nos. 8)
Shale and claystone/mudstone average slake durability index = 42%
(outcrop sample nos. 1, 5, 10)
Weighted slake durability index = 74 %

RQD = 85 % (core depth 26-118 ft)

*Thicknesses of various lithologic units
on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Representative core depth = 26 - 174 ft*

Allgheny and Pottsville Groups (Middle and Lower Pennsylvanian)

1 in : 30 ft   Elevation = 577 ft   0   10   20   40 Feet

Figure 4-18: Stratigraphic cross-section for LAW-52-11.8.

Figure 4-19: Stratigraphic cross-section for LAW-52-12.3.

Site: LIC-16-28

Inaccessible thinly bedded sandstone

Competent Design Unit
Sandstone: yellowish grey, slightly strong,
thickly bedded, moderately to slightly jointed
around the edges with the middle part being massive
Average unconfined compressive strength = 2925 psi
(core sample nos. 1-4)

Average slake durability index = 71 %
(core sample nos. 1-4)

RQD = 50 % (core depth 11-53 ft)

Representative core depth = 11- 53ft*

Black Hand Member of the Cuyhoga Formation (Lower Missisippian)

Elevation = 820 ft

1 in : 20 ft

0   5   10   20 Feet

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-20: Stratigraphic cross-section for LIC-16-28.

MEG-33-15

Inter-layered t Design Unit (15 % competent, 85 % incompetent)
Claystone/mudstone (redbeds) inter-layered with minor sandstone
Sandstone: yellowish grey, moderately strong, thin to medium
bedding, moderately to slightly jointed
Claystone/mudstone: red, very weak
Sandstone average unconfined compressive strength = 6194 psi
(outcrop sample nos. 2, 5, 8, 3, 4, 7)
Claystone/mudstone (redbeds) unconfined compressive strength = 181 psi
(outcrop sample nos. 1, 6, 9, 10)
Weighted unconfined compressive strength = 1083 psi

Sandstone average slake durability index = 87 %
(outcrop sample nos. 2, 5, 8, 3, 4, 7)
Claystone/mudstone (redbeds) average slake durability index = 10 %
(outcrop sample = 1, 6, 9, 10)
Weighted slake durability index = 22 %

RQD = 0 % (outcrop estimates)

sandstone

Mudstone/claystone

Dunkard group (Lower Permian and Upper Pennsylvanian)

1 in : 20 ft

0   5   10   20 Feet
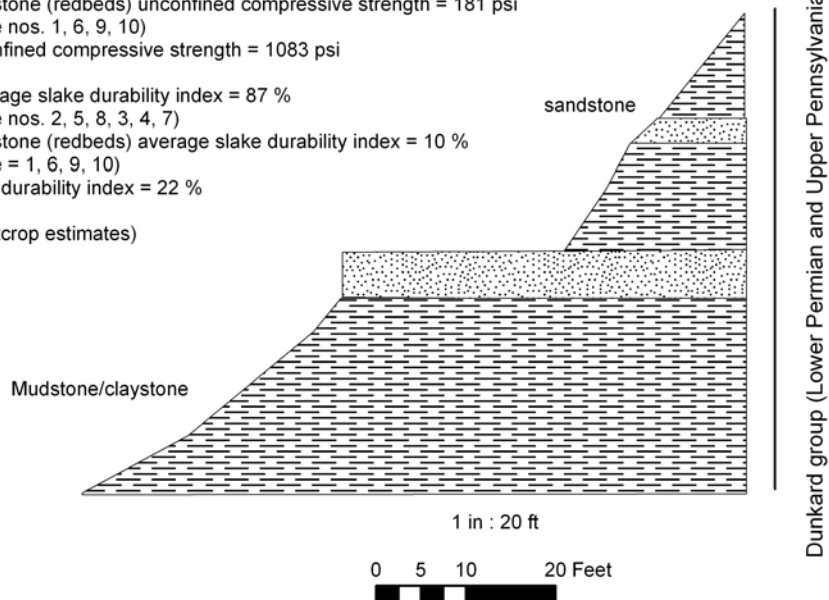
Figure 4-21: Stratigraphic cross-section for MEG-33-15.
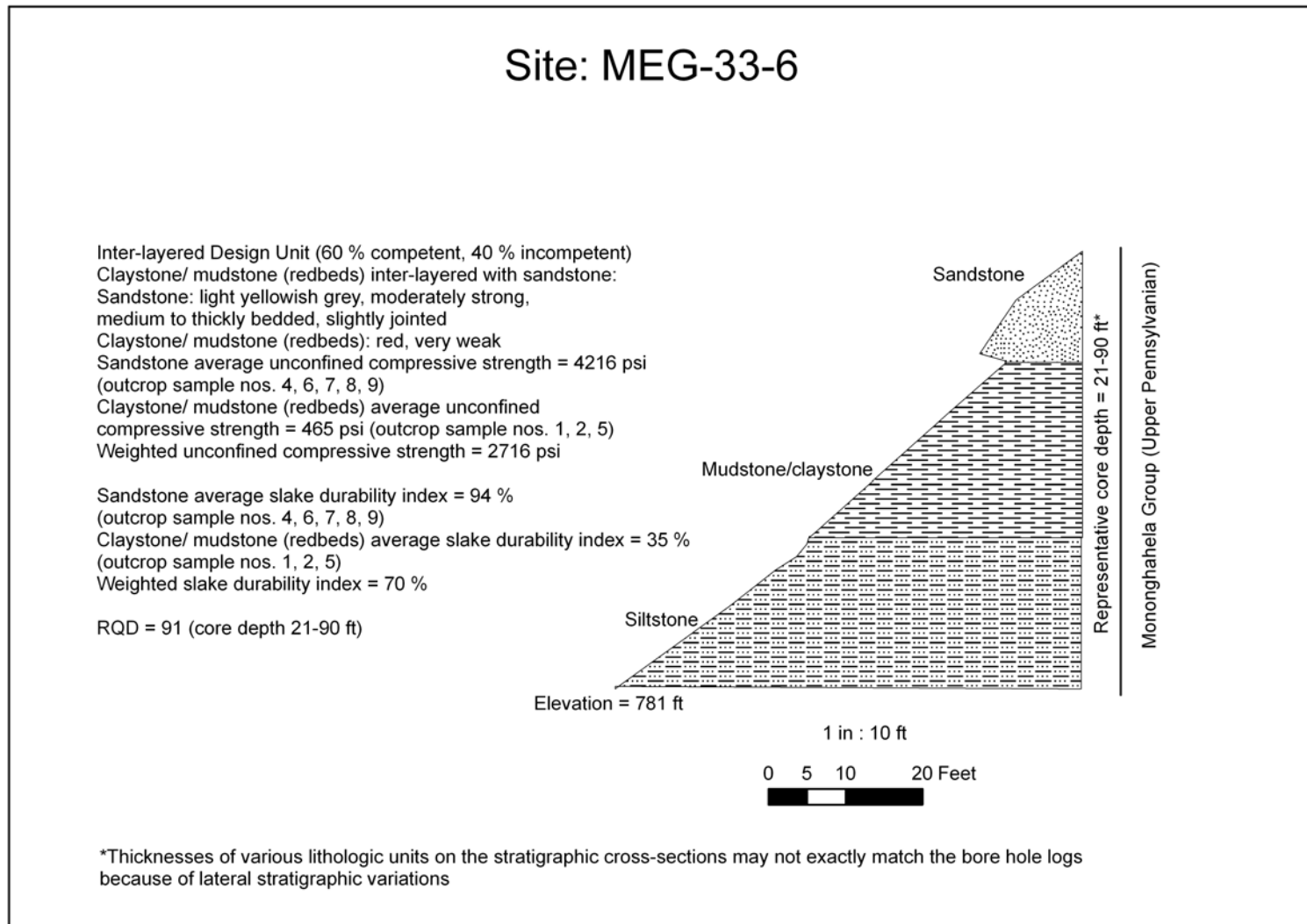
Figure 4-22: Stratigraphic cross-section for MEG-33-6.

Site: MUS-70-11

Competent Design Unit
Sandstone: yellow, moderately strong,
thickly bedded, slightly jointed around the edges
and intact in the middle
Average unconfined compressive strength = 4573 psi
(outcrop sample nos. 2, 6)

Average slake durability index = 89 %
(outcrop sample nos. 2, 6)

RQD = 89 % (ODOT archive core [MUS-70-11] 31.9-63.9 ft)

Incompetent Design Unit
Shale: dark grey, weak
Average unconfined compressive strength = 3125 psi
(outcrop sample nos. 1, 1A, 4, 5)

Average slake durability index = 70 %
(outcrop sample nos. 1, 1A, 4, 5)

RQD = 82 %
(ODOT archive core [MUS-70-1] 63.9-101.1 ft)

Representative core depth (ODOT archive) = 31 - 101.1 ft*

Allgheny and Pottsville Groups (Middle - Lower Pennsylvanian)

1 in : 10 ft

0   5   10   20 Feet

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs because of lateral stratigraphic variations

Figure 4-23: Stratigraphic cross-section for MUS-70-11.

Site: RIC-30-12.5

Competent Design Unit
Sandstone: brownish yellow,
slightly strong, thinly to medium bedded,
slightly jointed around the edges and
intact in the middle
Average unconfined compressive strength = 2571 psi
(outcrop sample nos. 1, 2)

Average slake durability index = 69 %
(outcrop sample nos. 1, 2)

RQD = 43 % (core depth 3-50 ft)

Representative core depth = 3 - 50 ft*

Logan and Cuyhoga Formations (Upper and Lower Mississippian)

0   2.5   5   10 Feet

1 in : 5 ft

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-24: Stratigraphic cross-section for RIC-30-12.5.

Site: STA-30-27.3

Siltstone

Inter-layered Design Unit (24 % competent, 76 % incompetent)
Shale inter-layered with minor siltstone
Siltstone: light grey, strong, thinly bedded, slightly jointed
Shale; dark grey, slightly strong
Siltstone average unconfined compressive strength = 11395 psi
(outcrop sample no. 2)
Shale average unconfined compressive strength = 3835 psi
(outcrop sample no. 1)
Weighted unconfined compressive strength = 5649 psi

Siltstone average slake durability index = 99 %
(outcrop sample no. 2)
Shale average slake durability index = 93 %
(outcrop sample no. 1)
Weighted slake durability index = 94 %

RQD = 29% (core depth 6-72 ft)
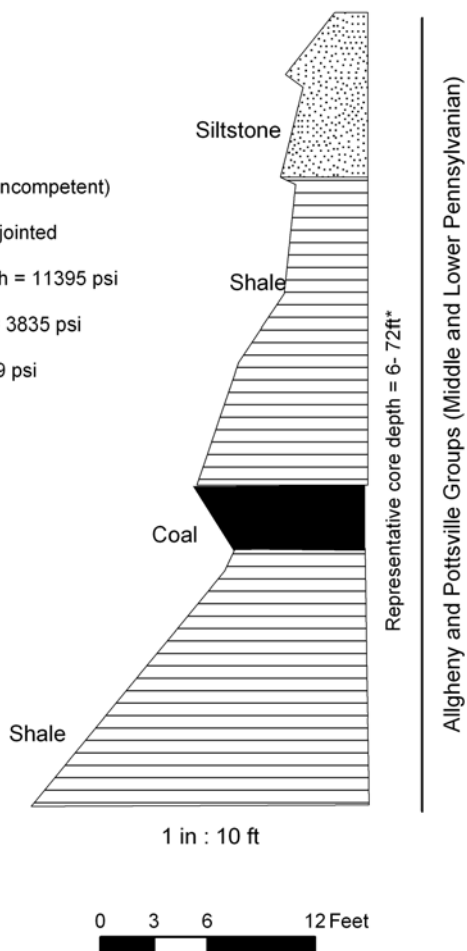
Shale

Coal

Shale

Representative core depth = 6- 72ft*

Allgheny and Pottsville Groups (Middle and Lower Pennsylvanian)

1 in : 10 ft

0   3   6   12 Feet

*Thicknesses of various lithologic units on the stratigraphic cross-sections may not exactly match the bore hole logs
because of lateral stratigraphic variations

Figure 4-25: Stratigraphic cross-section for STA-30-27.3.
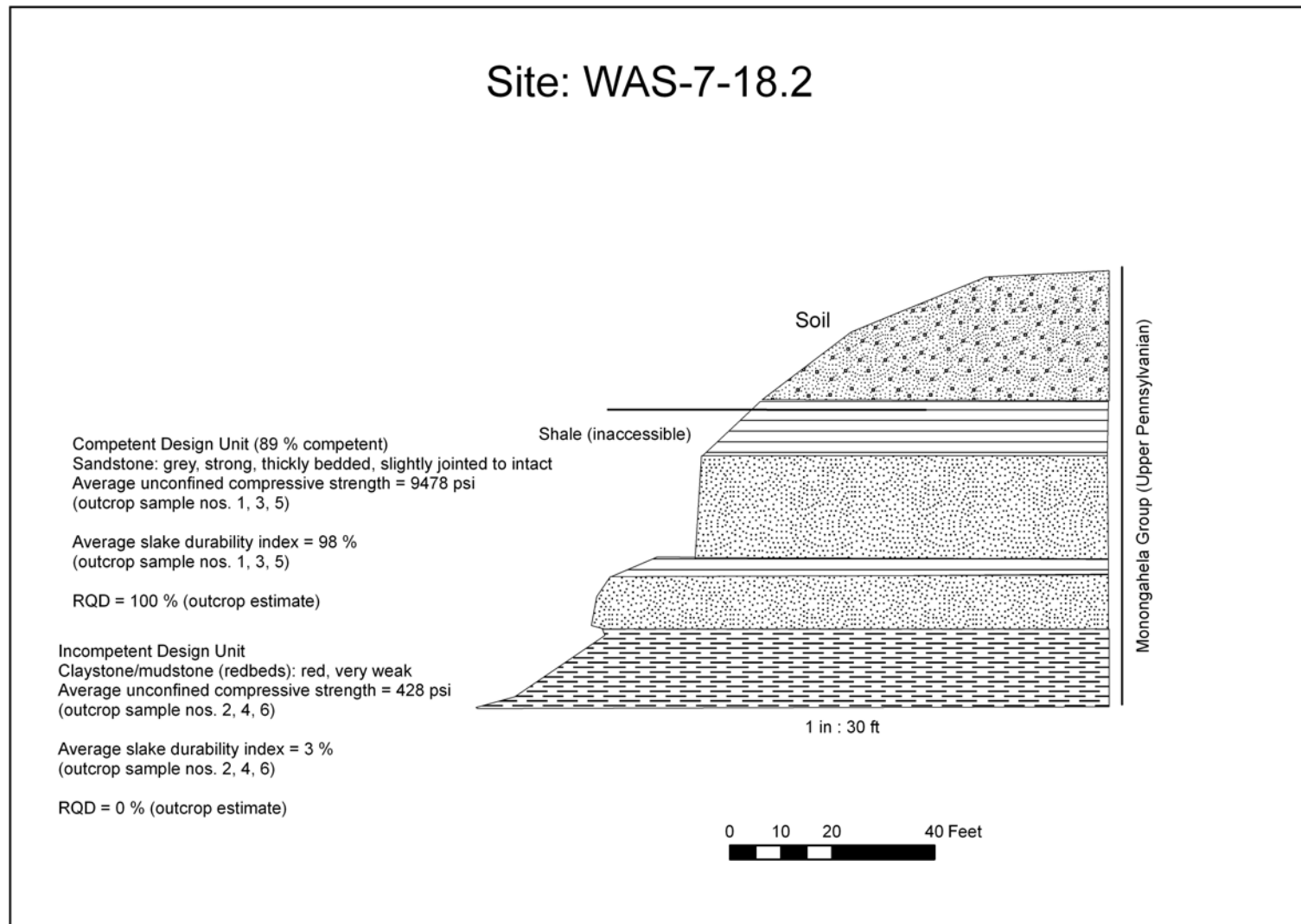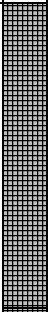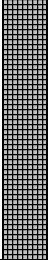
Figure 4-26: Stratigraphic cross-section for WAS-7-18.2.

APPENDIX 5

BOREHOLE LOGS

Site		ADA-32-12.8				Boring:			Page:	1	of:			LOG OF TEST BORING		
Location:		Lat.:			Long.:											
Project Type:		Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	4/10/2008	Finish:	4/16/2008					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:							Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Elevation 840 ft. +/-									
	1.0										
	2.0										
	3.0	Light brown silty clay with sand, damp									
	4.0										
	5.0										
	6.0										
	7.0										
	8.0								zones non-solutioned		
	9.0							#1			
	10.0			77%		100%			4148		
	11.0									97	
	12.0	Dolomite: Reddish brown to grey, slightly weathered, moderately strong, iron and carbon staining, vuggy; moderately fractured									
	13.0										
	14.0										
	15.0										
	16.0										
	17.0			58%		99%					
	18.0										
	19.0	18.4 ft vertical fracture 19.0-19.2 ft. highly fractured									
	20.0										

Site		ADA-32-12.8			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:		
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	21.0										
	22.0	Dolomite: Reddish brown to grey, slightly weathered, moderately strong, iron and carbon staining, vuggy; moderately fractured		58%		99%					
	23.0										
	24.0										
	25.0										
	26.0										
	27.0										
	28.0	Mechanical fractures 26.3 ft and 30.1 ft									
	29.0			98%		100%					
	30.0	Shale: Grey, slightly strong to moderately strong, arenaceous, calcareous, medium bedded, clayey seams observed									
	31.0										
	32.0										
	33.0							#2	8670		
	34.0									93	
	35.0										
	36.0										
	37.0			100%		100%					
	38.0										
	39.0										
	40.0										

Site		ADA-32-12.8			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location: Lat.: Long.:

Project Type: Rock Slope Research | Units: Eng | Datum: | **Date:** Start: | Finish:

Water: Seepage (▽): | Prior to Addition(▼): | Completion(▽): | Extended Readings: | Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
41.0							#3			
42.0			100%		100%			4205	94	
43.0										
44.0	Shale: Grey, strong to moderately strong, arenaceous, calcareous, medium bedded									
45.0										
46.0										
47.0										
48.0										
49.0			93%		100%					
50.0										
51.0										
52.0										
53.0										
54.0	Dolomite: Grey, moderately strong to strong, fossiliferous, zones; vertically fractured									
55.0							#4	10322		
56.0									99	
57.0			69%		100%					
58.0										
59.0										
60.0										

Site		ADA-32-12.8			Boring:			Page:	1	of:			LOG OF TEST		
Location:	Lat.:		Long.:										BORING		
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:						Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	61.0										
	62.0			69%		100%					
	63.0										
	64.0										
	65.0										
	66.0										
	67.0										
	68.0										
	69.0	Dolomite: Grey, moderately strong to strong (field investigation), fossiliferous, zones; vertically fractured		77%		100%					
	70.0										
	71.0										
	72.0										
	73.0										
	74.0										
	75.0										
	76.0										
	77.0			99%		100%					
	78.0										
	79.0										
	80.0										

Site		ADA-32-12.8			Boring:			Page:	1	of:		LOG OF TEST BORING	

Site: ADA-32-12.8 **Boring:** **Page:** 1 **of:** **LOG OF TEST BORING**

Location: Lat.: Long.:

Project Type: Rock Slope Research **Units:** Eng **Datum:** **Date:** **Start:** **Finish:**

Water: Seepage (▽): **Prior to Addition**(▼): **Completion**(▽): **Extended Readings:** **Drill Fluid:** Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
81.0	Dolomite: Grey, strong (field investigation), fossiliferous, zones; vertically fractured									
82.0			99%		100%					
83.0										
84.0										
85.0										
86.0										
87.0										
88.0										
89.0			76%		79%					
90.0	89.5-90.5 ft some clay seams									
91.0										
92.0										
93.0										
94.0	Bottom of Hole 94.1ft									
95.0										
96.0										
97.0										
98.0										
99.0										
100.0										

Site		ADA-41-15.1		800 ft.		Boring:			Page:	1	of:		LOG OF TEST BORING		
Location:		Lat.:		Long.:											
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	4/16/2008		Finish:	4/16/2008				
Water: Seepage (▽):			Prior to Addition (▼):		Completion (▽):		Extended Readings:						Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation: 760 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0	Grey silty clay with rock fragments, moist									
	7.0										
	8.0										
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0										
	15.0	Dolomite and limestone (60%) inter-bedded with claystone/mudstone (40%):									
	16.0	Dolomite and limestone: Grey, strong (field investigation), thinly bedded; moderately fractured		67%		98%					
	17.0	Claystone/mudstone: Grey, very weak, highly weathered									
	18.0	16.0-16.9 ft vertical fracture									
	19.0			0		73%					
	20.0	19.0-21 ft possible zone of loss									

Site		**ADA-41-15**			**Boring:**		**Page:**	**1**	**of:**	**LOG OF TEST BORING**	

Location:	Lat.:		Long.:						

Project Type: Rock Slope Research | **Units:** Eng | Datum: | **Date:** | Start: | Finish:

Water: Seepage (▽): | Prior to Addition(▼): | Completion(▽) | Extended Readings: | Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	21.0	19.0-21.0 ft possible zone of loss									
	22.0			0		73%					
	23.0										
	24.0										
	25.0										
	26.0										
	27.0										
	28.0							#1	Lst - 18681 Sh - 222	Lst-99 Sh-38	
	29.0	Dolomite and imestone (60%) inter-bedded with claystone/mudstone (40%):		60%		97%					
	30.0	Dolomite and limestone: Grey, very strong, thinly bedded									
	31.0	Claystone/mudstone: Grey, very weak									
	32.0										
	33.0										
	34.0										
	35.0										
	36.0										
	37.0			82%		100%					
	38.0										
	39.0										
	40.0										

Site		ADA-41-15			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location: Lat.: Long.:

Project Type: Rock Slope Research   Units: Eng   Datum: **Date:** Start: Finish:

Water: Seepage (▽):   Prior to Addition(▼):   Completion(▽):   Extended Readings: Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	41.0										
	42.0			82%		100%		#2			
	43.0										
									LST-15395	LST-99	
	44.0										
	45.0										
	46.0	Dolomite and limestone (60%) inter-bedded with claystone/mudstone (40%):									
	47.0	Dolomite and limestone: Grey, strong, thinly bedded		22%		100%					
	48.0	Claystone/mudstone: Grey, very weak									
	49.0										
	50.0	Bottom of Hole 50.3 ft									
	51.0										
	52.0										
	53.0										
	54.0										
	55.0										
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

Site		ATH-33-14.68		920 ft.		Boring:			Page:	1	of:			LOG OF TEST BORING		
Location:		Lat.:		Long.:												
Project Type:	Geo-Hazard		Units: Eng	Datum:		**Date:**	Start:	4/21/2008	Finish:	4/22/2008						
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:							Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
		Elevation: 940 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0										
	7.0										
	8.0										
	9.0										
	10.0										
	11.0	Yellowish brown silty soil									
	12.0										
	13.0										
	14.0										
	15.0										
	16.0										
	17.0										
	18.0										
	19.0										
	20.0										

Site		ATH-33-14.68			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location:	Lat.:		Long.:							

Project Type:	Geo-Hazard		Units: Eng	Datum:		Date:	Start:		Finish:		

Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:			Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	21.0										
	22.0										
	23.0										
	24.0										
	25.0										
	26.0										
	27.0										
	28.0										
	29.0										
	30.0	Yellowish brown silty soil									
	31.0										
	32.0										
	33.0										
	34.0										
	35.0										
	36.0										
	37.0										
	38.0										
	39.0										
	40.0										

Site		ATH-33-14.68			Boring:			Page:	1	of:		LOG OF TEST BORING	

Location: Lat.: | Long.:

Project Type: Geo-Hazard | Units: Eng | Datum: | **Date:** | Start: | Finish: | **LOG OF TEST BORING**

Water: Seepage (▽): | Prior to Addition(▼): | Completion(▽) | Extended Readings: | Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	41.0										
	42.0	Shale: Grey, slightly weathered, weak (field investigation), arenaceous, grading into sandstone									
	43.0										
	44.0			91%		100%					
	45.0										
	46.0										
	47.0										
	48.0										
	49.0										
	50.0	Sandstone: Grey and brown, slightly weathered, strong, coarse grained, ferruginous									
	51.0										
	52.0										
	53.0							#1	9084	98	
	54.0										
	55.0			97%		100%					
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

Site		ATH-33-14.68			Boring:			Page:	1	of:			LOG OF TEST		
Location:	Lat.:		Long.:										BORING		
Project Type:	Geo-Hazard		Units: Eng	Datum:		**Date:**	Start:			Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:						Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)			ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
	61.0											lost H₂O
	62.0											
	63.0											
	64.0											
	65.0			97%		100%						
	66.0											
	67.0											
	68.0											
	69.0	Sandstone: Grey and brown, slightly weathered, slightly strong, coarse grained, ferruginous										
	70.0											mixed mud
	71.0											
	72.0	61.1ft highly weathered joint - iron stained 63.4 ft iron stained weathered joint										
	73.0											
	74.0											
	75.0			100%		100%						
	76.0											
	77.0											
	78.0							#2	2581	87		
	79.0											
	80.0											

Site		ATH-33-14.68			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Geo-Hazard		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	TESTING DATA (Depth - Ft.)									
81.0	2 mm clay seam									
82.0										
83.0										
84.0										
85.0			98%		100%					
86.0										
87.0										
88.0										
89.0	Sandstone: Grey and brown, slightly weathered, slightly strong, coarse grained, ferruginous									
90.0										
91.0										
92.0										
93.0										
94.0										
95.0			98%		100%					
96.0										
97.0										
98.0							#3	3314	90	
99.0										
100.0										

Site		ATH-33-14.68			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:		Long.:										
Project Type: Geo-Hazard		Units: Eng	Datum:		Date:	Start:		Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	101.0										
	102.0										
	103.0										
	104.0										
	105.0			92%		100%					
	106.0										
	107.0	Sandstone: Grey, moderately strong, coarse to medium grained									
	108.0										
	109.0										
	110.0										
	111.0										
	112.0										
	113.0							#4	6047		
	114.0										
	115.0			90%		100%				95	
	116.0										
	117.0	Shale: Black, unweathered									
	118.0										
	119.0										
	120.0										

Site			ATH-33-14.68				Boring:			Page:	1	of:				LOG OF TEST BORING		
Location:		Lat.:			Long.:													
Project Type:	Geo-Hazard			Units: Eng	Datum:			**Date:**	Start:			Finish:						
Water: Seepage (▽):				Prior to Addition(▼):			Completion(▽)		Extended Readings:								Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	121.0										
	122.0										
	123.0										
	124.0										
	125.0			97%		100%					
	126.0										
	127.0	Sandstone: Grey, unweathered, very strong, coarse to medium grained									
	128.0										
	129.0										
	130.0										
	131.0										
	132.0										
	133.0							#5	17931		
	134.0										
	135.0			100%		98.30%					
	136.0										
	137.0										
	138.0										
	139.0										
	140.0										

Site		ATH-33-14.68			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location:	Lat.:		Long.:									

Project Type: Geo-Hazard | Units: Eng | Datum: | Date: | Start: | Finish:

Water: Seepage (▽):   Prior to Addition(▼):   Completion(▽)   Extended Readings: Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	141.0										
	142.0										
	143.0										
	144.0	Shale: Grey-green, moderately to highly weathered, very weak, pyritic		47%		87%					
	145.0										
	146.0										
	147.0										
	148.0										
	149.0										
	150.0										
	151.0										
	152.0										
	153.0										
	154.0										
	155.0										
	156.0										
	157.0										
	158.0										
	159.0										
	160.0										

`		BEL-470-6		PID:	82661	Boring:		B-001	Page:	1	of:	8	LOG OF TEST BORING		
Location:	Lat.:			Long.:											
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	3/26/2007		Finish:	3/28/2007				
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:						Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation 1080 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0										
	7.0										
	8.0	Soil and weathered rock									
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0										
	15.0										
	16.0										
	17.0	Limestone: Light grey, slightly weathered, very strong (field investigation); RQD = 100%									
	18.0										
	19.0	Shale: Dark grey, weak (field investigation); RQD = 100%		62%		100%					
	20.0										

Project Descr.:		BEL-470-6		PID:	82661	Boring:		B-001	Page:		2	of:	8	LOG OF TEST BORING		
Location:		Lat.:		Long.:			Station:					Offset:				
Project Type:		Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	3/26/2007		Finish:	3/28/2007				
Water: Seepage (▽):			Prior to Addition(▼):			Completion(▽) :			Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	21.0										
	22.0	Sandstone: Grey, strong (field investigation); RQD = 69%									
	23.0										
	24.0										
	25.0			62%		100%					
	26.0	Shale: Dark grey, modrerately strong (field investigation), contains minor siltstone; RQD = 25%									
	27.0										
	28.0										
	29.0										
	30.0	Clayey material: Dark grey, very weak (field investigation)									
	31.0	Limestone: Grey, very strong (field investigation)									
	32.0										
	33.0										
	34.0	Shale: Dark grey, very weak (field investigation), most of the material is lost; fractured		47%		63%					
	35.0										
	36.0										
	37.0	Limestone: Grey, very strong (field investigation)									
	38.0										
	39.0	Shale: Dark, moderately strong (field investigation)									
	40.0	Clayey material: Dark grey, very weak (field investigation)		70%		83%					

Project Descr.:		BEL-470-6		PID:	82661	Boring:		B-001	Page:	3	of:	8	LOG OF TEST BORING		
Location:	Lat.:			Long.:		Station:				Offset:					
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	3/26/2007	Finish:	3/28/2007					
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:						Drill Fluid: Water		

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
41.0	Clayey material: Dark grey, very weak									
42.0										
43.0										
44.0			70%		83%					
45.0	Coal									
46.0										
47.0										
48.0										
49.0										
50.0										
51.0										
52.0										
53.0										
54.0	Shale: Dark grey, moderately strong (field investigation), contains siltstone inter-layers; RQD = 100%		97%		100%					
55.0										
56.0										
57.0										
58.0										
59.0			55%		91%					
60.0										

Project Descr.:		**BEL-470-6**		PID:	82661	Boring:		**B-001**	Page:		**4**	of:	**8**	LOG OF TEST BORING		
Location:	Lat.:			Long.:		Station:						Offset:				
Project Type:	Rock Slope Research		Units: Eng	Datum:			**Date:**	Start:	3/26/2007			Finish:	3/28/2007			
Water: Seepage (▽):			Prior to Addition(▼):			Completion(▽)		Extended Readings:						Drill Fluid: Water		

Elev. / Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.	DEPTH
	Coal										
61.0	Clayey material: Dark grey, very weak										
62.0											
63.0	Shale inter-layered with siltstone: slightly to moderately strong (field investigation); RQD = 100%		55%		91%						
64.0											
65.0											
66.0											
67.0											
68.0	Limestone: Grey, very strong; RQD = 100%										
69.0											
70.0											
71.0	Shale: Green, weak (field investigation), contains limestone clasts										
72.0			100%		100%						
	Limestone: Grey, very strong (field investigation), consisting angular fragments (due to desiccation cracks); RQD=100%										
73.0											
74.0											
75.0	Shale: Green, weak, with limestone clasts; RQD = 100%										
76.0											
77.0	Limestone: Grey, very strong limestone, consists of angular fragments; RQD = 100%						#1	20760	100		
78.0							#2	2261	70		
79.0	Claystone/mudstone: Green, slightly strong, consists of limestone clasts; RQD = 81%		70%		100%		#3	3109			
80.0									87		

Project Descr.:		BEL-470-6		PID:	82661		Boring:		B-001	Page:		5	of:		8	LOG OF TEST			
Location:	Lat.:				Long.:			Station:					Offset:			BORING			
Project Type:	Rock Slope Research		Units: Eng	Datum:			**Date:**	Start:	3/26/2007		Finish:	3/28/2007							
Water:	Seepage (▽):		Prior to Addition(▼):			Completion(▽)			Extended Readings:							Drill Fluid: Water			

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.	DEPTH
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
	81.0											
	82.0	Shale: Green, slightly strong, contains siltstone interlayers; RQD = 100%										
	83.0											
	84.0											
	85.0	Sandstone: Grey; High angle fracture intercepted; RQD = 0%		70%		100%						
	86.0											
	87.0	Shale: Dark green, weak (field investigation); RQD = 71%										
	88.0											
	89.0											
	90.0											
	91.0											
	92.0	Sandstone: Grey, strong (field investigation); RQD = 98%										
	93.0											
	94.0			100%		98%						
	95.0											
	96.0											
	97.0											
	98.0											
	99.0											
	100.0	Shale: Dark grey, slightly strong (field investigation); RQD = 33%		67%		100%						

Project Descr.:		BEL-470-6		PID:	82661		Boring:		B-001	Page:		5	of:		8	LOG OF TEST BORING			
Location:	Lat.:			Long.:				Station:					Offset:						
Project Type:	Rock Slope Research		Units: Eng	Datum:				**Date:**	Start:		3/26/2007		Finish:		3/28/2007				
Water: Seepage (▽):			Prior to Addition(▼):			Completion(▽):			Extended Readings:								Drill Fluid: Water			

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.	DEPTH
	101.0											
	102.0											
	103.0											
	104.0			67%		100%						
	105.0	Shale: Grey, slightly strong (field investigation), becomes more organic from 108.4 to 111.4 ft										
	106.0											
	107.0											
	108.0											
	109.0											
	110.0											
	111.0											
	112.0	Limestone: Grey, very strong (field investigation)										
	113.0	Claystone/mudstone with limestone clasts: Green, slightly strong; RQD = 100%		83%		100%		#4	2669	95		
	114.0											
	115.0											
	116.0	Limestone: Grey, very strong (field investigation); RQD = 100%										
	117.0											
	118.0											
	119.0	Shale: Dark green, slightly strong (field investigation); RQD = 100%		77%		93%						
	120.0											

Project Descr.:	BEL-470-6		PID:	82661	Boring:	B-001	Page:	5	of:	8	LOG OF TEST BORING
Location:	Lat.:		Long.:		Station:			Offset:			
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start: 3/26/2007		Finish: 3/28/2007		
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.	DEPTH
121.0											
122.0											
123.0	Shale: Green, slightly strong (field investigation); RQD = 80%										
124.0			77%		93%						
125.0											
126.0											
127.0											
128.0											
129.0							#5	17116			
130.0	Sandstone: Grey, very strong; RQD = 100%								99		
131.0											
132.0											
133.0											
134.0			100%		100%						
135.0											
136.0							#6A,6B	1736, 1157			
137.0	Shale: Dark green, weak to moderately strong; RQD = 100%										
138.0									93		
139.0			96%		100%						
140.0											

Project Descr.:	BEL-470-6		PID:	82661	Boring:	B-001	Page:	5	of:	8	LOG OF TEST BORING	
Location:	Lat.:		Long.:		Station:				Offset:			
Project Type:	Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:	3/26/2007	Finish:	3/28/2007			

Water: Seepage (▽):   Prior to Addition(▼):   Completion(▽):   Extended Readings: Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.	DEPTH
	141.0											
	142.0	Shale: Dark green, weak; RQD = 100%										
	143.0											
	144.0			96%		100%						
	145.0											
	146.0											
	147.0											
	148.0	Limestone: Grey, very strong (field investigation); RQD =100%										
	149.0											
	150.0											
	151.0											
	152.0	Shale: Dark green, weak (field investigation), becoming organic at the bottom; RQD = 67%										
	153.0			94%		100%						
	154.0											
	155.0											
	156.0	Coal										
	157.0											
	158.0											
	159.0	Sandstone: Very strong, micaceous; RQD = 100%						#7	18384			
	160.0									98		

Project Descr.:		BEL-470-6		PID:	82661		Boring:		B-001	Page:		5	of:	8	LOG OF TEST BORING		
Location:	Lat.:			Long.:				Station:					Offset:				
Project Type:	Rock Slope Research		Units: Eng	Datum:			Date:	Start:	3/26/2007		Finish:	3/28/2007					
Water:	Seepage (▽):			Prior to Addition(▼):			Completion(▽)			Extended Readings:						Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.	DEPTH
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
	161.0											
	162.0	Sandstone: Very strong, micaceous; RQD = 100%										
	163.0											
	164.0	163.3-166.5 ft; RQD = 90%		94%		100%		#8	1719			
	165.0											
	166.0									70		
	167.0											
	168.0											
	169.0											
	170.0	Shale: Dark grey, slightly strong, contains siltstone inter-layers in the top part and limestone clasts										
	171.0	between 170 to 178 ft						#9	1796			
	172.0	169-178.5 ft; RQD = 84%										
	173.0									77		
	174.0			93%		96%						
	175.0											
	176.0											
	177.0											
	178.0											
	179.0											
	180.0											

Project Descr.:		BEL-470-6		PID:	82661		Boring:		B-001	Page:		5	of:	8	LOG OF TEST BORING		
Location:		Lat.:			Long.:			Station:				Offset:					
Project Type:	Rock Slope Research		Units: Eng	Datum:				Date:	Start:	3/26/2007		Finish:	3/28/2007				
Water:	Seepage (▽):			Prior to Addition(▼):		Completion(▽)			Extended Readings:						Drill Fluid: Water		

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.	DEPTH
								Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
181.0											
182.0											
183.0	182.5-184.5 ft; RQD = 84 %							1245	85		
184.0			84%		97%		#11				
185.0											
186.0											
187.0							#10	NT	68		
188.0											
189.0	Shale: Green, weak to slightly strong, inter-layered with siltstone between 188.4-198.5 ft										
190.0											
191.0	188.5-198.5; RQD = 100 %										
192.0											
193.0							#12	NT	97		
194.0			100%		100%						
195.0											
196.0											
197.0											
198.0	198.5-203.1 ft; RQD = 100 %										
199.0							#13	2241	94		
200.0											

Project Descr.:		BEL-470-6		PID:	82661	Boring:		B-001	Page:		5	of:	8	LOG OF	TEST
Location:	Lat.:			Long.:		Station:				Offset:				BORING	
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	3/26/2007		Finish:	3/28/2007				
Water: Seepage (▽):			Prior to Addition(▼):			Completion(▽)			Extended Readings:					Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
201.0										
202.0	Shale: Dark grey, weak (field investigation); RQD = 100%									
203.0										
204.0			90%		97%					
205.0										
206.0	Organic Shale: Dark, very weak (field investigation)									
207.0	Coal									
208.0										
209.0										
210.0	Shale: Dark grey, weak (field investigation), contains limestone clasts; RQD = 100%									
211.0										
212.0										
213.0										
214.0	Limestone: Grey, strong (field investigation), contains angular fragments (due to desiccation cracks); RQD = 100%		93%		100%					
215.0										
216.0										
217.0							#14	2999		
218.0	Shale: Green, slightly strong, consists of limestone clasts; RQD = 100%								77	
219.0										
220.0	Limestone: Green, strong (field investigation)									

Project Descr.:	BEL-470-6		PID: 82661		Boring:	B-001	Page:	5	of:	8	LOG OF TEST BORING	
Location:	Lat.:		Long.:			Station:			Offset:			
Project Type: Rock Slope Research		Units: Eng	Datum:			**Date:**	Start: 3/26/2007		Finish: 3/28/2007			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.	DEPTH
	221.0											
	222.0											
	223.0	Shale: Dark green, moderately strong; RQD = 100%		100%		100%						
	234.0											
	225.0											
	226.0							#15	4337	99		
	227.0											
	228.0											
	229.0											
	230.0											
	231.0	Limestone: Grey, strong (field investigation), contains angular fragments		93%		100%						
	232.0											
	233.0											
	234.0											
	235.0											
	236.0											
	237.0							#16	1276	17		
	238.0											
	239.0	Shale: Green, weak; RQD = 46%										
	240.0											

Project Descr.:		BEL-470-6		PID:	82661		Boring:		B-001	Page:		5	of:	8	LOG OF	TEST		
Location:		Lat.:			Long.:			Station:				Offset:			BORING			
Project Type:		Rock Slope Research		Units: Eng	Datum:			Date:	Start:	3/26/2007		Finish:	3/28/2007					
Water:	Seepage (▽):			Prior to Addition(▼):			Completion(▽)			Extended Readings:					Drill Fluid: Water			

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.	DEPTH
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
	241.0							#17	15670	99		
	242.0	Limestone: Grey, strong, occasionally contains fractures filled with greenish material; RQD = 100%										
	243.0							#18	11572	95		
	244.0			86%		97%						
	245.0											
	246.0											
	247.0											
	248.0	Claystone/mudstone: Green, slightly strong, consists of some limestone clasts; RQD = 100%										
	249.0							#19	2156	66		
	250.0											
	251.0											
	252.0											
	253.0			100%		100%						
	254.0											
	255.0											
	256.0	Limestone: Grey, strong, contains angular fragments										
	257.0											
	258.0											
	259.0											
	260.0											

Project Descr.:	BEL-470-6		PID:	82661	Boring:	B-001	Page:	5	of:	8	LOG OF TEST BORING	
Location:	Lat.:		Long.:		Station:				Offset:			
Project Type:	Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:	3/26/2007	Finish:	3/28/2007			
Water: Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.	DEPTH
								Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)		
261.0											
262.0	Claystone/mudstone with shale: Green, weak to slightly strong, with and without limestone clasts; RQD = 100%						#20,21	1384,2692	24, 97		
263.0											
264.0											
265.0			100%		100%						
266.0											
267.0	Limestone: Grey, strong, with angular clasts; RQD = 100%										
268.0											
269.0											
270.0											
271.0											
272.0											
273.0											
274.0											
275.0											
276.0											
277.0											
278.0											
279.0											
280.0											

Site			BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:		Lat.: 39.947990		Long.:80.76698										
Project Type:	Rock Slope Research		Units: Eng	Datum:		Date:	Start:	4/2/2008	Finish:	4/9/2008				
Water:	Seepage (▽:		Prior to Addition(▼.		Completion(▽		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes		Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
										Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation 980 ft. +/-										
	1.0											
	2.0											
	3.0	Silty Soil										
	4.0											
	5.0											
	6.0											
	7.0											
	8.0											
	9.0											
	10.0	Weathered arenaceous rock										
	11.0											
	12.0											
	13.0											
	14.0											
	15.0					75%		100%					
	16.0											
	17.0											
	18.0	Coal										
	19.0											
	20.0											

Site		**BEL-7-10**			Boring:			Page:	**1**	of:			**LOG OF TEST**		
Location:		Lat.:		Long.:									**BORING**		
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)			Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	21.0	Coal						#1	NT	NT	
	22.0										
	23.0	Clayey material (underclay) (22.5 - 24 ft)						#2			
	24.0									23	
	25.0			67%		98%					
	26.0										
	27.0	Shale: Dark grey, slightly weathered, weak (field investigation); RQD=85%									
	28.0										
	29.0										
	30.0										
	31.0	Sandstone: Grey, slightly weathered, moderately strong (field investigation), micaceous, fine grained; RQD = 100%									
	32.0										
	33.0										
	34.0							#3	NT		
	35.0			100%		100%				98	
	36.0										
	37.0										
	38.0	Silty Shale: Dark grey, slightly strong; RQD = 100%						#4	1795		
	39.0									95	
	40.0										

Site			BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST	
Location:		Lat.:			Long.:							BORING	
Project Type:		Rock Slope Research		Units: Eng	Datum:		**Date:**		Start:		Finish:		
Water:	Seepage (▽:			Prior to Addition(▼:		Completion(▽		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	41.0										
	42.0										
	43.0	Silty Shale: Dark grey, slightly strong; RQD = 100%									
	44.0										
	45.0			94%		100%					
	46.0										
	47.0										
	48.0	Limestone: Grey, strong; RQD = 100%						#5	12479	99	
	49.0							#6	2410	57	
	50.0	48.5 - 50 ft; RQD = 100%									
	51.0	50 - 59.9 ft; RQD = 94%						#7	2412	93	
	52.0										
	53.0										
	54.0	Claystone/mudstone: Green, slightly strong with limestone clasts									
	55.0			94%		98%					
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

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Site		BEL-7-10			Boring:			Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:			Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	61.0										
	62.0										
	63.0	Shale: Green, slightly strong; RQD = 100%									
	64.0									99	
	65.0	Sandstone: Grey, very strong cross bedded, middle part is massive and fine grained; RQD = 100 %		100%		100%		#8	21507		
	66.0										
	67.0										
	68.0							#9	1404	91	
	69.0										
	70.0										
	71.0										
	72.0	Shale: Grey, weak, contains some siltstone inter-layers; RQD = 97%						#10	1606	84	
	73.0										
	74.0										
	75.0			97%		98%					
	76.0										
	77.0										
	78.0										
	79.0	Micaceous sandstone: Fine grained									
	80.0										

Site		**BEL-7-10**			**Boring:**			**Page:**	**1**	**of:**	**LOG OF TEST BORING**	
Location:	Lat.:			Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Shale: Green, weak; RQD = 100%									
	81.0										
	82.0	Limestone: RQD = 0%									
	83.0										
	84.0										
	85.0	Claystone/mudstone: Green, slightly strong; RQD = 84%						#11	863		
	86.0									34	
	87.0										
	88.0										
	89.0			85%		99%					
	90.0										
	91.0	Claystone/mudstone:: Dark, slightly strong; RQD = 66%						#12	2897		
	92.0									60	
	93.0	Shale: Green, calcareous moderately strong; RQD = 100%						#13	6292		
	94.0									46	
	95.0			92%		100%					
	96.0	Claystone/mudstone (redbed): Red, very weak; RQD = 100%						#14	NT	20	
	97.0										
	98.0										
	99.0	Shale: Green, slightly strong (field investigation), contains siltstone inter-layers; RQD = 100%									
	100.0										

Site		BEL-7-10			Boring:			Page:	1	of:			LOG OF TEST BORING	

Location:	Lat.:		Long.:										

Project Type: Rock Slope Research | Units: Eng | Datum: | | **Date:** | Start: | | Finish: | | |

Water: Seepage (▽): | Prior to Addition(▼): | Completion(▽): | Extended Readings: | Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)		Slake Durability Index (%)	ODOT Class.
	101.0											
	102.0	Shale: Green, slightly strong (field investigation), contains siltstone inter-layers; RQD = 100%										
	103.0											
	104.0											
	105.0			100%		100%						
	106.0	Sandstone: Grey, strong, micaceous; RQD = 100%										
	107.0											
	108.0	Shale: Green, weak, slightly strong; RQD = 100%						#15	1381		87	
	109.0											
	110.0	Claystone/mudstone (redbeds): Red, very weak (field investigation); RQD = 100%										
	111.0											
	112.0											
	113.0											
	114.0											
	115.0	Shale: Dark green, weak (field investigation), contains minor redbed inter-layers; RQD = 86%		86%		95%						
	116.0											
	117.0											
	118.0											
	119.0											
	120.0											

Site		BEL-7-10			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)		Slake Durability Index (%)		ODOT Class.
	121.0	Shale: Dark green, weak (field investigation); RQD = 88%											
	122.0												
	123.0	Limestone: Yellow, very strong; RQD = 100%											
	124.0							#16	20588		100		
	125.0			98%		100%							
	126.0							#17	3811		95		
	127.0												
	128.0												
	129.0												
	130.0												
	131.0	Shale: Dark green, moderately strong; RQD = 90%											
	132.0												
	133.0												
	134.0							#18	13612		98		
	135.0	Limestone: Yellow, very strong; RQD = 40 %		68%		100%							
	136.0												
	137.0												
	138.0												
	139.0												
	140.0												

Site		**BEL-7-10**			Boring:			Page:	1	of:		LOG OF TEST		
Location:	Lat.:			Long.:								BORING		
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:							Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	141.0										
	142.0	Claystone/mudstone: Dark grey, moderately strong; RQD = 73%						#19	2139	5	
	143.0										
	144.0										
	145.0	Coal		93%		100%					
	146.0										
	147.0										
	148.0										
	149.0										
	150.0										
	151.0	Sandstone: Grey, very strong, fine to medium grained; RQD = 100%									
	152.0										
	153.0										
	154.0										
	155.0			97%		98%					
	156.0							#20	18087	99	
	157.0										
	158.0										
	159.0	Shale: Dark grey, slightly strong, contains minor silty inter-layers						#21	2660	87	
	160.0										

Site		BEL-7-10			Boring:			Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:			Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)		Slake Durability Index (%)	ODOT Class.
	161.0											
	162.0	Shale: Dark green, weak, contains limestone clasts; RQD = 81%										
	163.0											
	164.0											
	165.0	Limestone: Yellow, very strong (field investigation); RQD = 100%		90%		100%						
	166.0											
	167.0							#22	4204		89	
	168.0	Shale: Dark green, moderately strong; RQD = 94%										
	169.0											
	170.0											
	171.0											
	172.0											
	173.0											
	174.0							#23	4444		98	
	175.0	Calcareous shale: Green, moderately strong, contains limestone clasts; RQD = 92%		92%		100%						
	176.0											
	177.0											
	178.0											
	179.0											
	180.0											

Site		BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST

Site | | **BEL-7-10** | | | **Boring:** | | **Page:** 1 | **of:** | | **LOG OF TEST BORING**

Location:	Lat.:		Long.:		
Project Type: Rock Slope Research	Units: Eng	Datum:		**Date:** Start:	Finish:
Water: Seepage (▽:	Prior to Addition(▼.	Completion(▽.	Extended Readings:		Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	181.0										
	182.0	Claystone/mudstone: Green, slightly strong, contains limestone clasts; RQD = 93%									
	183.0							#24	2492	71	
	184.0										
	185.0	Sandstone: Grey, strong; RQD = 100%		100%		100%		#25	15520	99	
	186.0										
	187.0							#26	3099	97	
	188.0										
	189.0										
	190.0	Shale: Green, slightly strong, contains minor siltstone inter-layers; RQD = 100%									
	191.0										
	192.0										
	193.0										
	194.0										
	195.0			97%		97%					
	196.0	Limestone: RQD = 100%									
	197.0										
	198.0										
	199.0	Claystone/mudstone: Green, weak; RQD = 100%						#27	1013	33	
	200.0										

Site			BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:			Date:	Start:			Finish:		
Water: Seepage (▽:			Prior to Addition(▼:			Completion(▽		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	201.0										
	202.0	Shale: Green, weak; RQD = 74%									
	203.0										
	204.0										
	205.0										
	206.0										
	207.0										
	208.0										
	209.0			87%		100%					
	210.0							#28	16829		
	211.0	Limestone: Dark grey, very strong; RQD = 100%								100	
	212.0							#29	3038		
	213.0	Shale: Green, slightly strong								71	
	214.0										
	215.0			92%		100%					
	216.0	Limestone: Light grey, contains minor green shale									
	217.0										
	218.0										
	219.0	Shale: Green weak greenish; RQD = 74%									
	220.0	Sandstone									

Site		BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location:	Lat.:		Long.:			

Project Type: Rock Slope Research | Units: Eng | Datum: | Date: | Start: | Finish: |

Water: Seepage (▽: | Prior to Addition(▼. | Completion(▽ | Extended Readings: | Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	221.0										
	222.0	Shale: Dark green, weak (field investigation); RQD = 100%									
	223.0										
	234.0										
	225.0										
	226.0										
	227.0	Limestone: Greyish yellow, very strong (field investigation)									
	228.0										
	229.0	Shale: Green; RQD = 100%		100%		100%					
	230.0							#30	25669	100	
	231.0										
	232.0	Limestone: Greyish yellow, very strong; RQD = 100%									
	233.0										
	234.0										
	235.0			98%		100%					
	236.0	Shale: Green; RQD = 0%									
	237.0										
	238.0	Limestone: Greyish yellow									
	239.0										
	240.0										

Site		BEL-7-10			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	241.0										
	242.0										
	243.0	Claystone/mudstone: Green, slightly strong; RQD = 48%						#31	2411		
	244.0									72	
	245.0			89%		97%					
	246.0										
	247.0	Limestone : Greyish yellow, strong; RQD = 100%									
	248.0	Shale: Green; RQD = 100%									
	249.0										
	250.0							#32	12566		
	251.0									99	
	252.0	Limestone: Greyish yellow, strong; RQD = 100%									
	253.0										
	254.0										
	255.0			100%		98%					
	256.0										
	257.0										
	258.0	Shale: Green, weak (field investigation); RQD = 93%									
	259.0										
	260.0										

Site		**BEL-7-10**				**Boring:**		**Page:**	**1**	**of:**		**LOG OF TEST BORING**		
Location:		Lat.:		Long.:										
Project Type:		Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:		Finish:					
Water:	Seepage ( ):		Prior to Addition( ):		Completion( )		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	*MATERIAL DESCRIPTION* *And Notes*	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	261.0										
	262.0										
	263.0										
	264.0										
	265.0	Limestone: Greyish limestone, strong (field investigation), desiccation cracks observed; RQD = 100%		98%		100%					
	266.0										
	267.0										
	268.0										
	269.0										
	270.0	Shale: Green, weak (field investigation); RQD = 100%									
	271.0										
	272.0										
	273.0										
	274.0										
	275.0			100%		100%		#33	8036		
	276.0	Limestone: Greyish yellow, strong, desiccation cracks observed; RQD = 100%								99	
	277.0										
	278.0										
	279.0										
	280.0										

Site		BEL-7-10			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:		Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽:			Prior to Addition(▼:		Completion(▽		Extended Readings:						Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	281.0										
	282.0										
	283.0										
	284.0	Limestone bearing desiccation cracks: Greyish yellow, strong, desiccation cracks observed; RQD = 100%									
	285.0			100%		100%					
	286.0										
	287.0										
	288.0	Shale: Green, contains limestone clasts									
	289.0										
	290.0	290 ft End of Hole									
	291.0										
	292.0										
	293.0										
	294.0										
	295.0										
	296.0										
	297.0										
	298.0										
	299.0										
	300.0										

Site		BEL-70-22			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:		Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	3/31/2008	Finish:	4/2/2008			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation 1240 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0										
	7.0										
	8.0										
	9.0										
	10.0										
	11.0	Light yellow clayey soil used as fill material for paving the parking lot									
	12.0										
	13.0										
	14.0										
	15.0										
	16.0										
	17.0										
	18.0										
	19.0										
	20.0										

Site		BEL-70-22			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:		Lat.:		Long.:									
Project Type:		Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	21.0										
	22.0	Light yellow clayey soil used as fill material for parking lot									
	23.0										
	24.0							#1	11225		
	25.0									98	
	26.0	Sandstone: Grey, slightly weathered, moderately strong to strong, massive 23-25.5 ft and the rest being micaceous; highly fractured down to 34 ft; RQD = 62 %		62%		100%					
	27.0										
	28.0										
	29.0							#2	6518		
	30.0									96	
	31.0										
	32.0										
	33.0										
	34.0										
	35.0			36%		67%		#3	NT		
	36.0									31	
	37.0	Clayey material: Dark grey, soil like behavior									
	38.0										
	39.0	Sandstone: Grey; highly fractured									
	40.0										

Site		BEL-70-22			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:										
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	41.0										
	42.0	Shale: Dark grey, very weak, a redbed inter-layer is observed; RQD = 65%									
	43.0							#4	667	63	
	44.0										
	45.0			69%		98%					
	46.0										
	47.0	Limestone: Yellow, very strong (field investigation); RQD = 79%									
	48.0										
	49.0										
	50.0										
	51.0										
	52.0										
	53.0										
	54.0										
	55.0	Limestone: Yellow, very strong (field investigation), highly fractured; RQD = 5%		38%		48%					
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

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Site		BEL-70-22			Boring:		Page:	1	of:	LOG OF TEST BORING	

Location:	Lat.:		Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:		
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
61.0										
62.0										
63.0										
64.0										
65.0			70%		95%		#5	417		
66.0	Shale: Dark grey, very weak; RQD = 70%								97	
67.0										
68.0										
69.0										
70.0										
71.0										
72.0										
73.0										
74.0										
75.0			83%		98%					
76.0							#6	23113		
77.0	Limestone: Dark brown, very strong; RQD = 72%								100	
78.0										
79.0	Clayey material: Dark grey shale, very weak									
80.0							#7	NT	11	

Site		BEL-70-22			Boring:			Page:	1	of:			LOG OF TEST BORING		
Location:	Lat.:			Long.:											
Project Type:	Rock Slope Research		Units: Eng	Datum:		Date:	Start:			Finish:					
Water:	Seepage (▽):			Prior to Addition (▼):		Completion (▽):		Extended Readings:							Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	81.0										
	82.0										
	83.0							#8	1732		
	84.0									93	
	85.0			77%		97%					
	86.0	Shale: Dark grey shale, slightly strong; RQD = 77%									
	87.0										
	88.0										
	89.0										
	90.0										
	91.0										
	92.0										
	93.0	Coal									
	94.0										
	95.0	Shale: Dark grey, weak (field investigation); RQD = 76%		50%		97%					
	96.0										
	97.0										
	98.0										
	99.0										
	100.0	Coal									

Site		BEL-70-22			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	101.0										
	102.0	Coal									
	103.0										
	104.0			70%		98%					
	105.0										
	106.0										
	107.0	Shale: Dark grey, weak (field investigation); RQD = 90%									
	108.0										
	109.0							#9	11508	86	
	110.0										
	111.0	Minor inter-layers of greenish shale are observed									
	112.0										
	113.0			67%		98%		#10	16619		
	114.0										
	115.0	Limestone: Yellow, very strong (field investigation); highly fractured, RQD = 68 %									
	116.0										
	117.0										
	118.0										
	119.0										
	120.0										

Site		**BEL-70-22**			Boring:		Page:	1	of:	**LOG OF TEST BORING**	

Location:	Lat.:		Long.:								
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	121.0										
	122.0	Claystone/mudstone: Green, slightly strong; RQD = 82%						#11	2043		
	123.0										
	124.0					100%					
	125.0	Siltstone: Grey, siltstone, moderately strong, micaceous with limestone clasts; RQD = 100%		93%				#12	11809	98	
	126.0										
	127.0	Shale: Grey, moderately strong, with limestone clasts; RQD = 96%									
	128.0							#13	2019		
	129.0										
	130.0										
	131.0										
	132.0										
	133.0							#14	4036	98	
	134.0	Siltstone: Grey, moderately strong, micaceous with minor shale inter-layers; RQD = 100%		83%		95%					
	135.0										
	136.0										
	137.0							#15	1520	88	
	138.0										
	139.0	Shale: Dark grey, weak; RQD = 48%									
	140.0										

Site		BEL-70-22			Boring:		Page:	1	of:	LOG OF TEST BORING		
Location:	Lat.:			Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	141.0										
	142.0	Shale: Dark grey, weak; RQD = 58%									
	143.0										
	144.0			73.20%		95%					
	145.0										
	146.0	Limestone: Light grey, very strong (field investigation)									
	147.0							16	NT	NT	
	148.0										
	149.0										
	150.0										
	151.0										
	152.0										
	153.0										
	154.0										
	155.0										
	156.0										
	157.0										
	158.0										
	159.0										
	160.0										

Site		CLA-68-6.79			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	2/25/2008	Finish:	2/26/2008		
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Elevation 940 ft. +/-									
	1.0	Stiff brown silt and clay, slightly organic, damp									
	2.0	Loose, brown, fine to medium grained sand, slightly organic, damp									
	3.0										
	4.0	Medium dense, gray with light brown stone fragments with sand, damp									
	5.0										
	6.0										
	7.0										
	8.0	Very dense stone fragments with sand and silt, damp									
	9.0										
	10.0										
	11.0	Limestone: Light grey, weathered, strong to very strong, very fine to fine crystalline, medium to very thick bedded, fossiliferous, vuggy , fractured to intact		0		92%					
	12.0							#1	9568	99	
	13.0										
	14.0	13.9 ft clay seam									
	15.0										
	16.0			70%		99%					
	17.0										
	18.0										
	19.0										
	20.0										

Site		CLA-68-6.79			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	21.0	Limestone: light grey, moderately to slightly weathered, strong to very strong, very fine to fine crystalline, medium to very thick bedded, fossiliferous, vuggy; fractured to intact		70%		99%					
	22.0			100%		100%					
	23.0	plugged off while coring at 21ft									
	24.0										
	25.0										
	26.0										
	27.0			95%		100%		#2	10697	99	
	28.0										
	29.0										
	30.0										
	31.0	30.3-31.8 ft moderately weathered high angle fracture									
	32.0										
	33.0										
	34.0										
	35.0										
	36.0			98%		100%					
	37.0	37 ft medium reddish brown clay infilled vug									
	38.0										
	39.0										
	40.0	39.2-40.1 ft high angle fracture 40 ft becomes slightly styolitic; lost water									

Site		CLA-68-6.79			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	41.0	Limestone: light grey, moderately to slightly weathered, strong to very strong, very fine to fine crystalline, medium to very thick bedded, fossiliferous, vuggy; fractured to intact		98%		100%					
	42.0										
	43.0							#3	18926	99	
	44.0										
	45.0										
	46.0										
	47.0			90%		100%					
	48.0										
	49.0	Limestone: Bluish grey, slightly weathered, very strong, very thick bedded, styolitic, slightly argillaceous, intact									
	50.0										
	51.0										
	52.0	Bottom of boring 52.0 ft									
	53.0										
	54.0										
	55.0										
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

Site		CLE-275-5.25			Boring:			Page:	1	of:			LOG OF TEST BORING		
Location:	Lat.:		Long.:												
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	4/9/2008	Finish:	4/9/2008					
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water			

Elev.	Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength(Psi)	Slake Durability Index (%)	
		Elevation 740 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0	Brown Silty Clay									
	7.0										
	8.0										
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0										
	15.0										
	16.0										
	17.0	Began Core at 16.8 ft.									
	18.0	Grey claystone/mudstone (90%) and Limestone (10%): Claystone/mudstone: Grey, severely weathered, very weak (field investigation)		0%			39%		Shale washed away to 43.9 ft		
	19.0										
	20.0	Limestone: Grey, moderately strong (field investigation), very thinly bedded; fractured									

Site		CLE-275-5.25			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:		Lat.:		Long.:								
Project Type:		Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	*MATERIAL DESCRIPTION* *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength(Psi)	Slake Durability Index (%)	ODOT Class.
	21.0	Grey claystone/mudstone (90%) and limestone (10%):									
	22.0	Claystone/mudstone: Grey, severly weathered, very weak (field investigation)									
	23.0	Limestone: Grey, moderately strong (field investigation), very thinly bedded; fractured to highly fractured		0		39					
	24.0										
	25.0										
	26.0										
	27.0			0		18%					
	28.0										
	29.0										
	30.0										
	31.0										
	32.0			0		12%					
	33.0										
	34.0										
	35.0										
	36.0										
	37.0			0		24%					
	38.0										
	39.0										
	40.0			0		10%					

Site		CLE-275-5.25			Boring:		Page:	1	of:	LOG OF TEST BORING		
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength(Psi)	Slake Durability Index (%)	
	41.0			0		10%					
	42.0										
	43.0										
	44.0										
	45.0	Grey mudstone/claystone (60%) and Limestone (40%):		76%		92%		#1	Lst - 24413 Sh - 298	Sh - 28	
	46.0	Claystone/mudstone: Grey to dark grey, moderately weathered, very weak, very thinly bedded; moderately fractured to fractured						#2	694	32	
	47.0	Limestone: Grey, very strong, thinly bedded, fossiliferous									
	48.0										
	49.0										
	50.0			58%		100%					
	51.0										
	52.0										
	53.0										
	54.0										
	55.0			58%		100%					
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

Site		CLE-275-5.25			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength(Psi)	Slake Durability Index (%)	ODOT Class.
	61.0										
	62.0	Grey mudstone/claystone (60%) and Limestone (40%):									
	63.0	Claystone/mudstone: Grey to dark grey, moderately weathered, very weak, very thinly bedded;									
	64.0	moderately fractured to fractured		58%		100%					
	65.0	Limestone: Grey, very strong, thinly bedded, fossiliferous									
	66.0										
	67.0			62%		100%					
	68.0										
	69.0										
	70.0	Bottom of Hole 70.0 ft.									
	71.0										
	72.0										
	73.0										
	74.0										
	75.0										
	76.0										
	77.0										
	78.0										
	79.0										
	80.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:			Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	5/29/2008	Finish:	6/2/2008			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
		Elevation 990 ft +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0										
	7.0										
	8.0	Auger through soil to 15.5 ft									
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0										
	15.0										
	16.0	Shale: Brown to tan variegated, highly weathered, arenaceous									
	17.0										
	18.0			37%		100%					
	19.0	calcareous at 18.3 ft									
	20.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:			LOG OF TEST BORING		
Location:	Lat.:		Long.:											
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water		

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
								Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
21.0			37%		100%					
22.0	Claystone/mudstone: Brown to tan, moderately weathered, arenaceous, slightly ferruginous									
23.0										
24.0										
25.0	At 25 ft high angle joint									
26.0			44		100%					
27.0										
28.0										lost H$_2$O
29.0	3 in sandstone layer at 29 ft									
30.0	At 29.5 ft high angle joint									
31.0										
32.0										
33.0										
34.0	Becomes grey from 33.5-33.8 ft At 33.8 ft becomes brown and tan									
35.0										
36.0	At 35.4 ft highly fractured		51%		100%					
37.0	At 36.5 ft vertical jointing									
38.0										
39.0	Claystone/mudstone: Black, slightly weathered, very weak, carbonaceous; fractured						#1	332	45	
40.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:	**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	41.0			51%		100%		#1	290	45	
	42.0	Claystone/mudstone: Black, slightly weathered, very weak, carbonaceous; fractured									
	43.0										
	44.0										
	45.0										
	46.0			67%		100%					
	47.0										
	48.0										
	49.0										
	50.0										
	51.0										
	52.0										
	53.0										
	54.0	Coal									
	55.0	Black underclay									
	56.0	Claystone/mudstone: Grey, weak to very weak (field investigation)		48%		97%					
	57.0										
	58.0	Very weak clayey material						#2	NT	0	
	59.0										
	60.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	61.0			48%		97%					
	62.0	Claystone/mudstone: Grey, slightly weathered, weak to very weak (field investigation), slickensides observed									
	63.0										
	64.0	Becomes grey and red mottled									
	65.0							#3	NT		
	66.0			61%		100%				2	
	67.0										
	68.0										
	69.0	Becomes grey; slightly strong									
	70.0										
	71.0										
	72.0	Shale: Dark grey, weak, laminated, arenaceous, slickensides observed									
	73.0										
	74.0							#4	909		
	75.0										
	76.0	75.5 ft vertical and high angle fracture		65%		100%				89	
	77.0										
	78.0	Claystone/mudstone: Red, yellow, grey mottled, very weak, calcareous, slickensides observed									
	79.0	77.5 ft becomes red, yellow, grey mottled, very weak (field investigation)									
	80.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:		Lat.:		Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	81.0			65%		100%					
	82.0	Claystone/mudstone: Red, yellow, grey mottled, very weak, calcareous, slickensides observed									
	83.0							#5	616		
	84.0									19	
	85.0										
	86.0	Shale: Grey-green, moderately weathered laminated, arenaceous		81%		99%					
	87.0										
	88.0										
	89.0										
	90.0										
	91.0										
	92.0	91-92 ft high angle joints									
	93.0										
	94.0							#6	848		
	95.0									87	
	96.0			98%		100%					
	97.0	3 in brown sandstone at 97.5 ft									
	98.0										
	99.0										
	100.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:			LOG OF TEST BORING		
Location:	Lat.:		Long.:											
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:					
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	101.0			98%		100%					
	102.0	Sandstone: Grey, moderately strong, fine grained, micaceous									
	103.0							#7	6433	97	
	104.0										
	105.0										
	106.0			100%		100%					
	107.0	Becomes medium grained									
	108.0										
	109.0										
	110.0	Becomes fine grained									
	111.0										
	112.0	Becomes medium grained clay seam at 112.3 ft									
	113.0										
	114.0										
	115.0	Cross bedding at 115.3 ft									
	116.0			100%		100%					
	117.0										
	118.0							#8	6760	96	
	119.0										
	120.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:			LOG OF TEST BORING	
Location:		Lat.:		Long.:									
Project Type:		Rock Slope Research	Units: Eng	Datum:		Date:	Start:			Finish:			
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	121.0	Sandstone: Grey, moderately strong, fine grained, micaceous		100%		100%					
	122.0										
	123.0										
	124.0										
	125.0										
	126.0			100%		100%					
	127.0										
	128.0										
	129.0										
	130.0										
	131.0										
	132.0										
	133.0										
	134.0										
	135.0										
	136.0			66%		99%					
	137.0	Shale: Grey, slightly weathered, carbonaceous, slickensides observed									
	138.0	Coal									
	139.0	Underclay: Brown and grey, very weak (field investigation), carbonaceous						#9			
	140.0										

Site		GUE-77-8.2			Boring:		Page:	1	of:			LOG OF TEST		
Location:	Lat.:			Long.:								BORING		
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:						Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
141.0			66%		99					
142.0	Sandstone: Grey, moderately strong, fine grained, micaceous						#9			
143.0										
144.0									0.1	
145.0										
146.0			97		98					
147.0							#10	6538	97	
148.0										
149.0										
150.0	End of boring at 150 ft.									
151.0										
152.0										
153.0										
154.0										
155.0										
156.0										
157.0										
158.0										
159.0										
160.0										

Site			HAM-126-12.08			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:		Lat.:			Long.:									
Project Type:		Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	4/7/2008	Finish:	4/8/2008			
Water:	Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation 760 ft. +/-									
	1.0										
	2.0										
	3.0										
	4.0										
	5.0										
	6.0										
	7.0	Light brown silty clay fill material, occasional gravel									
	8.0										
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0										
	15.0										
	16.0	Limestone: Grey-brown, moderately weathered, strong, fossiliferous							Lst - 11616	NT	
	17.0			24%		56%		#2			
	18.0	Claystone/mudstone: Grey, slightly weathered, slightly strong, calcareous, fissile; friable, slightly fractured							severe weathering to 18.4 ft		
	19.0								Sh - 1475		
	20.0			80%		100%				Sh-66	

Site		HAM-126-12.08			Boring:		Page:	1	of:		LOG OF TEST BORING	

Location:	Lat.:		Long.:								
Project Type:	Rock Slope Research	Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:				Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	21.0	Claystone/mudstone: Grey, slightly weathered, weak, calcareous									
	22.0			80%		100%					
	23.0										
	24.0										
	25.0										
	26.0										
	27.0										
	28.0										
	29.0			49%		89%					
	30.0										
	31.0										
	32.0	Limestone (70%) inter-bedded with shale (30%): Grey to brown									
	33.0										
	34.0										
	35.0										
	36.0										
	37.0			57%		100%					
	38.0	6 in brown soil like material, lost water									
	39.0										
	40.0										

Site		HAM-126-12.08			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:		
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Limestone (70%) inter-bedded with shale (30%): Grey to brown									
	41.0			57%		100%					
	42.0										
	43.0										
	44.0										
	45.0	Limestone (60%) inter-bedded with shale (40%): Grey to brown									
	46.0										
	47.0										
	48.0										
	49.0										
	50.0			53%		100%					
	51.0										
	52.0										
	53.0										
	54.0										
	55.0										
	56.0										
	57.0	Iron staining at 57 ft		65%		100%					
	58.0										
	59.0										
	60.0										

Site		HAM-126-12.08			Boring:			Page:	1	of:		LOG OF TEST BORING	

Location: Lat.:   Long.:

Project Type: Rock Slope Research   Units: Eng   Datum: **Date:**   Start: Finish:

Water: Seepage (▽):   Prior to Addition(▼):   Completion(▽)   Extended Readings: Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
61.0										
62.0			65%		100%					
63.0										
64.0	6 in vertical fracture in core, weathered fracture									
65.0	Limestone (60%) inter-bedded with claystone/mudstone (40%):						#3	Lst - 17496		
66.0	Limestone: Grey, very strong Claystone/mudstone: Grey, slightly strong							Sh - 1956	Sh-24	
67.0										
68.0										
69.0										
70.0			49%		100%					
71.0										
72.0										
73.0								Lst - 20563		
74.0							#1			
75.0								Sh -426		
76.0									Sh-21	
77.0	Limestone (50%) inter-bedded with claystone/mudstone (50%):		58%		100%					
78.0	Limestone: Grey, very strong									
79.0	Claystone/mudstone: Grey, very weak									
80.0										

Site		HAM-126-12.08			Boring:		Page:	1	of:	LOG OF TEST BORING	
Location:	Lat.:		Long.:								
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:		
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:			Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	81.0	Limestone (50%) inter-beddedand claystone/mudstone/ (50%):									
	82.0	Limestone: Grey, very strong Claystone/mudstone: Grey, very weak		58%		100%					
	83.0										
	84.0										
	85.0	Limestone (55%) inter-bedded with									
	86.0	claystone/mudstone (45%)									
	87.0										
	88.0										
	89.0			43%		100%					
	90.0										
	91.0										
	92.0										
	93.0										
	94.0										
	95.0	Limestone (60%) inter-bedded with									
	96.0	claystone/mudstone (40%): Limestone: Grey, very strong Claystone/mudstone: Grey, weak									
	97.0			79%		100%					
	98.0							#4	Lst - 15849	NT	
	99.0								Sh - 1316		
	100.0	End of boring 100.0 ft								Sh-24	

Site		LAW-52-11			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:		Long.:										
Project Type: Rock Slope Research		Units: Eng	Datum:		Date:	Start:	2/24/2008	Finish:	2/26/2008				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	1.0	Elevation = 650ft									
	2.0										
	3.0										
	4.0	Soil									
	5.0										
	6.0										
	7.0										
	8.0										
	9.0										
	10.0										
	11.0										
	12.0										
	13.0										
	14.0	Highly to severly weathered sandtone and shale									
	15.0										
	16.0										
	17.0										
	18.0										
	19.0										
	20.0										

Site		LAW-52-11			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type: Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	21.0										
	22.0										
	23.0	Highly to severly weathered sandtone and shale									
	24.0										
	25.0										
	26.0										
	27.0	Sandtstone: Grey, slightly weathered, weak (field investigation), highly fractured; RQD = 44%									
	28.0										
	29.0										
	30.0			44%	37%						
	31.0										
	32.0										
	33.0	Clayey material with low recovery									
	34.0										
	35.0										
	36.0										
	37.0										
	38.0	Claystone/mudstone: Dark grey, slightly weathered, very weak		96%	96%			#1	833	12	
	39.0										
	40.0										

Site		**LAW-52-11**				**Boring:**		**Page:**	**1**	**of:**			**LOG OF TEST BORING**	
Location:	Lat.:			Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water:	Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	41.0										
	42.0	Claystone/mudstone: Dark, slightly weathered, very weak									
	43.0			96%		96%					
	44.0										
	45.0										
	46.0										
	47.0										
	48.0	Claystone/mudstone: Dark, slightly weathered, slightly strong (field investigation); RQD = 91%									
	49.0										
	50.0			96%		100%					
	51.0										
	52.0										
	53.0	Claystone/mudstone: Green slightly weathered, slightly strong; RQD = 100%									
	54.0										
	55.0							#2	1651		
	56.0									69	
	57.0							#3	1263		
	58.0	Claystone/mudstone: Grey, weak; highly fractured, RQD = 21%		82%		100%				73	
	59.0	56-58 ft; RQD = 21%									
	60.0	58-66 ft; RQD = 83%						#4	2102	81	

Site		LAW-52-11			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type: Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev. / Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
61.0			82%		100%					
62.0										
63.0										
64.0										
65.0	Shale: Dark green, slightly strong; RQD = 83%									
66.0										
67.0			77%		100%					
68.0	Shale: Grey, slightly strong (field investigation); highly fractured, RQD = 17%									
69.0										
70.0										
71.0										
72.0							#5	12097		
73.0	Sandstone: Grey, strong, micaceous; RQD = 100%								96	
74.0										
75.0	Shale: Grey, weak; RQD = 100%						#6	1341	84	
76.0										
77.0	Sandstone: Very strong; RQD = 100%		97%		100%		#7	16719	98	
78.0	Shale: Grey, very weak, micro fractures present; RQD = 89%									
79.0	Limestone: Greyish yellow; RQD = 100%									
80.0							#8	1498	76	

Site		LAW-52-11			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
	81.0	Shale: Grey, weak, micro fractures present; RQD = 92%						#8	1498	76	
	82.0										
	83.0	Sandstone: Strong; RQD = 100%		97%		100%					
	84.0										
	85.0	Shale: Grey, slightly strong; RQD = 100%						#9	1629	89	
	86.0										
	87.0	Shale: Grey, moderately weathered; RQD = 85%									
	88.0										
	89.0							#10	1373	82	
	90.0			91%		96%					
	91.0	Sandstone: Grey, Strong; RQD = 100%									
	92.0										
	93.0	Shale: Grey, slightly strong with one 4 in thick limestone						#11	1630	93	
	94.0										
	95.0										
	96.0										
	97.0	Sandstone: Grey, strong, micaceous; RQD = 100%						#12	12233	97	
	98.0			93%		100%					
	99.0										
	100.0	Shale: Grey, slightly strong, contains minor limestone inter-layers; RQD = 79%						#13	1710	89	

Site		LAW-52-11			Boring:			Page:	1	of:		LOG OF TEST BORING	

Location: Lat.: Long.:

Project Type: Rock Slope Research Units: Eng Datum: **Date:** Start: Finish:

Water: Seepage (▽): Prior to Addition(▼): Completion(▽): Extended Readings: Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
								Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
101.0										
102.0	Shale: Grey, slightly strong, contains minor limestone inter-layers; RQD = 79%		93%		100%					
103.0										
104.0										
105.0										
106.0										
107.0	Shale: Grey, weak; RQD = 100%									
108.0							#14	1454	89	
109.0										
110.0			66%		67%					
111.0										
112.0	Clayey material									
113.0										
114.0										
115.0										
116.0	112.8-116 ft core loss									
117.0	Clayey material									
118.0	Sandstone: Greyish brown, slightly weathered, moderately strong		87%		100%		#15	7440	92	
119.0										
120.0										

434

Site		LAW-52-11			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type: Rock Slope Research			Units: Eng	Datum:		Date:	Start:			Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen./RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
121.0										
122.0										
123.0			87%		100%					
124.0										
125.0										
126.0										
127.0	Sandstone: Brownish grey, slightly weathered, moderately strong, massive, medium to coarse grained; RQD = 100%									
128.0										
129.0										
130.0			100%		100%					
131.0							#16	7192	94	
132.0										
133.0										
134.0										
135.0										
136.0										
137.0										
138.0			100%		100%					
139.0										
140.0										

Site		LAW-52-11			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	141.0										
	142.0										
	143.0										
	144.0										
	145.0										
	146.0										
	147.0	Sandstone: Brownish grey, slightly weathered, moderately strong, massive and not micaceous, medium to coarse grained; RQD									
	148.0	= 100%		100%		100%					
	149.0										
	150.0										
	151.0										
	152.0										
	153.0										
	154.0										
	155.0										
	156.0										
	157.0										
	158.0										
	159.0										
	160.0	Coal									

Site		LAW-52-11			Boring:		Page:	1	of:			LOG OF TEST BORING	

Location: Lat.: Long.:

Project Type: Rock Slope Research Units: Eng Datum: **Date:** Start: Finish:

Water: Seepage (▽): Prior to Addition(▼): Completion(▽) Extended Readings: Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
								Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	
161.0										
162.0	Claystone/mudstone: Grey, weak; RQD = 74%									
163.0							#17	1454		
164.0									17	
165.0										
166.0										
167.0	Shale: Grey, slightly strong; RQD = 100%						#18	2855	85	
168.0										
169.0							#19	10718		
170.0									97	
171.0	Shale: Grey, moderately strong, contains siltstone inter-layers		95%		100%					
172.0										
173.0										
174.0										
175.0	Sandstone									
176.0										
177.0	Shale: Grey, slightly strong; RQD = 100%						#20	1705	86	
178.0	Limestone: Dark grey, very strong (field investigation), contains desiccation cracks		87%		100%					
179.0										
180.0										

437

Site		LAW-52-11			Boring:			Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:		Long.:											
Project Type: Rock Slope Research		Units: Eng	Datum:		Date:	Start:		Finish:						
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	181.0										
	182.0										
	183.0	Limestone: Dark grey, very strong (field investigation), contains desiccation cracks		87%		100%					
	184.0										
	185.0										
	186.0										
	187.0										
	188.0										
	189.0										
	190.0			100%		100%					
	191.0										
	192.0										
	193.0										
	194.0										
	195.0	Claystone/mudstone: Brownish green, very weak; RQD = 100%						#21	703		
	196.0	End of hole 196 ft								0	
	197.0										
	198.0										
	199.0										
	200.0										

Site		**LIC-16-28.47**		Boring:		Page:	1	of:		**LOG OF TEST BORING**	
Location:	Lat.: 40° 35' 51.30"		Long.: 82° 16' 15.74"								
Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	10/10/2007	Finish:	10/10/2007		
Water: Seepage (▽):		Prior to Addition(▼):		Completion(▽):		Extended Readings:				Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	Elevation 845 ft. +/-									
1.0										
2.0										
3.0										
4.0										
5.0										
6.0										
7.0										
8.0										
9.0										
10.0										
11.0										
12.0	Sandstone: Dark yellow, highly weathered, slightly strong, medium to coarse grained		21%		50%		#1	2064		
13.0									69	
14.0							#2	1179		
15.0									38	
16.0			11%		100%					
17.0										
18.0										
19.0										
20.0										

Site		LIC-16-28.47			Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:									
Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	10/10/2007	Finish:	10/10/2007			
Water: Seepage (▽):			Prior to Addition (▼):		Completion (▽):		Extended Readings:					Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	21.0										
	22.0			11%		100%					
	23.0										
	24.0							#3	5140	93	
	25.0										
	26.0	Sandstone: Dark yellow, highly weathered, slightly strong, medium to coarse grained; moderately fractured									
	27.0										
	28.0			48%		96%					
	29.0										
	30.0										
	31.0										
	32.0										
	33.0										
	34.0										
	35.0										
	36.0			87%		100%					
	37.0										
	38.0										
	39.0										
	40.0										

Site		**LIC-16-28.47**			Boring:		Page:	1	of:		**LOG OF TEST BORING**	
Location:	Lat.:			Long.:								
Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	10/10/2007	Finish:	10/10/2007			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:				Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	41.0			68%		100%					
	42.0										
	43.0										
	44.0	Sandstone: Dark yellow, highly to moderately weathered, slightly strong, medium to coarse grained; moderately fractured						#4	3318	85	
	45.0										
	46.0										
	47.0			68%		100%					
	48.0										
	49.0										
	50.0										
	51.0										
	52.0										
	53.0										
	54.0										
	55.0										
	56.0										
	57.0										
	58.0										
	59.0										
	60.0										

Site		MEG-33-6.13			Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:	Lat.:			Long.:									
Project Type: Rock Slope Research			Units: Eng	Datum:		**Date:**	Start: 4/23/2008		Finish: 4/23/2008				
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:				Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes			Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
											Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
		Elevation 810 ft. +/-											
	1.0												
	2.0												
	3.0												
	4.0												
	5.0												
	6.0												
	7.0												
	8.0	Shale: Red, clayey material, very soft											
	9.0												
	10.0												
	11.0												
	12.0												
	13.0												
	14.0												
	15.0												
	16.0												
	17.0												
	18.0												
	19.0												
	20.0												

Site		MEG-33-6.13			Boring:		Page:	1	of:	LOG OF TEST BORING	
Location:	Lat.:		Long.:								
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽)		Extended Readings:			Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Sandstone									
	21.0	Shale: Brown, highly weathered									
	22.0	Claystone/mudstone: Grey, weak, laminated,									
	23.0	Sandstone: Grey, moderately strong to strong, micaceous						1	4689		
	24.0									96	
	25.0			82%		100%					
	26.0										
	27.0										
	28.0										
	29.0										
	30.0										
	31.0							3	11600	99	
	32.0										
	33.0										
	34.0										
	35.0			98%		100%					
	36.0										
	37.0										
	38.0	At 37.5 ft becomes argillaceous									
	39.0										
	40.0	Claystone/mudstone: Grey, weak (field investigation), moderately weathered									

Site		**MEG-33-6.13**				**Boring:**		**Page:**	**1**	**of:**		**LOG OF TEST BORING**	
Location:		Lat.:		Long.:									
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Claystone/mudstone: Grey, slightly weathered, arenaceous									
	41.0										
		At 41ft highly weathered, calcareous									
	42.0										
	43.0	At 42.5 ft becomes red, yellow, grey mottled									
	44.0										
	45.0			74%		98%		6	437		
	46.0									24	
	47.0	At 47 ft no longer calcareous									
	48.0										
	49.0	At 49 ft slickensides observed									
	50.0										
	51.0										
	52.0	At 52 ft becomes grey									
	53.0										
		Sandstone: Grey, calcareous, fine grained									
	54.0										
	55.0			87%		99%					
	56.0	Claystone/mudstone: Grey, laminated									
	57.0										
		At 57 ft fractured, possibly bioturbated									
	58.0										
	59.0	Sandstone: Grey, fine grained, micaceous									
	60.0										

Site		MEG-33-6.13			Boring:			Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:										
Project Type:	Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:				
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
	61.0	Claystone/mudstone: Grey, moderately weathered									
	62.0	Sandstone: Grey, slightly weathered, fine grained, micaceous									
	63.0										
	64.0										
	65.0			100%		100%					
	66.0										
	67.0										
	68.0	At 67.5 ft becomes calcareous									
	69.0										
	70.0	Sandstone: Brown, medium grained, non calcareous, slightly ferruginous to 72 ft									
	71.0										
	72.0										
	73.0	At 73.1 ft clay vein									
	74.0										
	75.0			100%		100%					
	76.0	At 75.5 ft becomes micaceous									
	77.0	Calcareous from 76.6 ft to 77.3 ft									
	78.0										
	79.0										
	80.0										

Site		MEG-33-6.13		Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:		Long.:								
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:		Finish:			
Water: Seepage (▽):			Prior to Addition(▼):		Completion(▽):		Extended Readings:			Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
	81.0	Sandstone: Brown, grey, tan, medium grained, slightly ferruginous									
	82.0										
	83.0	At 83.1 ft clay inclusion									
	84.0										
	85.0	At 85 ft becomes micaceous		100%		100%					
	86.0										
	87.0										
	88.0										
	89.0										
	90.0	End of boring at 90 ft									
	91.0										
	92.0										
	93.0										
	94.0										
	95.0										
	96.0										
	97.0										
	98.0										
	99.0										
	100.0										

Site		RIC-30-12.5				Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type: Rock Slope Research		Units: Eng	Datum:		Date:	Start:	1/15/2008	Finish:	1/15/2008				
Water: Seepage (▽):		Prior to Addition(▼):		Completion(▽)		Extended Readings:					Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Elevation 1300 ft. +/-									
	1.0	Aggregate base									
	2.0	Very stiff, dark brown , sandy silt, little clay, few rock fragments									
	3.0										
	4.0										
	5.0	Sandstone: Yellowish orange and white, highly weathered, fine to coarse grained									
	6.0										
	7.0	Sandstone: Yellowish brown and white, moderately weathered, moderately strong, fine to coarse grained, thinly bedded, well cemented with silica, highly to moderately fractured; RQD = 44%		15%		88%					
	8.0										
	9.0										
	10.0										
	11.0								#1	4414	92	
	12.0											
	13.0	12.4 ft contains a 1.1 ft thick clay seam									
	14.0	Sandstone: Yellowish brown and white, moderately weathered, fine to coarse grained, moderately strong, thinly bedded, well cemented with siliceous cement; highly to moderately fractured; RQD = 44%		35%		83%					
	15.0										
	16.0										
	17.0										
	18.0										
	19.0										
	20.0										

Site		RIC-30-12.5				Boring:		Page:	1	of:		LOG OF TEST BORING	
Location:	Lat.:			Long.:									
Project Type: Rock Slope Research			Units: Eng	Datum:		**Date:**	Start:	1/15/2008	Finish:	1/15/2008			
Water: Seepage (▽):			Prior to Addition(▼):			Completion(▽)		Extended Readings:				Drill Fluid: Water	

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)		ODOT Class.
								Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	
21.0			44%		100%					
22.0										
23.0							#2	3019	87	
24.0										
25.0	At 25.4 - 30 ft dark yellowish brown and red									
26.0			49%		94%					
27.0	At 26.5-28 ft highly broken with loss									
28.0	Sandstone: Red, white and yellowish brown,									
29.0	moderately weathered, slightly strong, fine to coarse grained, thinly bedded, well cemented with siliceous									
30.0	cement, highly to moderately fractured; RQD = 44%									
31.0										
32.0										
33.0										
34.0										
35.0										
36.0			47%		98%					
37.0										
38.0										
39.0										
40.0										

Site		RIC-30-12.5			Boring:		Page:	1	of:	LOG OF TEST BORING	
Location:	Lat.:			Long.:							
Project Type: Rock Slope Research		Units: Eng	Datum:		**Date:**	Start:	1/15/2008	Finish:	1/15/2008		
Water: Seepage (▽):			Prior to Addition(▼:		Completion(▽		Extended Readings:				Drill Fluid: Water

Elev. Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD (for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
41.0			47%		98%					
42.0										
43.0							#3	2202	73	
44.0										
45.0			67%		100%					
46.0	Sandstone: Gray, white and yellowish brown, slightly									
47.0	strong, thinly bedded, contains shale layer (10% core),									
48.0	fine to medium grained, highly to moderately fractured; RQD = 69%									
49.0										
50.0	End of hole 50 ft									
51.0										
52.0										
53.0										
54.0										
55.0										
56.0										
57.0										
58.0										
59.0										
60.0										

Site		STA-30-27.1				Boring:			Page:	1	of:		LOG OF BORING		TEST	
Location:		Lat.: 40.765372		Long.: -81.1747729												
Project Type: Rock Slope Research			Units: Eng	Datum:		Date:	Start:	4/9/2008		Finish:	4/14/2008					
Water:	Seepage (▽):		Prior to Addition(▼):		Completion(▽):		Extended Readings:							Drill Fluid: Water		

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake Durability Index (%)	ODOT Class.
		Elevation 1212 ft. +/-									
	1.0										
	2.0	stiff, brown, sandy silt, trace stone fragments, damp		10 14							
	3.0			12	26	14	18				
	4.0			7 11							
	5.0			10	21	18	18				
	6.0										
	7.0	Sandstone: light brown, highly weathered									
	8.0	Sandstone: Yellowish to yellowish brown, highly weathered, slightly strong, fine grained, very thinly to thinly bedded, argillaceous; highly fractured						#2	2240		
	9.0										
	10.0			0%		100%				68	
	11.0										
	12.0	11.6 ft light grey and grey sandstone									
	13.0	Inter-bedded siltstone and shale: Shale: Dark grey, highly weathered, weak (field description), laminated						#1	NT		
	14.0	Siltstone: Light grey, moderately weathered, slightly strong (field description)								82	
	15.0										
	16.0			0%		98%					
	17.0										
	18.0										
	19.0										
	20.0										

Site		STA-30-27.1				Boring:		Page:	1	of:		LOG OF	TEST	
Location:		Lat.:		Long.:								BORING		
Project Type: Rock Slope Research			Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water:	Seepage (▽):		Prior to Addition(▼):			Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	21.0										
	22.0			0%		98%					
	23.0	Sandstone: Yellowish to yellowish brown, highly weathered, slightly strong (field description), fine grained, very thinly to thinly bedded, argillaceous; highly fractured									
	24.0										
	25.0										
	26.0										
	27.0			23%		100%					
	28.0										
	29.0										
	30.0	Shale: Moderately weathered, very weak, laminated to very thin bedded; highly fractured									
	31.0							#3	804		
	32.0	11.6 ft light grey and grey sandstone								80	
	33.0							#4	2394		
	34.0	Shale inter-bedded with siltstone: Dark grey, highly weathered, weak, laminated, siltstone is light grey, moderately weathered, slightly strong								86	
	35.0										
	36.0			24%		100%					
	37.0	36.7-38.1 ft calcareous siltstone / 36.9-37.5 ft limestone, light grey, strong									
	38.0										
	39.0										
	40.0										

Site		STA-30-27.1				Boring:			Page:	1	of:		LOG OF TEST		
Location:		Lat.:		Long.:									BORING		
Project Type: Rock Slope Research			Units: Eng	Datum:		**Date:**	Start:			Finish:					
Water:	Seepage (▽):			Prior to Addition(▼):		Completion(▽):			Extended Readings:						Drill Fluid: Water

Elev.	Depth	MATERIAL DESCRIPTION *And Notes*	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.) Uniaxial Compressive Strength (psi)	Slake DurabilityIndex (%)	ODOT Class.
	41.0			24%		100%					
	42.0										
	43.0							#5	9259		
	44.0									97	
	45.0										
	46.0										
	47.0			34%		100%					
	48.0	Sandstone: light grey to grey, moderately weathered, strong, very fine grained, thinly to medium bedded, argillaceous, micaceous; fractured to moderately fractured									
	49.0										
	50.0										
	51.0										
	52.0										
	53.0										
	54.0										
	55.0										
	56.0			63%		100%					
	57.0							#6	10238		
	58.0									96	
	59.0										
	60.0										

Site		STA-30-27.1				Boring:		Page:	1	of:		LOG OF TEST BORING		
Location:		Lat.:		Long.:										
Project Type: Rock Slope Research			Units: Eng	Datum:		**Date:**	Start:			Finish:				
Water:	Seepage (▽):		Prior to Addition(▼):			Completion(▽)		Extended Readings:					Drill Fluid: Water	

Elev.	Depth	MATERIAL DESCRIPTION And Notes	Strata	Std. Pen. / RQD(for every drilling run)	N Value	Rec.	Pen.	Sample ID	TESTING DATA (Depth - Ft.)			ODOT Class.
									Uniaxial Compressive Strength (psi)	Slake Durability Index (%)		
	61.0			63%		100%						
	62.0											
	63.0											
	64.0											
	65.0	Sandstone: light grey and grey, moderately weathered, moderately strong (field investigation), very fine grained, thinly to medium bedded, argillaceous, micaceous; fractured to moderately fractured										
	66.0											
	67.0			61%		92%						
	68.0											
	69.0											
	70.0											
	71.0											
	72.0	End of boring at 72.0 ft										
	73.0											
	74.0											
	75.0											
	76.0											
	77.0											
	78.0											
	79.0											
	80.0											

RD Grade +/- 94 ft.

APPENDIX 6

RQD AND HARDNESS DATA FOR OUTCROP SAMPLES

Table 6-1: RQD and hardness data for outcrop samples.

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
ADA-32-12	1	Claystone/mudstone	0	S1
	2	Limestone	94.5	R4
	3	Claystone/mudstone		
	3A	Claystone/mudstone		
	4	Limestone		
	5	Claystone/mudstone		
	6	Limestone		
ADA-32-12B	1	Arenaceous Limestone		
	2	Limestone		
	3	Arenaceous Limestone		
	4	Limestone		
ADA-41-15	1	Limestone	96.8	R4
	2	Claystone/mudstone	0	
	3	Claystone/mudstone		
	4	Limestone		
	5	Claystone/mudstone		
	6	Fossiliferous Limestone		
	7	Limestone	96.5	R3
ATH-33-14	1	Sandstone		
	2	Sandstone		
	3	Sandstone		
	4	Sandstone		
	5	Sandstone		
ATH-33-26		Claystone/mudstone		
ATH-50-22	1	Claystone/mudstone	0	S1
	2	Limestone		
	3	Claystone/mudstone		
	4	Limestone		
	5	Claystone/mudstone		
	6	Limestone	100	R4
	7	Limestone		
	8	Claystone/mudstone		
	9	Siltstone		
	10	Sandstone	98.2	R4
	11	Green Shale		
ATH-50-28	1	Claystone/mudstone		

Table 6A-1 (contd.).

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
ATH-50-28	2	Claystone/mudstone		S1
	3	Claystone/mudstone		R4
BEL-470-6	1	Underclay		
	2	Limestone	82	
	4	Claystone/mudstone		
	5	Limestone		
	6	Green Shale		
	7	Limestone		
	8	Limestone		
	1-A	Underclay		
	1-B	Underclay		
	2-A	Limestone		R4
	2-B	Limestone		
	4A	Claystone/mudstone	0	
	4B	Claystone/mudstone		
	5A	Limestone	0	
	5B	Limestone		
	6A	Green Shale		R3
	6B	Green Shale	0	R3
	7A	Limestone	0	
	7B	Limestone		
	8A	Limestone		
BEL-70-1.58	1	Shale		
	2	Claystone/mudstone		
BEL-70-22	1	Dark Grey Shale	0	S1
	2	Sandstone	45.7	
	4	Sandstone	39.9	
	3A	Claystone/mudstone	0	
	3B	Claystone/mudstone		
	4A	Sandstone		R4
	4B	Sandstone		
BEL-7-10	1	Limestone	77.1	
	2	Limestone		
	3	Underclay		R4
	4	Limestone		
	5	Limestone		
	6	Limestone	0	
	7	Limestone		

Table 6A-1 (contd.).

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
BEL-7-10	10	Dark Grey Shale		
CLA-4-8	1	Limestone	80	R4
	2	Limestone		
	3	Limestone		
	4	Limestone		
	5	Limestone		
	6	Limestone		
CLA-68-7	1	Limestone	100	R4
	2	Limestone		
	3	Limestone		
CLE-275-5	1	Limestone	0	R4
	2	Claystone/mudstone	0	S5
	3	Limestone		
	4	Limestone		
	5	Claystone/mudstone		
	6	Limestone		
	7	Limestone		
	8	Claystone/mudstone		
	9	Limestone		
COL-11-16		Dark Grey Shale		
COL-30-30		Dark Grey Shale		
COL-7-3	1	Sandstone		
	2	Claystone/mudstone		
COL-7-5	1	Dark Grey Shale		R2
	2	Sandstone	89.2	R4
	3	Dark Grey Shale		R2
	4	Dark Grey Shale		
	5	Dark Grey Shale		
	#1	Sandstone		
	#3	Sandstone		
	#4	Dark Grey Shale		
	1A	Dark Grey Shale		
FRA-270-23	1	Dark Shale	0	R1
GUE-22-6.9	1	Siltstone	72.9	R3
	2	Dark Grey Shale		S2

Table 6A-1 (contd.).

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
GUE-22-6.9	3	Siltstone	0	
GUE-70-12.9	1	Dark Grey Shale		
GUE-77-21	1	Dark Grey Shale		
GUE-77-8	1	Underclay	0	
	2	Siltstone		
	3	Sandstone	56.3	R2
HAM-126-12	1	Fossileferous Limestone		R4
	2	Fossileferous Limestone		
	3	Fossileferous Limestone		
	4	Fossileferous Limestone		
	5	Fossileferous Limestone		
	6	Fossileferous Limestone		
	7	Fossileferous Limestone		
	8	Fossileferous Limestone		
	9	Claystone/mudstone		S2
HAM-74-6	1	Claystone/mudstone	0	
	2	Fossileferous Limestone	0	R4
	3	Claystone/mudstone	0	S3
	4	Fossileferous Limestone	0	
	5	Claystone/mudstone	0	
	6	Fossileferous Limestone	0	
JEF-22-8	1	Dark Grey Shale		
	1	Shale		
	2	Dark Grey Shale		
	3	Shale		
	4	Shale		

Table 6A-1 (contd.).

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
JEF-7-23	3	Sandstone		
	5	Dark Grey Shale		
JEF-7-6	1	Sandstone		
	2	Claystone/mudstone		
	4	Claystone/mudstone		
JEF-CR77-0.4	1	Sandstone	90.3	R4
	2	Grey Shale	0	S3
	3	Underclay		
LAW-52-11	1	Claystone/mudstone		
	2	Sandstone		
	3	Siltstone		R1
	4	Sandstone	95	R2
	5	Claystone/mudstone		
	6	Sandstone		
	7	Sandstone		
	8	Limestone		
	9	Sandstone		
	10	Claystone/mudstone		
LAW-52-12	1	Sandstone		
	2	Claystone/mudstone		
	3	Claystone/mudstone		
	4	Sandstone		
	5	Sandstone		
	6	Claystone/mudstone		
LIC-16-28	1	Sandstone	86.4	R2
MEG-33-15	1	Claystone/mudstone		S1
	2	Sandstone	100	R2
	3	Sandstone		
	4	Sandstone		
	5	Sandstone		
	6	Claystone/mudstone		
	7	Sandstone		
	8	Sandstone		
	9	Claystone/mudstone		
	10	Claystone/mudstone		
MEG-33-6	1	Claystone/mudstone		
	2	Claystone/mudstone		S2

Table 6A-1 (contd.).

Site	Sample No.	Rock Type	Field RQD (%)	Hardness
MEG-33-6	3	Siltstone		R1
	4	Sandstone	60.6	R4
	5	Claystone/mudstone		
	6	Sandstone		
	7	Sandstone		
	8	Siltstone		
	9	Siltstone		
MUS-70-11	1A	Dark Grey Shale		
	1	Dark Grey Shale		S5
	2	Sandstone	100	R4
	3	Sandstone		
	4	Dark Grey Shale		
		Dark Grey Shale		
	6	Sandstone		
MUS-70-25	1	Claystone/mudstone		
RIC-30-12	1	Sandstone	75.4	R3
	2	Sandstone		
STA-30-27	1	Dark Grey Shale		R1
	2	Sandstone		R3
	3	Sandstone		
TUS-77-03	1	Dark Grey Shale		
	2	Dark Grey Shale		
WAS-7-18	1	Sandstone	100	R4
	2	Claystone/mudstone		S1
	3	Sandstone		
	4	Claystone/mudstone		
	5	Sandstone		
	6	Claystone/mudstone		
	7	Shale		
	8	Sandstone		
	9	Claystone/mudstone		
	10	Claystone/mudstone		
	11	Sandstone		
WAS-77-15	2	Claystone/mudstone		
	3	Claystone/mudstone		

APPENDIX 7

DISCONTINUITY DATA

APPENDIX 7-A

DISCONTINUITY DATA
(DIP AMOUNT, DIP DIRECTION, APERTURE, CONTINUITY, AND
GROUNDWATER CONDITION)

Key for codes used in Table 7A-1.

Aperture Width
1. Very Tight (<0.1 mm, <0.004in)
2. Tight (0.1-0.25 mm, 0.004-0.01in)
3. Partly open (0.25-0.5 mm, 0.01-0.02in)
4. Open (0.5-2.5 mm, 0.02-0.1 in)
5. Moderately wide (2.5 mm -1 cm, 0.1 – 0.4 in)
6. Wide (> 1 cm, >0.4 in)
7. Very wide (1 – 10 cm, 0.4 – 4 in)
8. Extremely wide (10 – 100 cm, 4 in – 3.3ft)
9. Cavernous (> 1m, 3.3 ft)

Continuity
1. Very low continuity < 3.3 ft (< 1 m)
2. Low continuity 3.3 - 10 ft (1 - 3 m)
3. Medium continuity 10 ft - 33 ft (3 - 10 m)

4. High continuity 33 - 66 ft (10 - 20 m)
5. Very high continuity > 66 ft (> 20 m)

Groundwater
Condition
1. The discontinuity is dry with no evidence of water flow.
2. The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
3. The discontinuity is damp but no free water is present.
4. The discontinuity shows seepage, occasional drops of water, but no continuous flow.
5. The discontinuity shows a continuous flow of water.

Table 7A-1: Discontinuity data (dip, dip direction, aperture, continuity, and groundwater condition).

ADA-32-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	125	3	2	2
89	315	4	2	2
82	195	7	2	2
90	126	7	2	2
85	280	1	2	2
80	40	8	2	2
86	169	7	2	2
90	332	-	2	2
90	30	-	3	2
85	305	7	3	2
89	305	7	3	2
80	140	3	1	2
89	141	3	1	2
40	70	5	1	2
90	130	5	1	2
90	310	-	-	2
89	215	-	1	2
89	139	-	1	2
77	218	3	3	2
86	305	4	1	2
90	25	-	3	2
81	320	7	1	2
83	20	-		2
75	325	3	2	2
90	250	-	2	2

ADA-32-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
85	335	8	3	2
89	75	7	3	2
90	340	3	2	2
90	25	-	3	2
90	315	-	1	2
76	331	3	3	2
75	340	4	3	2
84	63	-	3	2
90	126	7	3	2
83	295	2	1	2
83	303	-	1	2
82	133	2	1	2
90	206	-	1	2
83	306	-	1	2
89	130	3	1	2
90	310	2	2	2
84	310	3	2	2
75	85	-	1	2
85	343	9	3	2
70	175	6	2	2
83	330	3	1	2
90	305	5	1	2
90	310	2	2	2
90	125	9	3	2
86	140	3	3	2

Table 7A-1(contd.).

ADA-32-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
84	320	3	3	2
85	35	-	2	2
90	130	2	3	2
89	136	2	3	2
83	45	-	2	2
80	325	2	3	2
90	320	2	2	2
81	30	3	3	2
90	115	2	2	2
90	130	2	2	2
86	135	2	2	2
85	50	5	1	2
90	310	1	1	1

ADA-41-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
88	15	6	1	2
87	125	6	1	2
84	135	5	1	2
90	45	5	1	2
79	125	5	1	2
84	140	5	1	2
89	50	5	1	2
85	320		1	2
88	60	5	1	2
90	139	6	1	2
89	50	-	1	2
90	140	7	1	2
90	50	-	1	2
89	135	-	1	2
89	45	5	1	2
90	145	-	1	2
82	323	-	1	2
87	143	-	1	2
70	23	-	1	2
89	57	-	1	2
89	147	-	1	2
84	145	-	1	2
86	135	-	1	2
87	144	-	1	2
83	50	-	1	2

Table 7A-1(contd.).

ADA-41-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
86	145	-	1	2
90	140	-	1	2
89	161	-	1	2
89	140	-	1	2
89	135	-	1	2
81	154	-	1	2
90	135	-	1	2
90	135	-	1	2
78	15	-	1	2
90	206	-	1	2
80	135	-	1	2
90	210	-	1	2
79	135	-	1	2
90	127	-	1	2
85	185	-	1	2
87	209	-	1	2
84	132	-	1	2
90	205	-	1	2
85	138	-	1	2
85	184	-	1	2
90	105	-	1	2
90	140	-	1	2
90	207	-	1	2
80	195	-	1	2
85	235	-	1	2

ADA-41-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
89	213	-	1	2
90	212	-	1	2
90	149	-	1	2

Table 7A-1(contd.).

ATH-33-14				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
70	20	4	2	2
90	20	4	2	2
80	55		3	4
90	85	7	2	3
90	98	7	2	3
78	75		4	2
74	90	3	2	2
82	94	9	2	2
74	28	8	2	2
70	10	4	2	2
88	42	8	2	2
74	37	3	2	2
84	25	4	2	2

ATH-50-22				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
88	122	4	1	2
83	21	4	1	2
77	213	-	1	2
61	284	-	1	2
88	64	-	1	2
77	298	-	1	2
73	221	-		
84	120	3	1	2
79	248	-	1	2
74	329	4	1	2
85	24	-	1	2
66	183	-		
80	315	4	1	2
81	233	-	1	2
81	337	4	1	2
81	220	-	1	2
88	306	3	1	2
70	330	3	1	2
84	281	3	1	2
83	15	-		
72	336			
89	350	2	1	2
78	134	5	2	2
82	193	6	2	2
89	109	-		2

Table 7A-1(contd.).

Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
		ATH-50-22		
65	206	-		
83	215	-		
88	180	6	1	2
82	139	-	1	2
89	12	2	1	2
85	160	6	1	2
83	85	-	2	2
77	194	2	2	2
77	172	5	2	2
76	265	-	2	2
80	125	6	2	2
75	232	-	2	2
90	298	-	1	2
83	217	-		2
82	108	3	1	2
81	105	3	1	2
78	189	-	1	2
81	120	-	1	2
76	208	4	1	2
90	264	-		
68	148	-		
82	193	-	1	2
81	280	-	1	2
73	203	2	1	2
86	314	-	2	2

Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
		ATH-50-22		
87	237	-	2	2
80	156	6	2	2
86	274	-	2	2
75	155	3	2	2
70	235	3	2	2
69	217	-	2	2
87	101	-		2
70	170	5	2	2
87	130	-	1	2
83	243	-	1	2
81	285	-	1	2
80	204	2	1	2
88	105	-		2
73	141	2	1	2
44	223	-		2
89	289	-	1	2
86	228	-		2
70	161	5	1	2
69	183	-		2
80	270	-		2
90	333	-	1	2
81	209	-		2
75	82	-		2
77	188	-	1	2
86	257	-		2

Table 7A-1(contd.).

ATH-50-22				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
81	176	-	1	2
89	127	-	1	2
74	212	-		2
86	293	-	1	2
75	201	-	1	2
88	70	5	2	2
89	27	6	2	2
80	129	-	1	2

BEL-7-10				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
82	149	-	1	2
82	149	-	1	2
82	149	-	1	2
77	332	4	1	2
81	54	-	1	2
81	127	-	1	2
87	243	-	1	-
70	108	-	1	2
86	176	-	1	2
6	225	-	1	2
81	19	4	1	2
89	36	4	1	2
72	353	4	1	2
73	194	4	1	2
74	215	4	1	2
84	352	4	1	2
72	143	4	1	2
80	97	4	1	2
86	151	4	1	2
78	77	-	-	2
89	215	-	1	2
86	71	-	-	
87	135	3	1	2
85	62	-	2	
84	303	-	2	2

Table 7A-1(contd.).

BEL-7-10				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
89	195	-	2	2
55	307	-	2	2
66	38	-	-	-
84	282	-	-	-
63	111	-	-	-
81	68	3	1	2
66	121	3	1	2
81	55	3	1	2
75	129	3	1	2
68	143	3	1	2
73	83	3	1	2
84	196	3	1	2
74	123	4	1	2
83	309	4	1	2
68	52	4	1	2
83	141	4	1	2
78	90	-	-	-
72	252	4	-	-
89	117	4	-	-
90	58	-	-	-
90	135	4	-	-
89	255	-	-	-
57	108	-	-	-
78	116	6	1	1
90	208	-	-	-

BEL-7-10				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
86	210	6	-	-
84	125	-	-	-
64	58	-	-	-
75	0	-	-	-
81	120	-	-	-
71	32	-	-	-
84	334	4	1	1
69	90		1	
76	136		1	
84	82		1	
86	244		1	
87	117		1	
85	292		1	
84	85		1	
78	140		1	
73	155		1	
76	80		1	
69	350		1	
85	170		1	
86	305		1	
89	83		1	
73	125		1	
90	240		1	
65	135		-	
76	40		-	

Table 7A-1(contd.).

BEL-7-10				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
65	40		-	
85	140		-	
82	75		-	
80	20		-	
76	130		-	
83	100		-	
63	115		-	
80	91		-	
80	20		-	

BEL-470-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
77	4			
79	108	2	1	2
77	3			
88	302	2	1	2
87	179			
82	88	2	1	2
82	334			
72	13			
87	104	2	1	2
89	182			
80	307	2	1	2
79	4			2
78	301	2	1	2
75	12			
85	115	2	1	2
72	110			
83	98	2	1	2
82	2			
79	288	2	1	2
78	3			
77	284	2	1	2
83	5			
78	100	4	1	2
81	11			
88	151	4	1	2

Table 7A-1(contd.).

BEL-470-6					BEL-470-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition	Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
71	300	2	1	2	84	292	2	1	2
82	103	4	1	2	78	8			
80	272	4	1	2	84	125	2	1	2
84	6				81	9			
84	126	2	1	2	82	306	2	1	2
85	3				74	2			
72	290	2	1	2	76	118	2	1	2
70	3				76	3			
79	282	4	1	2	87	132	2	1	2
65	16				66	6			
87	122	2	1	2	72	303	2	1	2
78	8				60	285	2	1	2
90	117	2	1	2	84	10			
87	123	2	1	2	83	300	2	1	2
64	12				81	6			
82	300	2	1	2	86	280	2	1	2
71	358				84	104	2	1	2
88	302	2	1	2	85	359			
78	3				84	272	6	1	2
85	77	2	1	2	89	125	2	1	2
87	107	4	1	2	87	1			
74	358				82	286	2	1	2
80	4				80	358			
85	286	2	1	2	87	353			
88	5				73	96	4	1	2

Table 7A-1(contd.).

BEL-470-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	99	2	1	2
83	356			
82	252	2	1	2
74	353			
82	274	2	1	2
75	352			
90	107	2	1	2
81	350			
83	63	2	1	2
87	354			
87	102	4	1	2
88	87	4	1	2
76	357			
59	83	2	1	2
85	88	2	1	2
64	350			
84	281	2	1	2
77	354			
87	70			
79	102			
79	81	2	1	2
73	354			
85	53	4	1	2
66	88	4	1	2
76	78	4	1	2

BEL-470-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
78	2			
76	273			
82	9			
83	357			
85	344			
84	260			
78	357			
70	304			
62	283			
40	211			
79	354			
62	72			
81	142			
77	15			
83	287			
85	356			
77	350			
65	84			
79	75			
89	347			
84	64			
88	263			
84	348			
85	282			
70	353			

Table 7A-1(contd.).

CLA-4-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
89	31	7	2	2
83	175	4	1	2
89	234			
87	7	5	1	2
75	17		2	2
89	294		2	2
83	167	6	2	2
88	92	5	2	2
86	4		2	2
90	282			
83	281		3	2
80	356		3	2
4	93			
90	332			
84	275		3	2
80	1			
83	278			
84	240		2	2
83	184	5	2	2
84	276		2	2
85	275	7	2	2
0	0			
81	186		1	2
87	284	7	1	2
83	156			

CLA-4-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	32	8	3	2
87	275		3	2
90	6	8	3	2
87	355			
84	287			
77	206			
86	284			
84	169			
86	270	8	2	2
89	280		2	2
73	6	3	2	2
78	275			
5	299			
86	275			
80	356		2	2
86	203			
84	358		3	2
90	278	7	2	2
65	353			
87	345			
80	358		3	2
84	279		2	2
0	0			
81	8			
84	281			

Table 7A-1(contd.).

CLA-4-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	0			
80	12		1	2
90	271			
84	277			
80	326			
76	278			
0	0			
82	335			

CLE-275-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
76	25	4	1	2
84	265	4	1	2
85	210	4	1	2
74	290	4	1	2
88	30	4	1	2
81	300	4	1	2
90	346	4	1	2
81	283	4	1	2
83	210	4	1	2
90	231	4	1	2
84	286	4	1	2
90	41	3	1	2
89	270	3	1	2
89	270	3	1	2
90	36	4	1	2
90	286	4	1	2
84	210	4	1	2
86	210	4	1	2
80	220	5	1	2
85	346	6	1	2
87	283	6	1	2
89	220	3	1	2
90	284	3	1	2
87	337		1	2
86	287		1	2

Table 7A-1(contd.).

CLE-275-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
80	230		1	2
85	335		1	2
90	110		1	2
89	210	4	1	2
90	280	4	1	2
80	210	3	1	2
81	105	3	1	2
84	345		1	2
89	215		1	2
90	345		1	2
88	215		1	2
90	220	3	1	2
83	336	3	1	2
90	320	3	1	2

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
82	178		1	2
65	130	2	1	2
54	25	2	1	2
54	101	2	1	2
80	26	2	1	2
57	152	5		
74	248	5		
52	186	5		
71	127			
40	203			
76	178			
84	119	5		
88	180			
71	220			
78	196			
80	105	5		
69	156			
73	184			
55	180			
79	150			
71	253			
75	189	5	3	
73	143	5	3	
68	253	5	3	
52	173	5	1	

Table 7A-1(contd.).

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
35	158	5	1	
73	160	5	3	
71	147	5	3	
80	236	5	3	
79	192	5	2	
77	187	4	2	
83	180	4	2	
66	272			
70	193		1	
77	179		1	
83	200			
71	134			
67	239			
65	132	5	3	2
42	233			
80	186		3	
74	160	5		
63	258			
60	191			
71	135			
82	152			
70	155			
50	234	5	3	
76	150			
78	248	5	3	

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	185			
76	148		3	
75	245	5	5	
68	207			
84	157	5	3	
80	246			
66	199	5	3	
75	187	2	2--3	2
88	233	2		2
58	154	2		2
35	336	2	2--3	2
58	266	2		2
40	60	2		2
80	173	2	2--3	2
61	150	2		2
86	161	2		2
79	229	2		2
70	226	2		2
62	145	2		2
8	113	1	4	2
75	164	2		2
64	162	2		2
58	153	2		2
71	161	2		2
68	177	2		2

Table 7A-1(contd.).

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
76	323	2		2
57	178	2		2
30	151	2		2
8	136	1	4	2
61	180	2	2--3	2
75	178	2		2
82	82	2		2
73	176	2		2
89	169	2	2--3	2
62	160	2		2
15	160	2	4	2
65	174	2	2	2
68	177	2	2	2
58	173	2	2	2
79	92	2	1	2
82	88	2	1	2
74	171	2	2	2
84	80		4	2
71	156		2	2
74	169	6	2	2
73	180	5	3	2
90	181	5	3	2
78	308	1	1	2
81	354	1	1	0
89	344	3	3	2

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	342	3	3	2
72	250	3	2	2
77	177	2	2	2
73	286	2	1	2
67	180	5	2	2
74	208	8	1	2
85	302	5	3	2
70	167	5	3	2
82	146	6	2	2
63	167	5	2	2
89	282	2	1	2
90	333			
77	168			
83	85			
64	179	4	3	2
84	166	4	3	2
78	178	7	3	2
73	171	7	3	2
65	122			2
67	199			2
58	113			2
82	163			2
65	172			2
81	255			2
85	347	6	3	2

Table 7A-1(contd.).

COL-7-5				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
75	233	2	2	2
86	345			2
77	179			2
70	88	3	2	2
82	175	3	2	2
88	289	2	2	2
83	191			2
88	113	5	2	2
89	135	2	1	2
6	128	2	1	2
82	200	2	1	2
80	98	2	1	2
87	132	2	3	2
72	155	2	3	2
75	152	2	3	2
80	260	2	3	2
78	156	2	3	2
77	244	2	1	2
79	156	2	3	2
74	143	2	3	2
88	204	2	3	2
87	124	2	3	2
87	188	2	3	2
70	253	2	3	2

FRA-270-23				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
79	217	5	1	1
79	130	5	1	1
79	133	5	1	1
84	48	5	1	1
84	150	5	1	1
81	139	5	1	1
88	43	5	1	1
84	140	5	1	1
81	215	5	1	1
89	313	5	1	1
88	43	5	1	1
80	125	5	1	1
89	41	5	1	1
85	214	5	1	1
67	131	5	1	1
90	212	5	1	1
58	139	5	1	1
59	130	5	1	1
90	231	5	1	1
78	35	5	1	1
68	128	5	1	1
66	137	5	1	1
81	51	5	1	1
82	118	5	1	1
83	226	5	1	1

Table 7A-1(contd.).

FRA-270-23				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	112	5	1	1
84	204	5	1	1
65	121	5	1	1
89	27	5	1	1
83	220	5	1	1
86	216	5	1	1
72	104	5	1	1
72	132	5	1	1
90	217	5	1	1
45	142	5	1	1
76	242	5	1	1
58	139	5	1	1
81	253	5	1	1
79	242	5	1	1
85	151	5	1	1
70	150	5	1	1
85	39	5	1	1
85	214	5	1	1
68	125	5	1	1

GUE-22-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
59	140	5	2	2
78	251	5	2	2
76	159	5	2	2
72	243	5	2	2
89	55		2	2
68	343		2	2
83	2		2	2
65	140			
75	246	5	2	2
79	183			
85	4			2
68	331	5	2	2
72	238	5	2	2
52	10			
74	328	6	2	2
62	131	5	2	2
81	328		1	2
87	215	5	1	1
81	34	6	2	2
85	123	6	2	2
87	223	6	2	2
80	124	6	2	2
85	323	6	2	2
82	231	6	2	2
75	313	6	2	2

Table 7A-1(contd.).

GUE-22-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
81	28	6	2	2
73	27	6	1	4
81	302	6	1	4
85	113	6	2	4
58	39	6	1	2
85	140	6	1	1
67	220	6	1	2
71	307		1	2
72	228		1	2
88	132		2	2
90	47		1	2
83	72	6	1	2
71	170	6	1	2
86	236	6	2	2
81	146	6	1	2
78	40	6	2	2
71	317	6	2	2
80	54	6	1	2
86	310	6	2	2
73	12	6	1	1
72	180		1	1
70	50	4	1	1
81	208	6	2	2
85	294	4	2	2
60	47	6	2	2

GUE-22-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
71	124	6	1	2
85	85	4	1	2
70	40		1	2
57	55	4	2	2
72	140			
79	218		1	2
88	155			
76	272	5	2	2
59	70	6	2	2
40	312			
80	245	6	2	2
90	213	6	2	2
83	289	6	2	2
56	105	4	2	2
86	344			
76	171			
81	181			
76	170			
80	107			
78	343			
62	130			
73	195			
75	109			

Table 7A-1(contd.).

GUE-77-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
78	88		2	1
87	325		2	1
82	269		2	1
44	155		2	1
32	63		2	1
89	200		1	1
68	191		1	1
88	257		1	1
84	78	5	1	1
85	312	7	1	1
90	233	1	1	1
89	42		1	1
83	5	5	2	1
71	87		1	1
89	265	5	2	1
81	319			
90	182	2	1	2
12	130	1	3	2
77	116	4	2	1
59	10	5	1	1
64	281	5	2	1
88	198	5	1	1
89	308		1	1
89	233		1	1
51	13	3	1	1

GUE-77-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
42	198			
70	25	1	1	1
82	273		2	2
81	352		7	1
90	343	1	1	1
75	26	5	2	1
65	15	5	1	1
71	334	6	2	1
79	315	5	2	1
81	215		2	1
90	145	5	1	1
80	256		2	2
65	5	5	1	2
64	133	5	2	2
66	132	6	1	2
85	237	6	1	2
68	121	1	1	2
84	220		1	2
74	116		1	2
48	224		1	2
83	220		1	2
70	335	3	1	2
77	337	3	1	1
80	154	3	2	2
53	265			

Table 7A-1(contd.).

GUE-77-8				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	27	4	1	1
81	263	3	3	1
78	334	4	1	1
82	303	6	1	2
68	334	4	2	1
75	338	4	1	1
74	68	4	1	1
74	4	4	1	1
71	8	4	1	1
72	1	4	1	1
84	245			
76	324	6	1	1
65	37	3	1	1
53	350	3	1	1
72	246	2	1	1
83	342	3	1	1
43	346	3	1	1
65	310	4	1	1
72	50	4	1	1

HAM-74-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
247	77	4	1	2
205	86	4	1	
62	70	4	1	
215	80	4		2
244	87	4		2
164	85	4	1	2
169	77	4	1	2
27	86		1	2
226	66			2
165	86			2
216	88		1	2
4	51		1	2
240	90	4	1	
15	75	4		2
63	84	4		2
320	86	4		2
76	75	4	1	2
62	77	4	1	
155	79	4	1	
258	87	4	1	
195	87	4	1	
252	89	4		
4	81	4		
247	87	4		
168	88	4	1	2

Table 7A-1(contd.).

HAM-74-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
58	88	4	1	
355	80		1	
61	84		1	
154	86			
237	90			
173	82	4		2
74	78	4		
354	82	4		
63	85	4		2
333	90	4		2
70	78	4	1	2
343	86	4	1	2
229	84	4	1	2
341	87	4	1	2
243	77	4	1	2
174	82	4	1	
4	27	4	1	
68	77	4	1	
78	88	4		2
347	86	4		2
64	87	4		
146	88	4		2
55	88	4	1	2
236	85	4	1	
350	87	4	1	

HAM-126-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
81	290	5	1	3
90	87	5	1	3
85	97		1	3
79	63		1	3
81	72		1	3
85	342		1	3
87	327		1	3
81	182		1	3
90	351		1	3
87	324	5	1	3
87	245		1	3
78	358		1	3
79	24		1	3
90	50		1	3
78	345		1	3
86	48		1	3
74	82		1	3
77	9		1	3
90	75		1	3
77	14		1	3
71	53		1	3
88	114		1	3
73	12		1	3
85	11		1	3
87	276	2	1	3

Table 7A-1(contd.).

HAM-126-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
79	347		1	3
88	65		1	3
87	158		1	3

JEF-CR77-0.4				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
83	28		1	
89	215		1	2
74	34		1	2
73	19		3	
63	20			2
74	134	6	2	2
72	21	6	2	
72	62	6	2	
75	17	1		
70	253		4	2
79	25		2	2
56	0		1	
69	342		1	
64	44			
72	31		1	
81	55	2		
82	327	2		
18	138	2		
7	100	2		
74	324	2		2
84	56	2		2
77	358	2	2	
51	304	2	2	2
58	298	2	2	
77	321	2		2

Table 7A-1(contd.).

JEF-CR77-0.4				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
72	55	2	2	
85	165	2		2
75	36	2		2
42	325	2		
80	46	2		2
76	339	2		
78	59	2		
82	80	2		
4	4	2		
89	107	2		
54	350	2		
72	40	2		
61	51			

LAW-52-11				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	320		1	
71	198		1	2
75	128	7	1	2
58	241	5	1	2
59	132		1	2
65	49	5	1	2
77	225		1	2
87	313		1	2
43	201	5	1	2
35	203		1	
65	113		1	
69	220		1	
60	319		1	
54	211		1	2
59	346		1	
56	246		1	
73	232	5	2	2
86	113		1	
84	183		1	
50	234		1	
68	240	7	2	
78	226	7	2	2
74	147		2	2
80	234	7	2	
80	173	5	1	

Table 7A-1(contd.).

LAW-52-11				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	250		1	
89	223		2	2
69	122	5	1	
89	222		2	2
73	221	7	1	
68	240	6	4	
64	182	5	3	
87	252	2	2	
74	156	4	2	2
66	320	7	2	2
53	334	3	3	2
46	304	5	3	2
38	301	5	2	2
81	223		3	
87	239		1	
77	73		1	
73	246	4	1	
52	212	7	2	
60	315		1	2
82	158	5	1	
80	256		1	2
44	181		1	
88	230	7	2	
77	135		2	

LIC-16-28				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
40	152	3	3	2
42	131	3	3	2
50	129	3	3	2
32	130	3	3	2
37	133	3	3	2
24	125	3	3	2
0	0	1	5	2
82	51			2
85	153		2	2
87	149	2	3	2
63	147	3	3	2
84	346		3	2
67	159		3	2
51	176		3	2
80	189		3	2
65	187		3	2
79	113		3	2
81	176		3	2
82	2	3	3	2
83	126		3	2
75	29		3	2
0	0	2	5	2
50	174			2
76	301			2
56	177			2

Table 7A-1(contd.).

LIC-16-28				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
64	173			2
56	162			2
85	98			

MEG-33-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
70	151	5	2	2
89	356	4	2	2
78	255			2
81	192	5	2	2
81	109	5	2	2
81	32			
86	286			
79	293	5	2	2
86	10			2
89	122	6	2	2
76	226		2	2
75	221	5	2	2
90	124	7	2	2
80	51		2	2
83	322	4	2	2
86	97			
77	310		2	2
83	26	5	2	2
72	322	4	2	2
90	209			2
80	63		2	2
89	131		2	2
84	15			2
63	278			2
81	342	3	2	2

Table 7A-1(contd.).

MEG-33-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
74	238			
82	59		2	2
86	222	9		2
90	262			2
67	160			2
81	94	4	2	
90	51			
80	294			2
90	206		2	2
86	134	4		2
85	245		2	2
76	130	5		2
48	252			2
64	307	3		2
87	118	3	1	2
67	238	3	1	2
73	320	3	1	2
70	196	3	1	2
71	269	3	1	2
72	304			2
89	220		2	2
85	183	5	2	2
86	253			2
85	53	9	2	2
78	250			2

MEG-33-6				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
78	311	5	2	2
72	14		2	2
63	274			2
89	18			2
76	152	5	2	2
82	358		2	2
88	2	6	2	2
88	107	4	2	2

Table 7A-1(contd.).

MEG-33-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	214		2	2
88	277	5	2	2
83	143	6	2	2
86	265			
84	174			
75	239			
71	160	8	2	2
83	229		2	2
69	135		2	2
72	220			2
78	89	6	2	2
84	39		2	2
74	152	4	2	2
74	245		2	
78	104	7	2	2
78	152	7	2	2
81	225			2
80	119	7	2	2
75	110		2	2
84	45		2	2
74	15		2	2
80	275	6	2	2
83	215		2	2
81	310	6	2	2
72	305	6	2	2

MEG-33-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
80	285	7	2	2
80	150	7	2	2
74	125		2	2
86	220		2	2
84	120	7		2
60	110	7	2	2
80	335	7	2	2
90	210		2	2
80	295	7	2	2
82	290	7	2	2
65	80	7	2	2
90	170	6	2	2
73	30		2	2
70	340	5	2	2
78	740		2	2
89	250	4	2	2
75	50		2	2
90	290		2	2
66	110	7	2	2
79	60		2	2
85	330		2	2
90	70	6	2	2
85	200	7	2	2
80	105	7	2	2
87	215		2	2

Table 7A-1(contd.).

MEG-33-15				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
90	330	5	2	2
74	140		2	2
81	195	4	2	2
80	30		2	2
88	300		2	2
90	215	8	2	2
83	120		2	2
83	120	7	2	2

MUS-70-11				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
88	145	8	1	2
73	223	8	3	2
89	224	8	3	2
86	302		3	2
76	213	8	3	2
80	60	8	3	2
70	139		1	2
89	17			
67	233			
86	147			
86	154			
83	266	8	3	2
85	32			
87	136			
77	210			
76	119	8	3	2
90	203		3	
81	115	8	3	2
78	209			
83	20			
87	285	8		
82	45			
84	152	8	3	2
89	240			
85	220			

Table 7A-1(contd.).

MUS-70-11				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
85	130	8	3	2
77	150	4	2	2
73	235	2	2	2
81	241	2	2	2
75	189			
83	236	2	1	2
83	160		1	2
77	235			
72	163			
79	65	2	2	2
60	148	2	2	2
80	74		2	0
89	301			
84	249	8	2	2
77	223			
60	146	2	2	2
77	203			
74	145			
69	198			
59	140			
78	49	1		
82	145			
88	253	8	2	2
84	155			
64	224			

MUS-70-11				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
59	313			
80	223			
87	201			
68	207			
78	152			
87	268			
63	184			
76	113			
73	222			
82	75	8	3	
64	138			
77	165			
86	240	8	2	
90	159			
88	78	8	2	
77	352	8	2	

Table 7A-1(contd.).

RIC-30-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
78	300	2	2	2
80	200	2	2	
73	38	2	2	3
88	131	2	2	1
85	140	2	2	1
84	23	1	1	1
90	129	1	1	1
71	23	1	1	1
81	129	1	1	1
69	30	1	1	1
83	140	1	1	1
79	222	1	1	1
79	222	4	1	1
9	188	2	4	3
82	211	2	2	4
82	211	2	2	1
86	101	2	2	1
78	211	2	2	1
62	38	1	1	1
80	129	1	1	3
80	129	1	1	3
85	38	1	1	4
85	305	1	1	3
71	299	3	1	3
3	157	5	1	3

RIC-30-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
87	105	5	1	3
69	297	5	1	3
71	290	1	1	3
65	204	1	1	3
85	108	1	1	3
87	27	2	1	3
87	278	2	1	3
78	273	2	1	3
86	313	1	1	3
88	18	2	1	3
88	97	2	1	3
87	196	2	1	1
88	270	2	1	1
79	212	1	1	1
81	115	1	1	1
80	117			
82	287			
90	108			
87	291			
5	213			
84	118			
89	287			
83	289			
86	243			
5	110			

Table 7A-1(contd.).

RIC-30-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
88	11			
74	193			
77	112			
74	272			
83	105			
85	260			
62	140			
65	235			
76	298			
69	277			
74	291			
76	279			
88	191			
57	303			
82	220			
84	280			
89	107			
73	163			
89	295			
89	198			
87	111			
90	320			
85	112			
89	312			
88	204			

RIC-30-12				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
85	291			
79	206			
89	293			
83	293			
81	265			
7	43			
84	123			
87	26			
86	139			
78	234			
90	293			
87	155			
78	108			
89	275			
76	208			
87	114			
90	203			
48	266			
86	198			
77	127			
88	196			
88	106			
84	108			

Table 7A-1(contd.).

STA-30-27				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
61	94	4	1	2
85	271	4	1	2
84	98	4	1	2
85	13	4	1	2
75	97	4	1	2
77	92	4	1	2
90	258	4	1	2
83	93	4	1	2
65	98	4	1	2
70	99	4	1	2
82	96	4	1	2
81	107	4	1	2
81	216	4	1	2
77	103	4	1	2
82	204	4	1	2
70	61	4	1	2
82	126	4	1	2
85	198	4	1	2
71	348	4	1	2
90	100	4	1	2
4	158	4	1	2
88	106	4	1	2
87	298	4	1	2
90	210	4	1	2
75	285	4	1	2

STA-30-27				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
88	288	4	1	2
71	159	4	1	2
81	209	4	1	2
90	284	4	1	2
87	176	4	1	2
83	340	4	1	2
80	138	4	1	2
71	288	4	1	2
75	286	4	1	2
88	202	4	1	2
86	184	4	1	2
69	204	4	1	2
84	257	4	1	2
82	213	4	1	2
79	200	4	1	2
76	145	4	1	2
76	283	4	1	3
74	349	4	1	3
82	272	4	1	3
80	72	4	1	3
88	18	4	1	3
84	90	4	1	3
74	194	4	1	3
84	102	4	1	3
79	263	4	1	3

Table 7A-1(contd.).

STA-30-27				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
79	289	4	1	3
81	177	4	1	3
87	88	4	1	3
86	350	4	1	3
73	103	4	1	3
79	61	4	1	3
83	278	4	1	3
84	95	4	1	3
83	78	2	1	3
82	218	2	1	3
84	24	2	1	3
82	11	2	1	3
78	282	2	1	3
83	36	2	1	3
85	23	2	1	3
86	187	2	1	3
82	250	2	1	3
70	321	2	1	3
85	24	2	1	3
81	277	2	1	3
78	300	2	1	3
84	18	2	1	3
85	77	2	1	3
90	342	2	1	3
88	287	2	1	3

STA-30-27				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
77	14	2	1	3
88	340	2	1	3
71	280	2	1	3
81	23	2	1	3
85	93	2	1	3
80	232	2	1	3
86	7	2	1	3
76	48	2	1	3
85	286	2	1	3
78	344	2	1	3
71	241	2	1	3
77	14	2	1	3

Table 7A-1(contd.).

WAS-7-18				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
72	334		1	2
85	285			
69	185	2	1	2
79	282		1	2
73	202	2	1	2
77	95		1	2
90	355	2	1	2
87	280		1	2
82	15	2	1	2
86	263		1	2
89	278		1	2
88	350	3	1	2
81	148			
83	197		1	2
84	193		1	2
87	147			
81	95		1	2
89	353	3	1	2
90	252	2	1	2
64	169	3	1	2
78	100			
73	143		1	2
78	161		1	2
87	307		2	2

WAS-7-18				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
69	139	6		
89	263	6	2	2
82	226		2	2
86	331			
83	218		2	2
75	122		2	2
83	73		2	2
74	159	6	2	2
75	110			
90	20	2	2	2
82	125			
72	73	6	2	2
65	110			
79	65	5	2	2
89	115			
89	63	6	2	2
88	5		2	2
81	46		1	2
88	289			
88	187			
86	105			
78	99	7	2	2
89	25			
74	112			
81	38	4	2	2

Table 7A-1(contd.).

WAS-7-18				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
86	340		1	2
76	56			
84	181	4	2	2
87	247			
90	343			
86	192			
71	137			
77	345	3	2	2
80	68	6	2	2
84	175		2	2
89	10	7	2	2
69	71	4	1	2
79	185	6	1	2
71	102			2
78	204		1	2
77	100	6	2	2
88	126			2
79	217	4	2	2
80	143			2
73	124		2	2
74	67	6	1	2
61	80			2
85	348	7	2	2
80	91	4	2	2
74	178		2	2

WAS-7-18				
Dip	Dip Direction	Aperture	Continuity	Groundwater Condition
83	138		2	2
88	246	4	2	2
84	176		2	2
89	155			2
87	80			2
81	115			2
88	187	4	2	2
87	171		2	2
79	95			2
88	25	6	2	2
89	252			2
67	240	4	2	2

APPENDIX 7-B

STEREONET PLOTS AND ROSE DIAGRAMS OF DISCONTINUITY
DATA
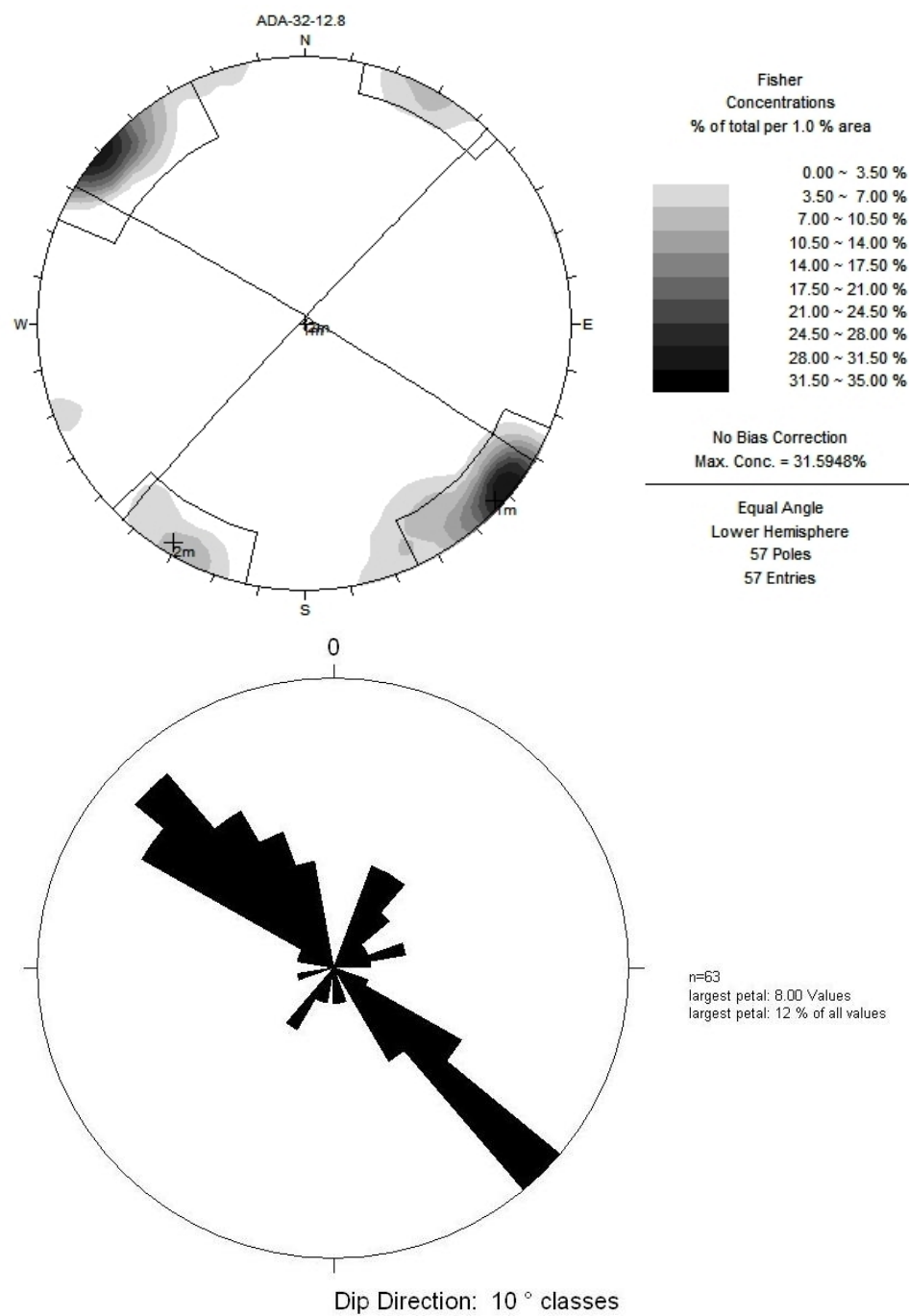
Figure 7B-1: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for ADA-32-12.8 site.
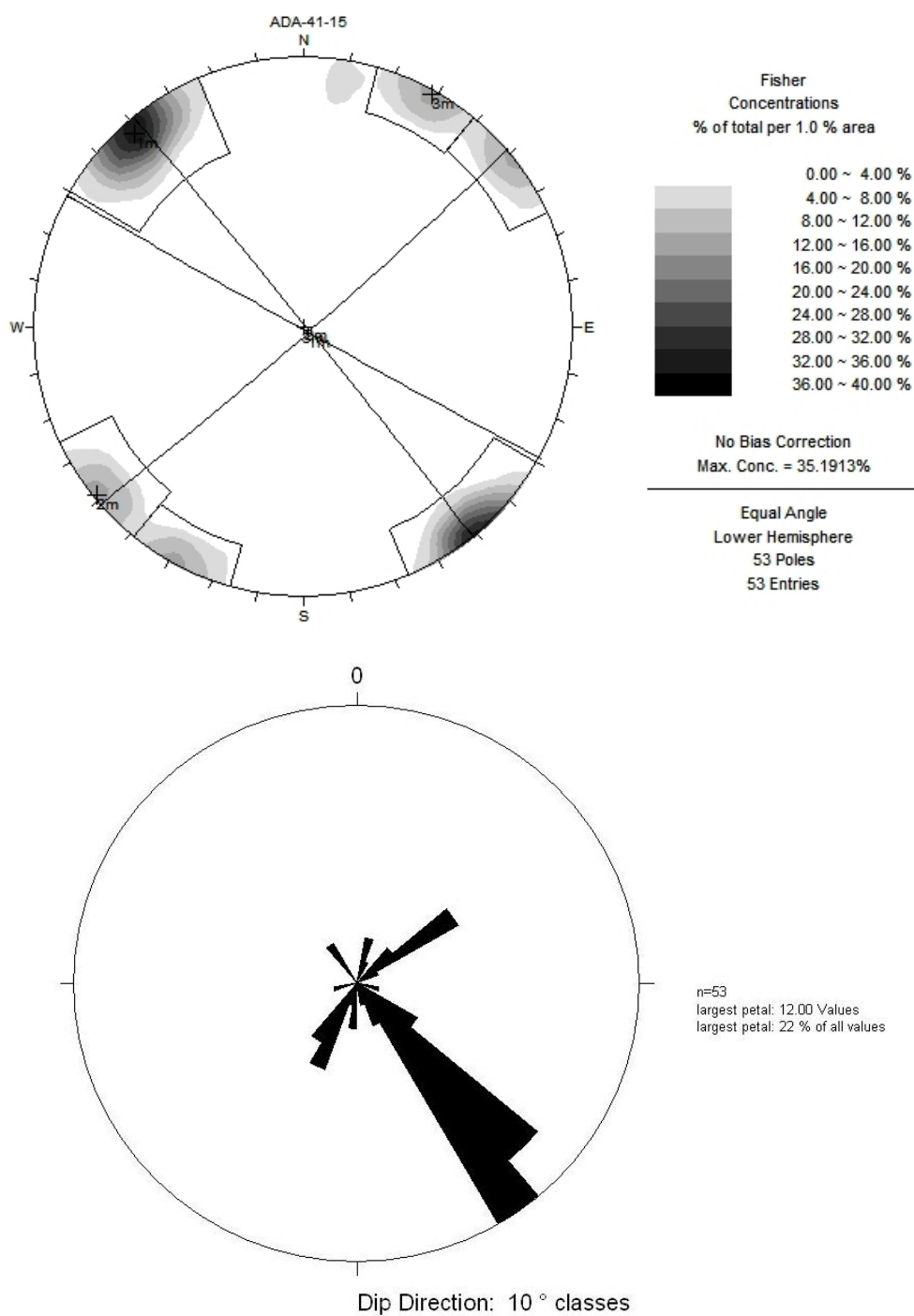
Figure 7 B-2: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for ADA-41-15 site.
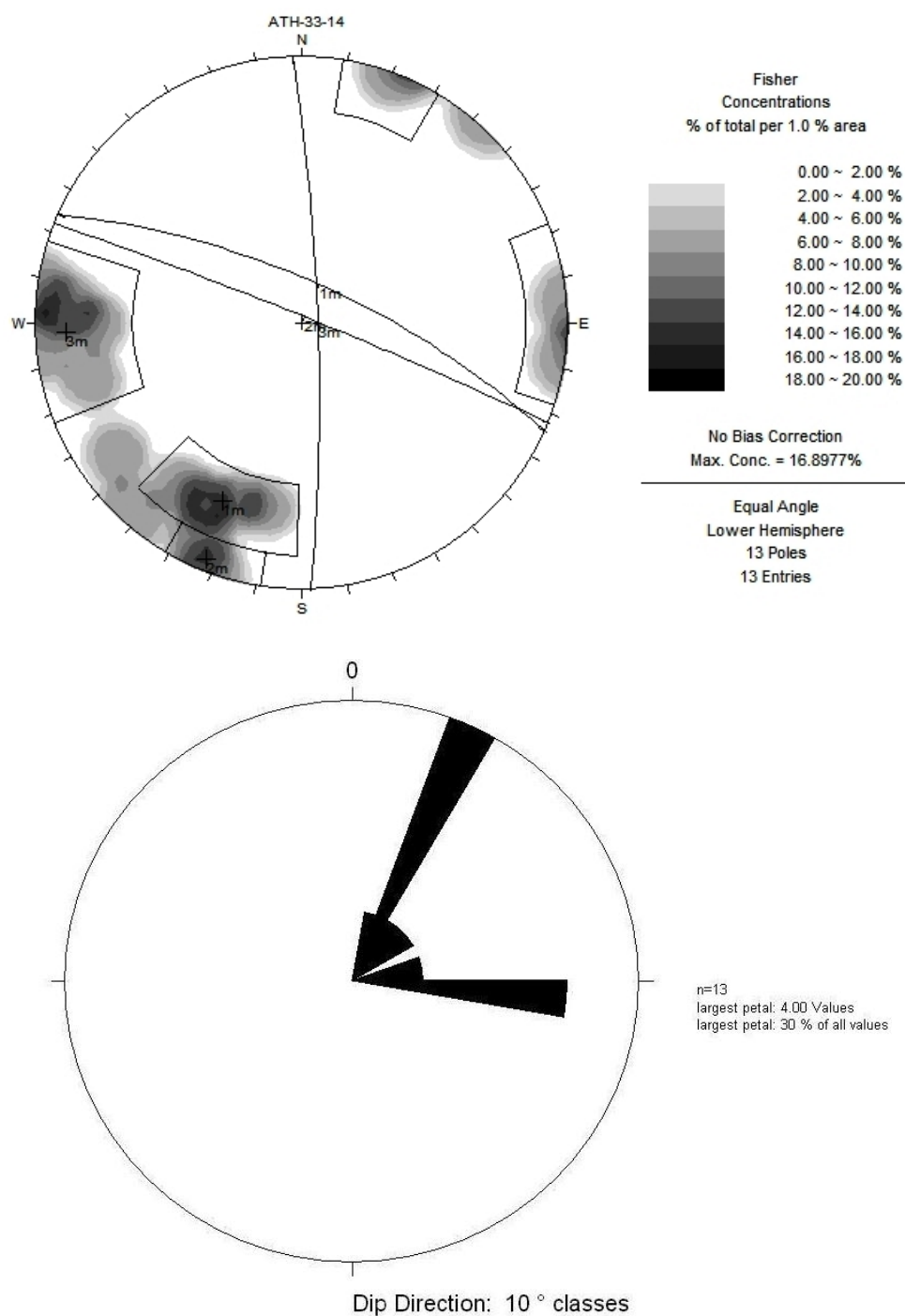
Figure 7B-3: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for ATH-33-14 site.
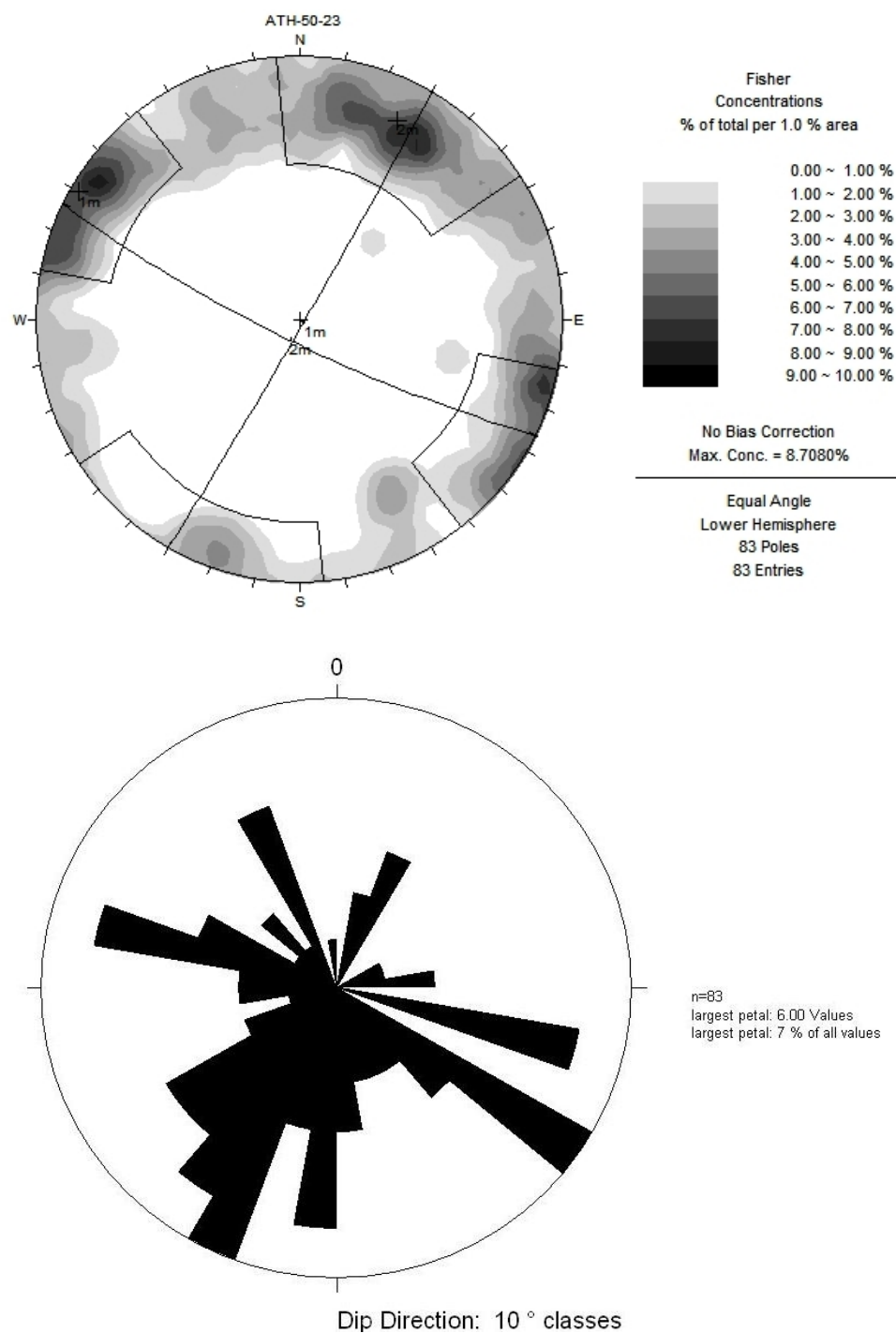
Figure 7B-4: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for ATH-50-23 site.
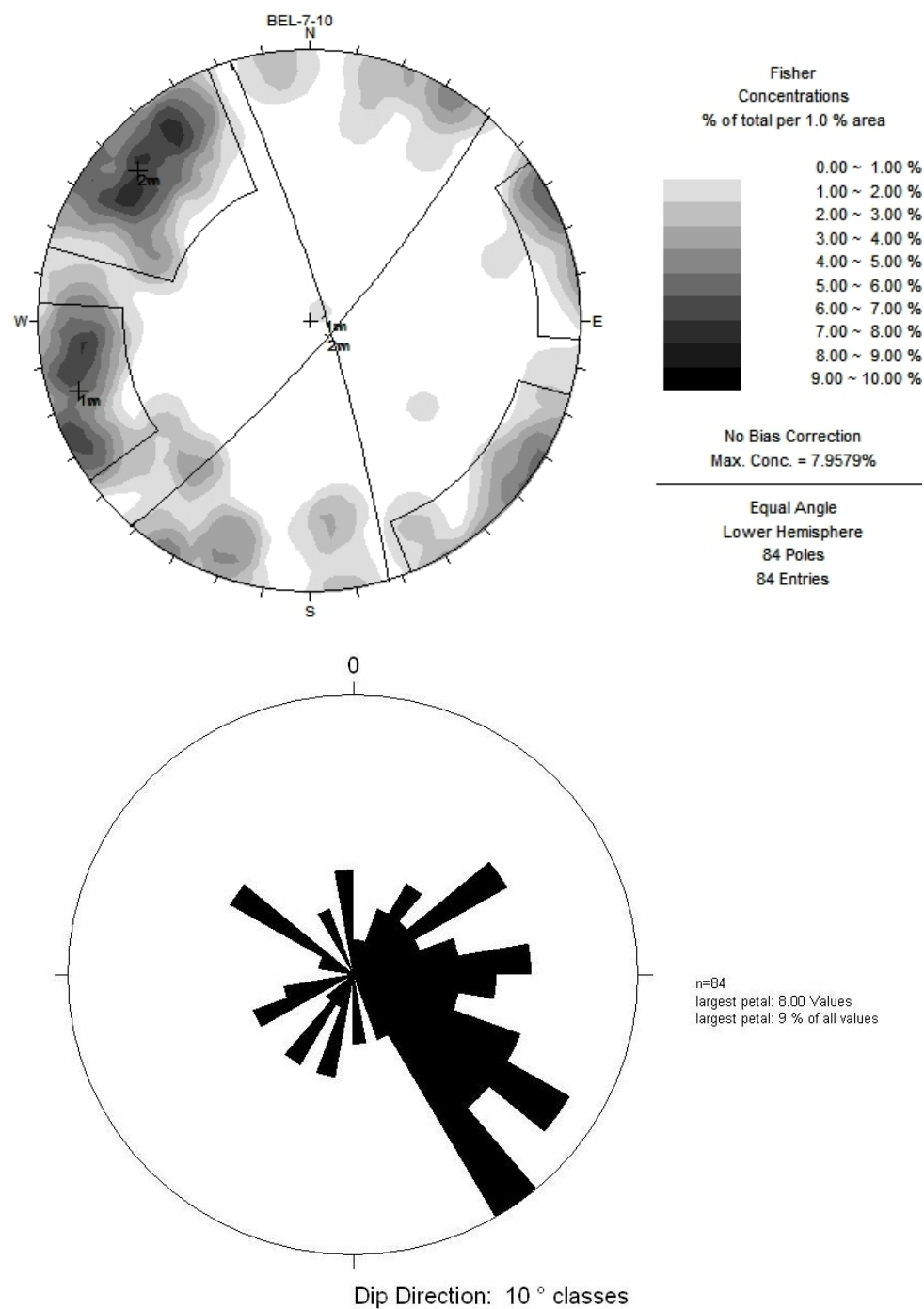
Figure 7B-5: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for BEL-7-10 site.
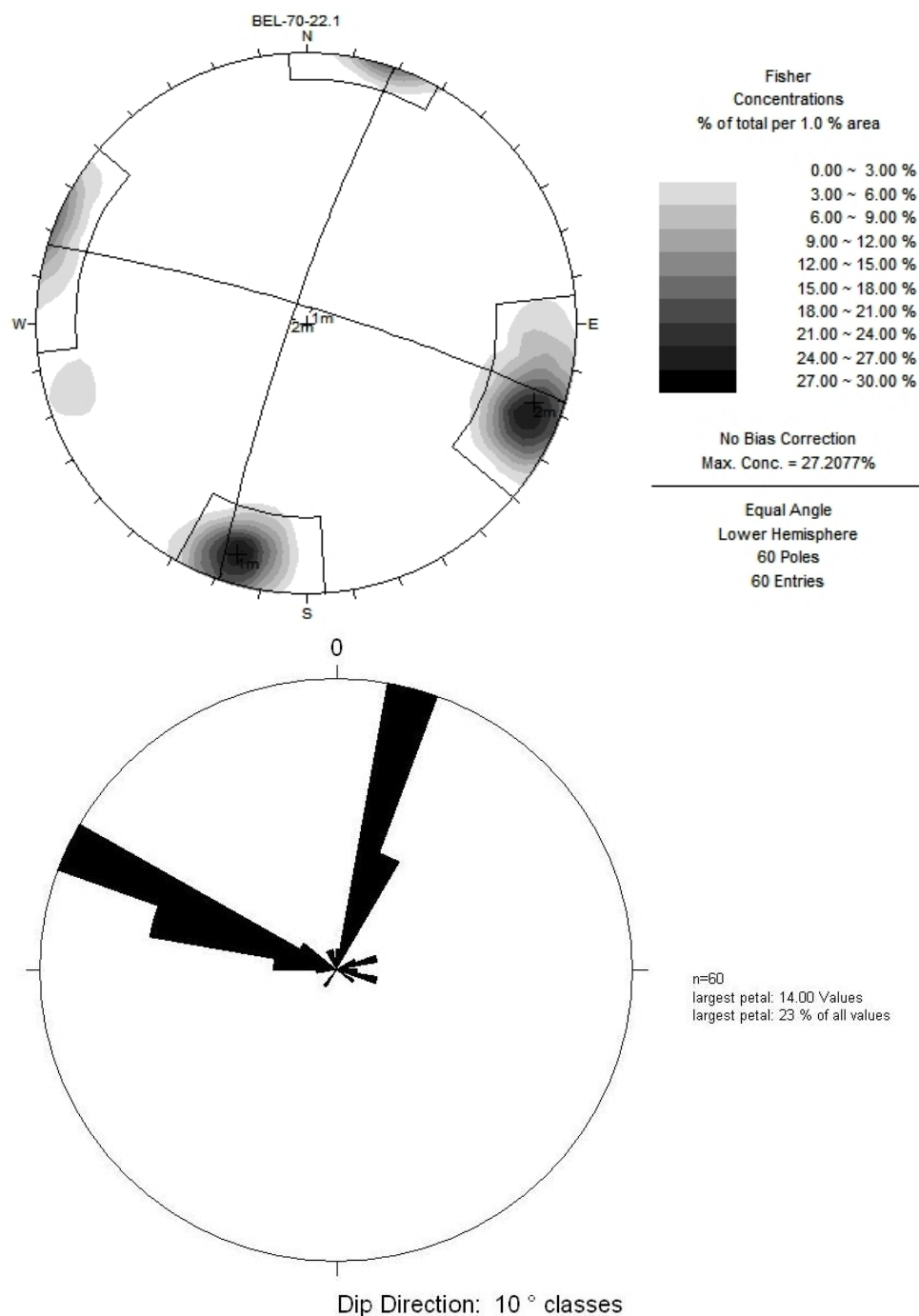
Figure 7B-6: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for BEL-70-22.1 site.
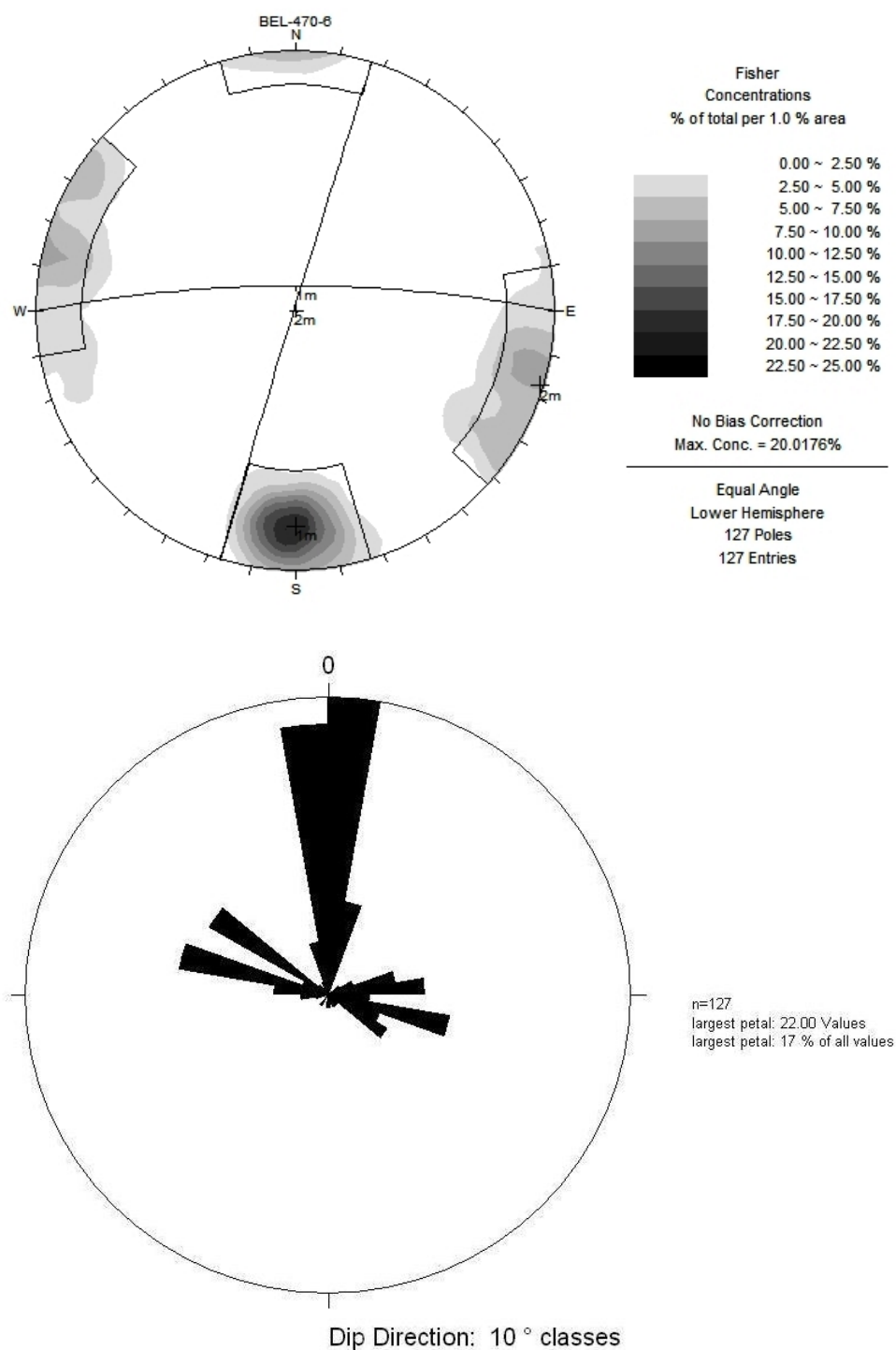
Figure 7B-7: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for BEL-70-22.1 site.
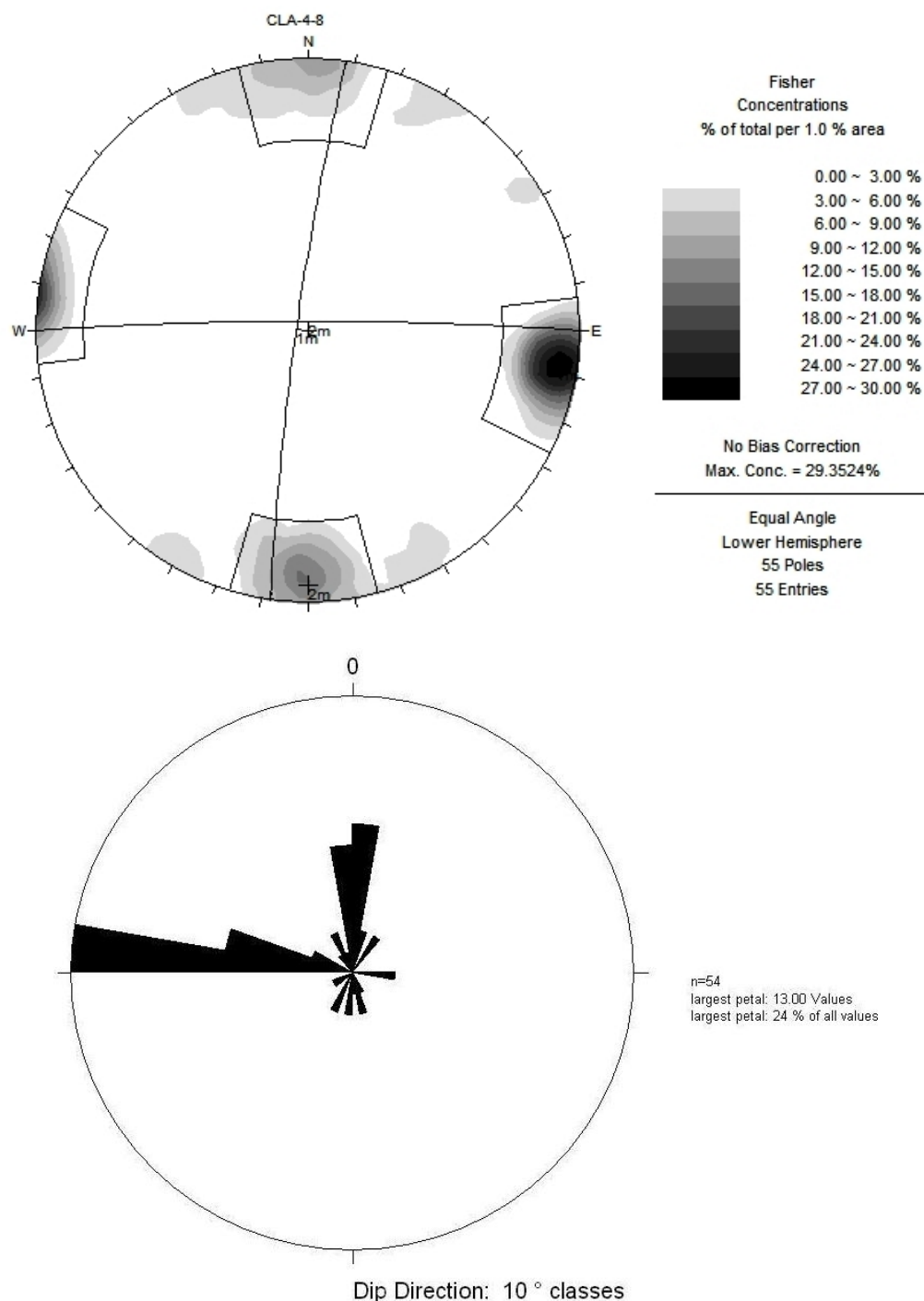
Figure 7B-8: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for CLA-4-8 site.
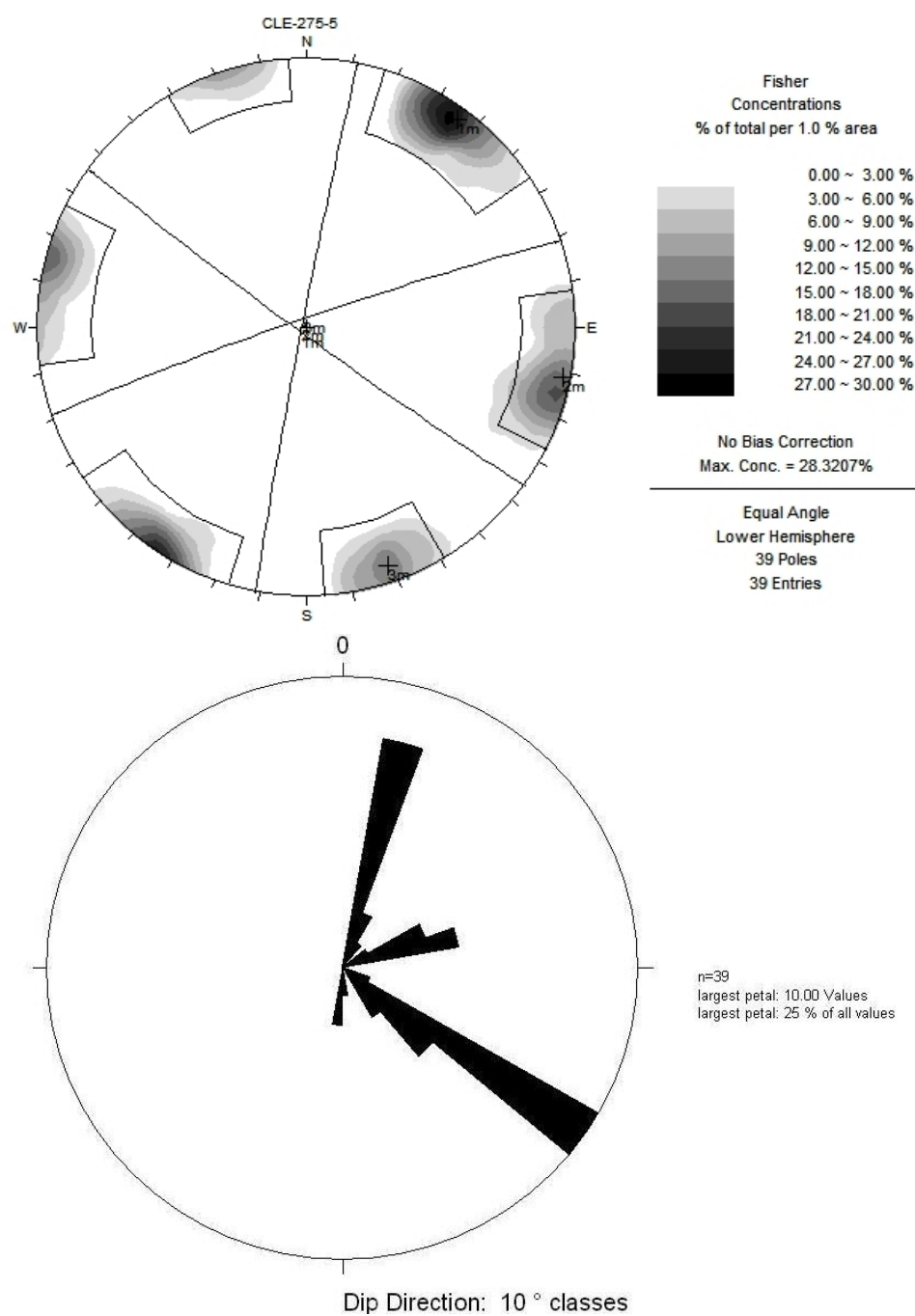
Figure 7B-9: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for CLE-275-5 site.
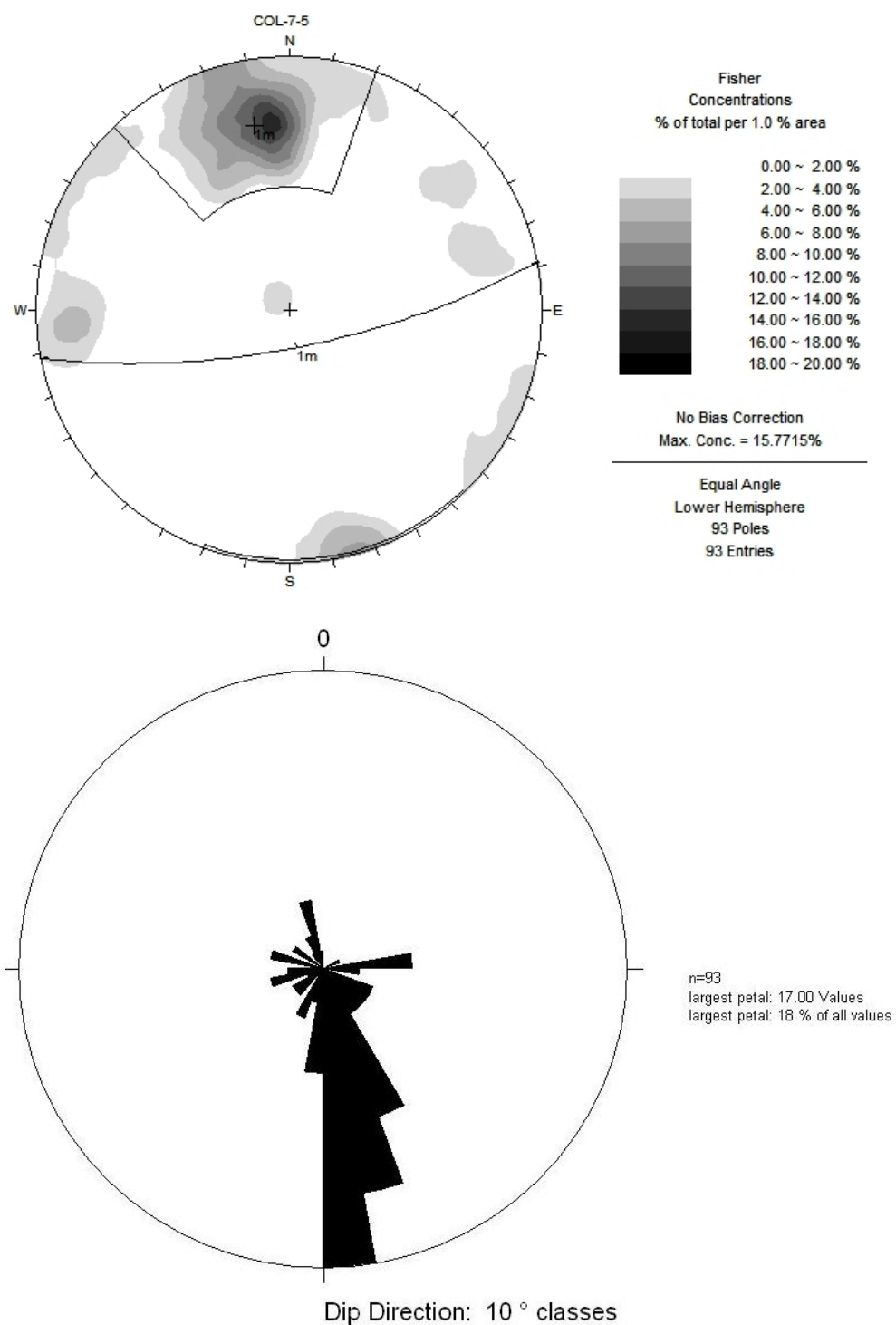
Figure 7B-10: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for COL-7-5 site.
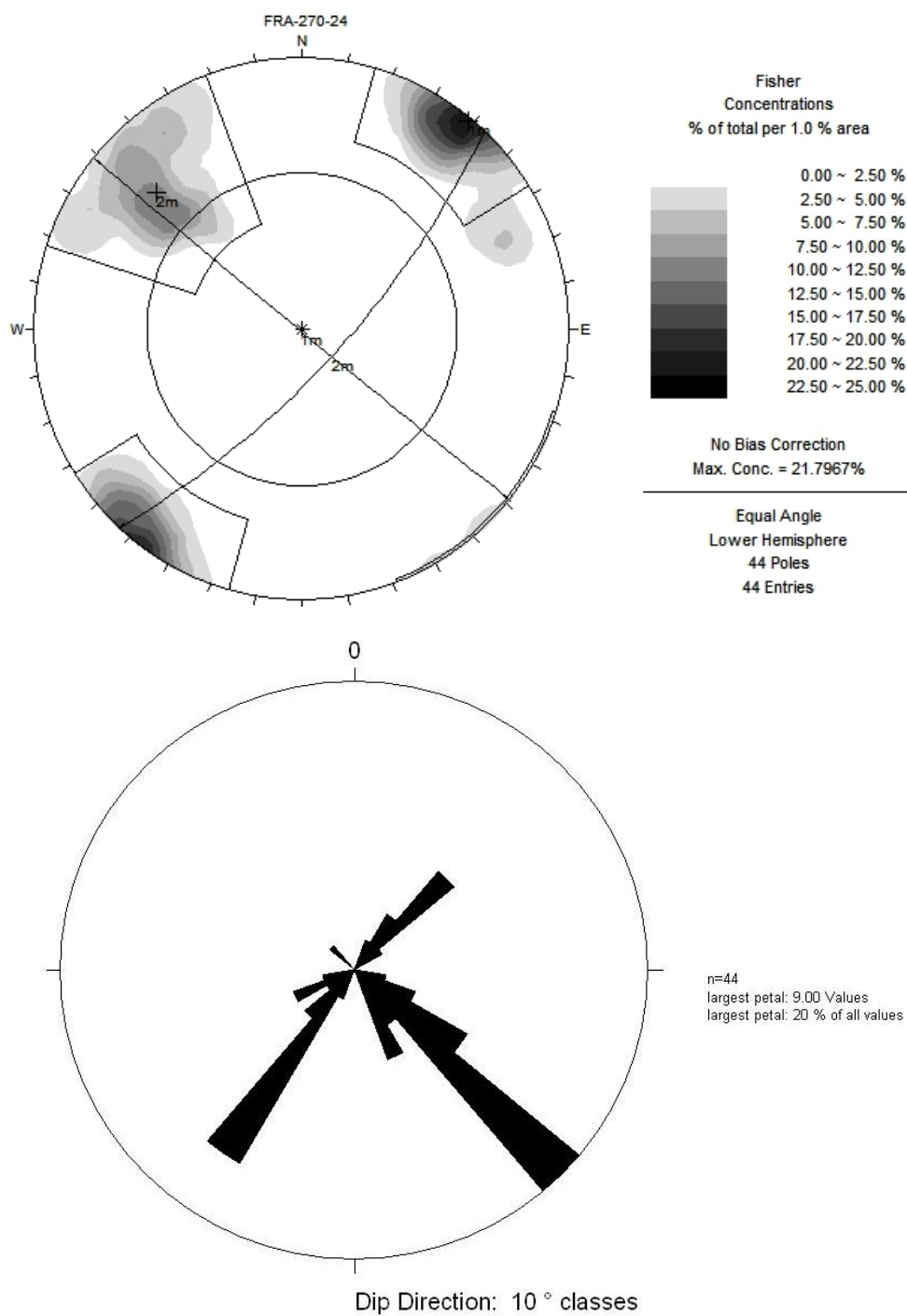
Figure 7B-11: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for FRA-270-24 site.
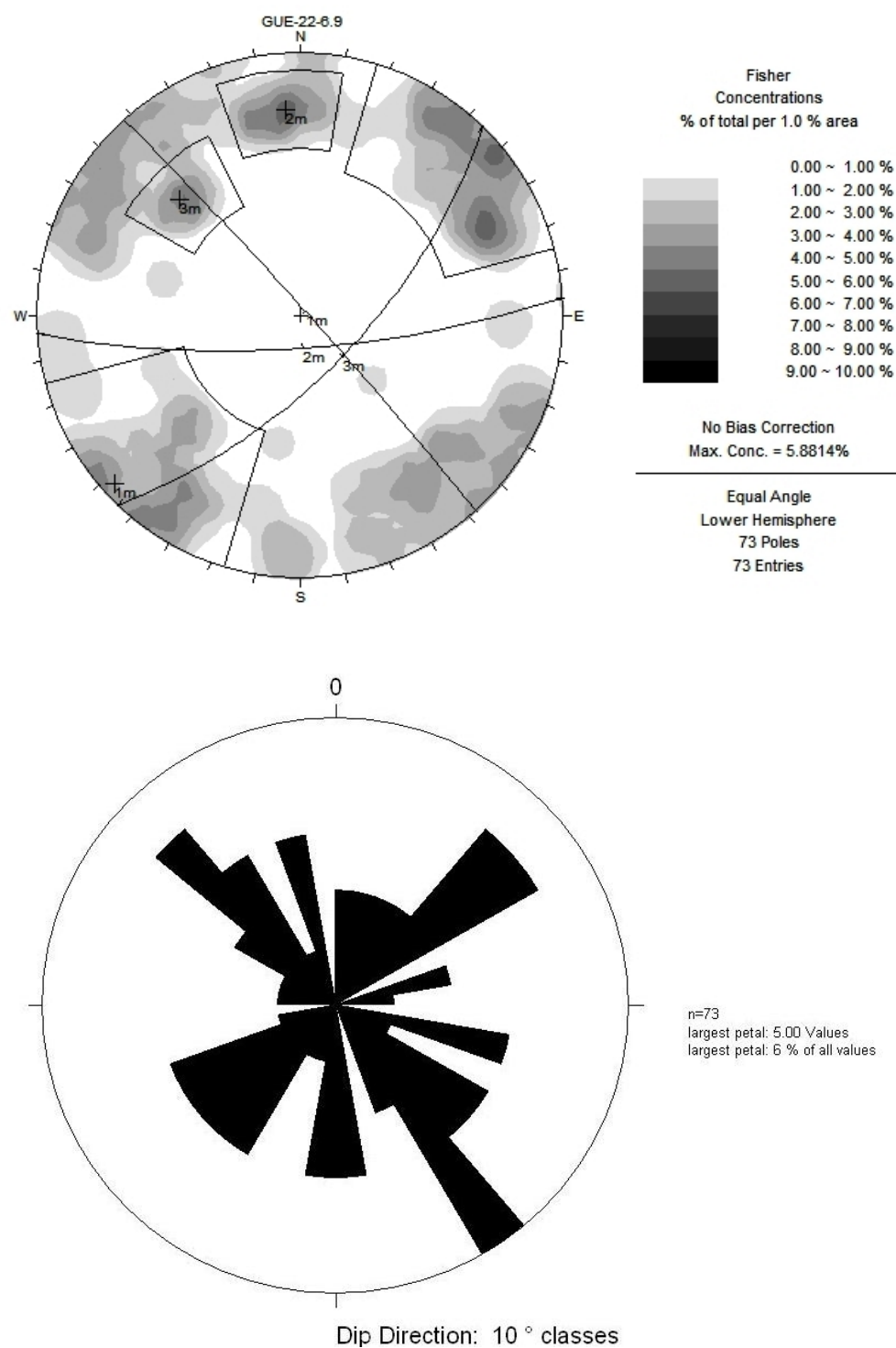
Figure 7B-12: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for GUE-22-6.9 site.
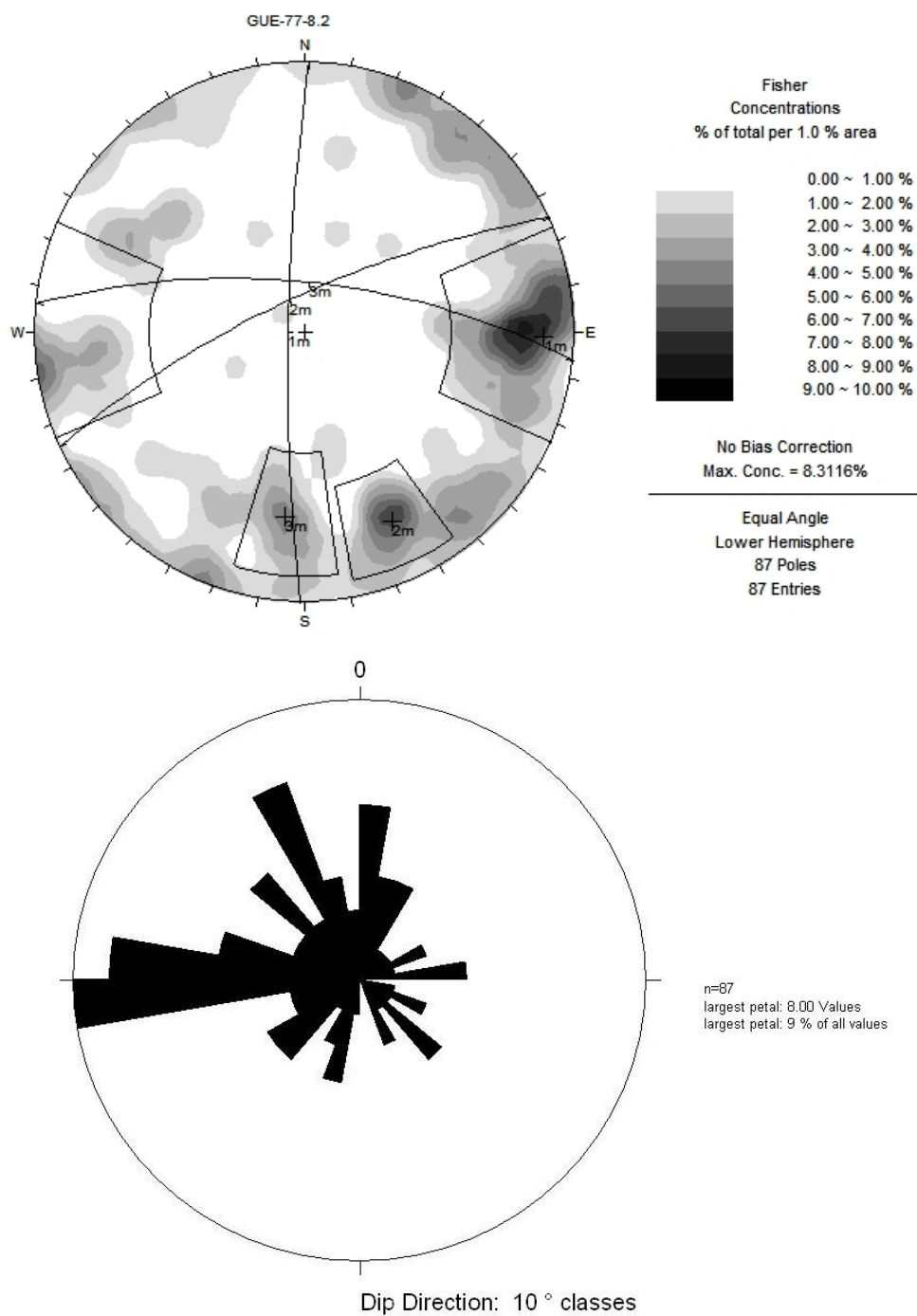
Figure 7B-13: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for GUE-77-8.2 site.
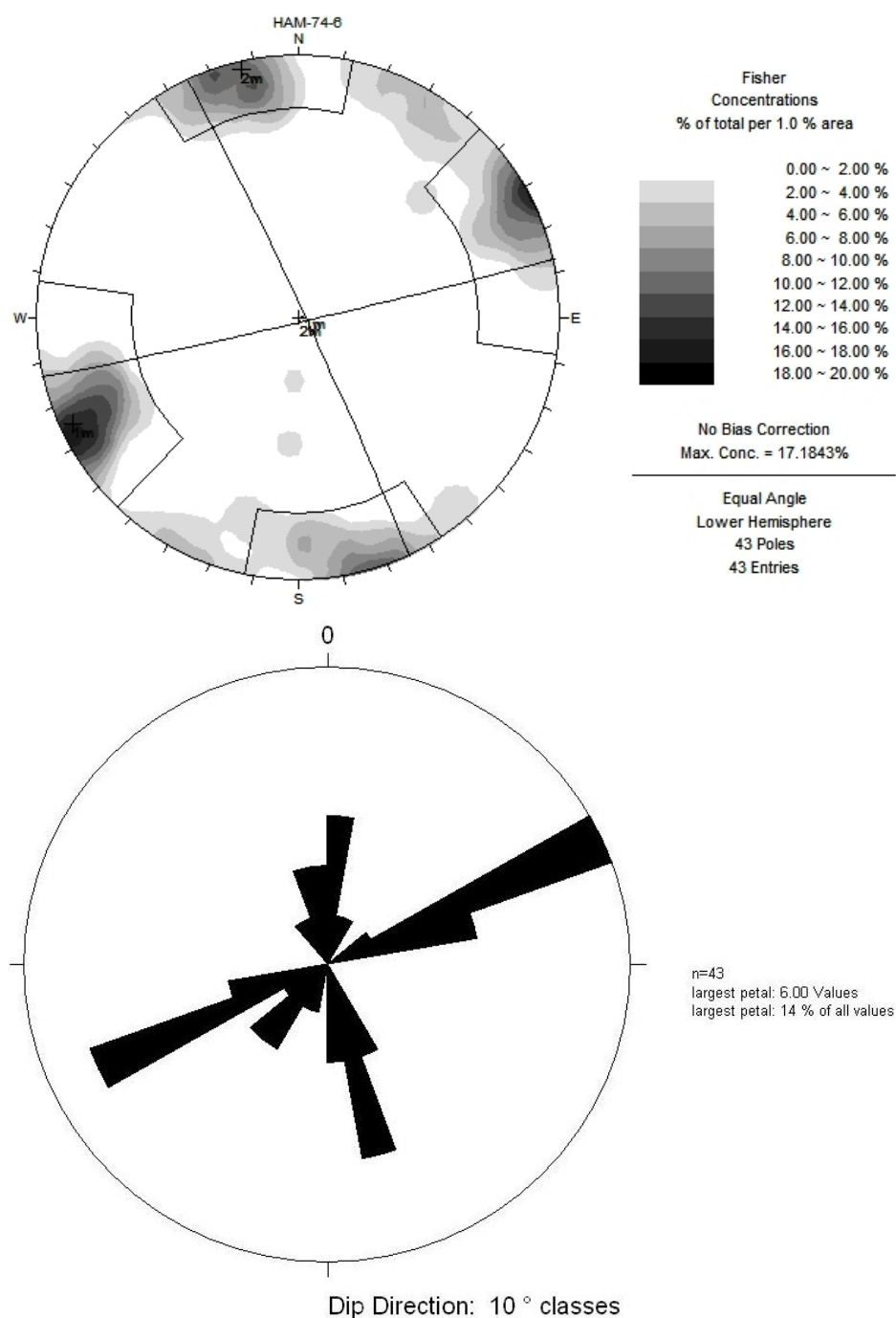
Figure 7B-14: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for HAM-74-6 site.
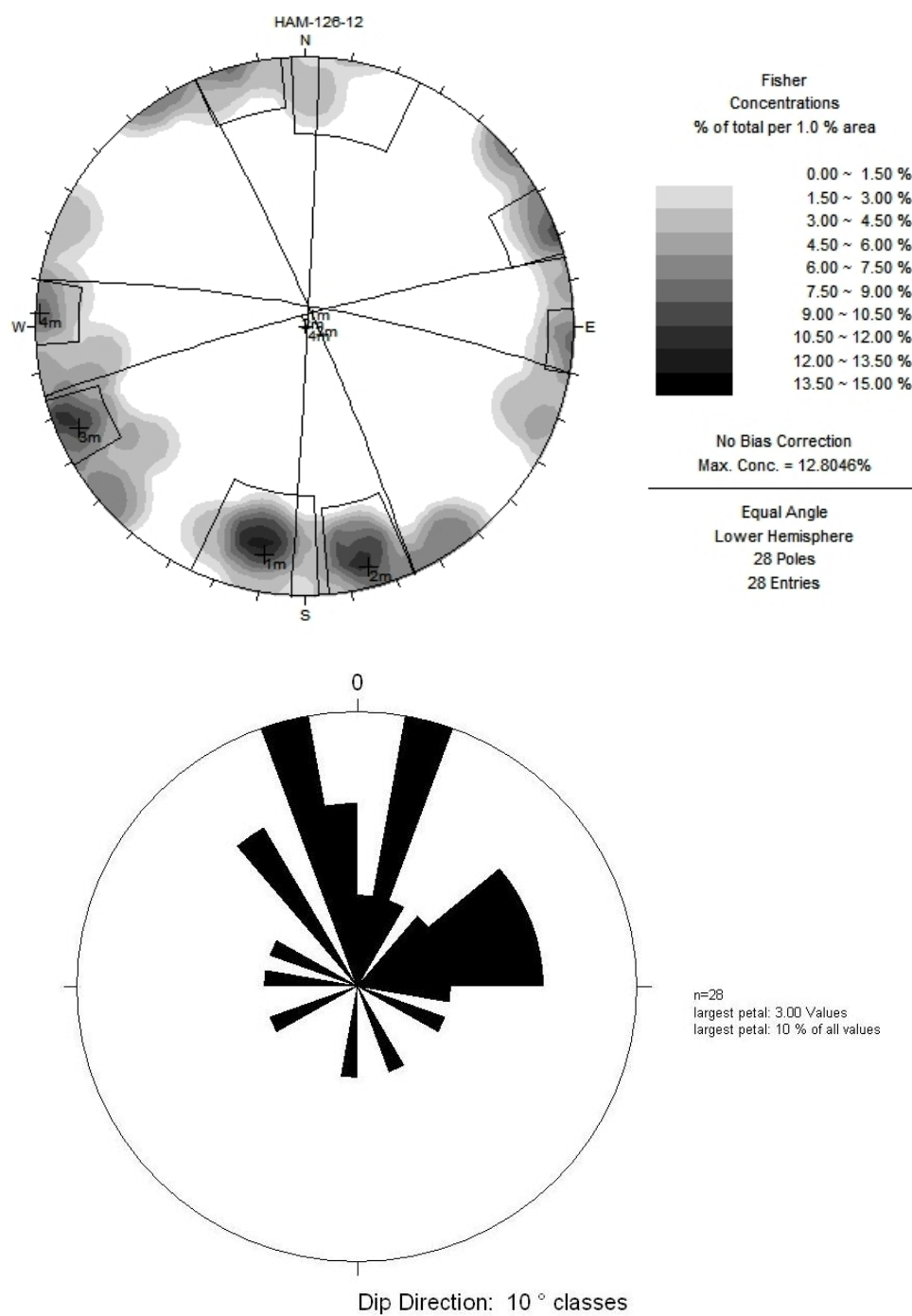
Figure 7B-15: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for HAM-126-12 site.

JEF-CR77-0.38

N

Fisher
Concentrations
% of total per 1.0 % area

0.00 ~ 1.50 %
1.50 ~ 3.00 %
3.00 ~ 4.50 %
4.50 ~ 6.00 %
6.00 ~ 7.50 %
7.50 ~ 9.00 %
9.00 ~ 10.50 %
10.50 ~ 12.00 %
12.00 ~ 13.50 %
13.50 ~ 15.00 %

No Bias Correction
Max. Conc. = 12.1918%

Equal Angle
Lower Hemisphere
39 Poles
39 Entries

0

n=39
largest petal: 5.00 V
largest petal: 12 %

Dip Direction: 10 ° classes
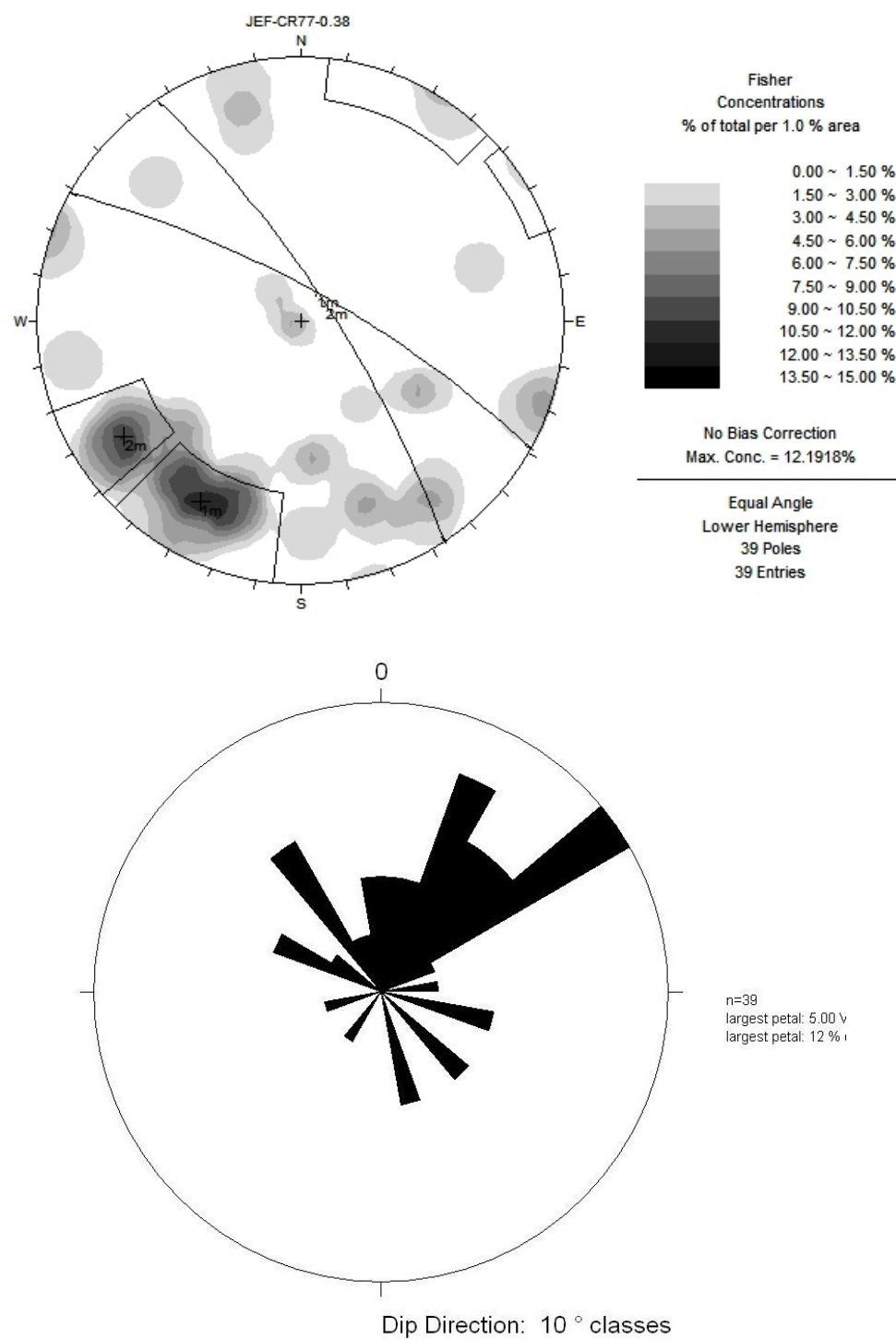
Figure 7B-16: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for JEF-CR77-0.38 site.
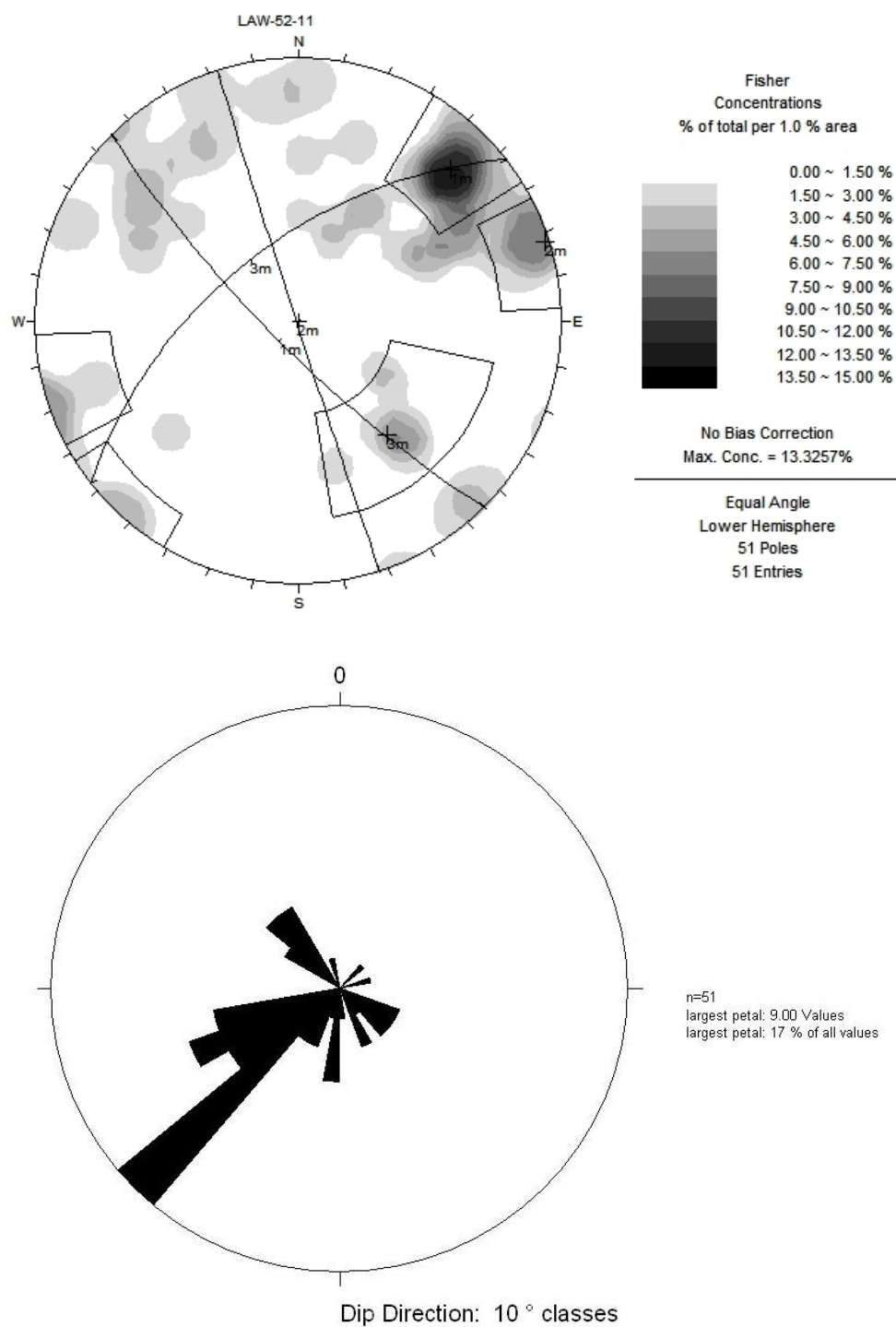
Figure 7B-17: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for LAW-52-11 site.
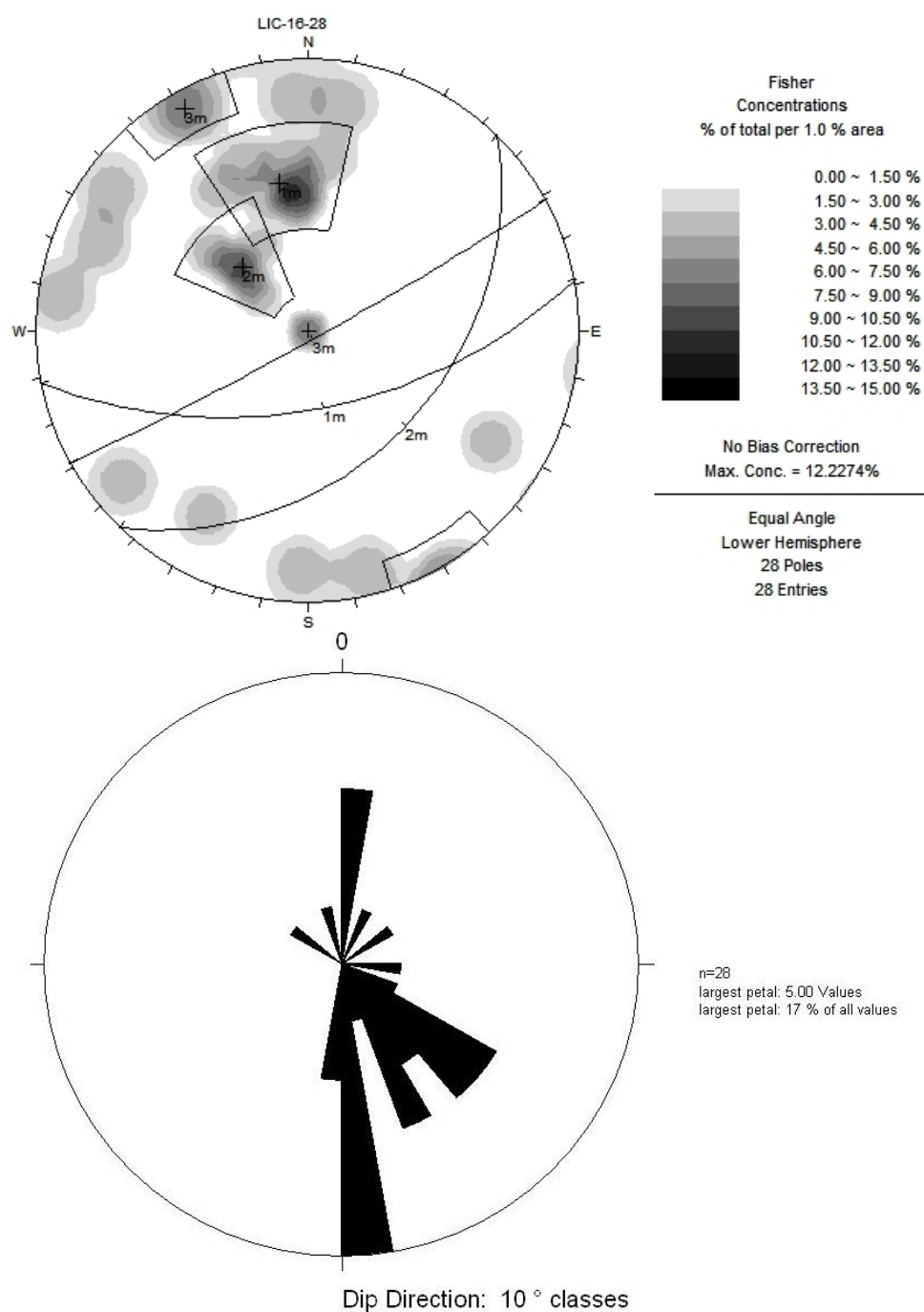
Figure 7B-18: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for LIC-16-28 site.

MEG-33-6

Schmidt
Concentrations
% of total per 1.0 % area

0.00 ~ 1.50 %
1.50 ~ 3.00 %
3.00 ~ 4.50 %
4.50 ~ 6.00 %
6.00 ~ 7.50 %
7.50 ~ 9.00 %
9.00 ~ 10.50 %

No Bias Correction
Max. Conc. = 8.6207%

Equal Angle
Lower Hemisphere
58 Poles
58 Entries

n=58
largest petal: 4.00 Values
largest petal: 6 % of all values

Dip Direction: 10 ° classes
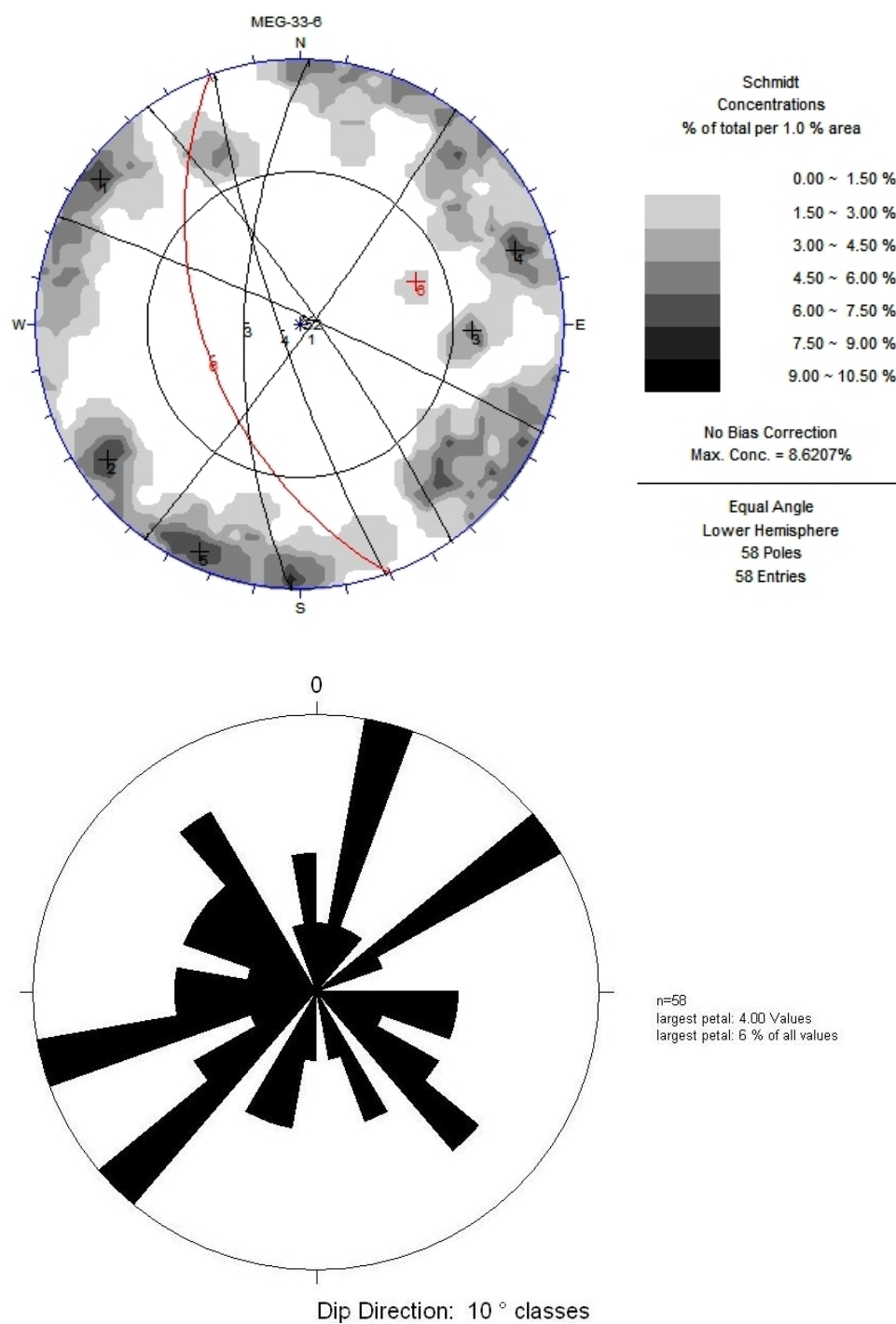
Figure 7B-19: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for MEG-33-6 site.
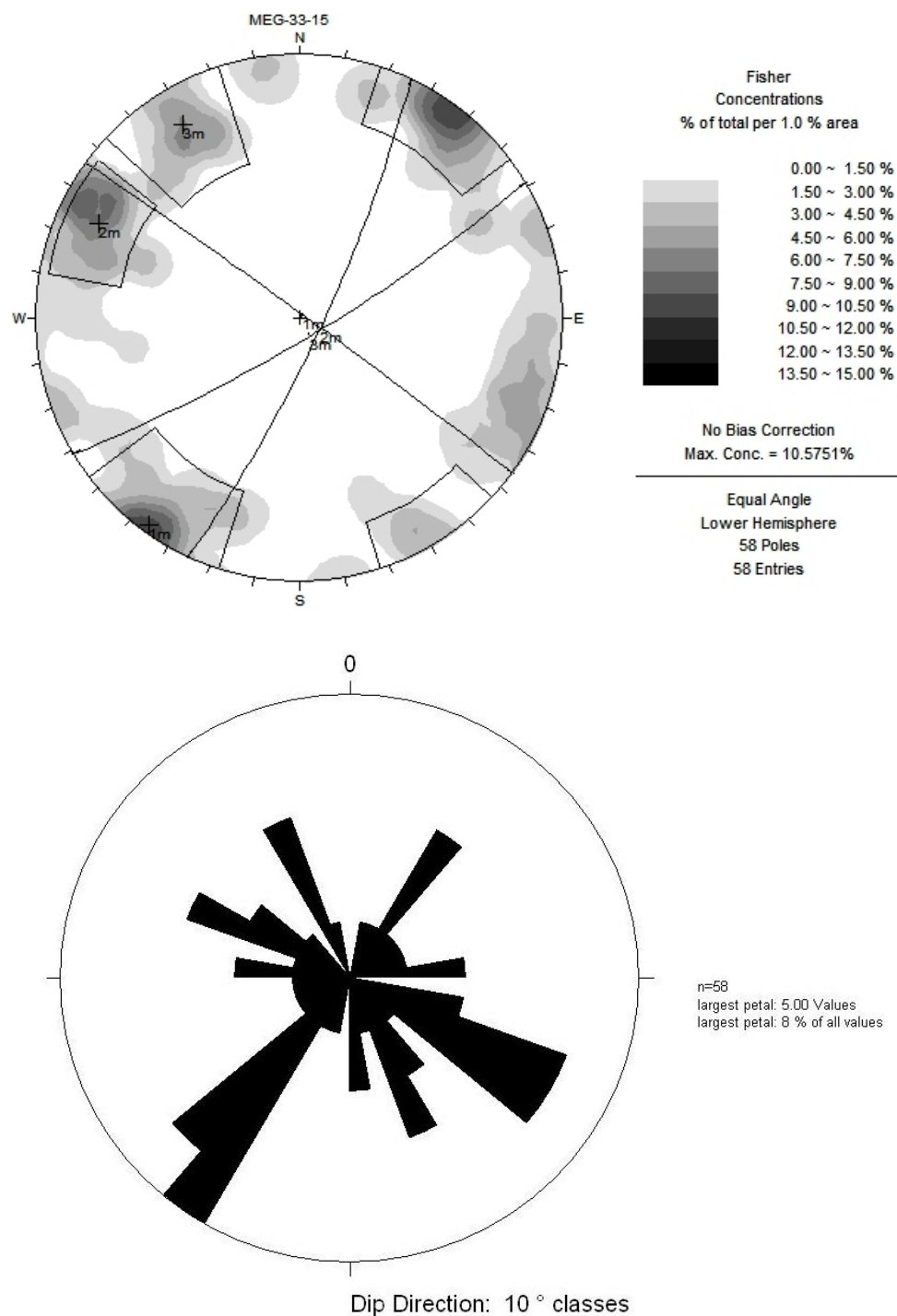
Figure 7B-20: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for MEG-33-15 site.
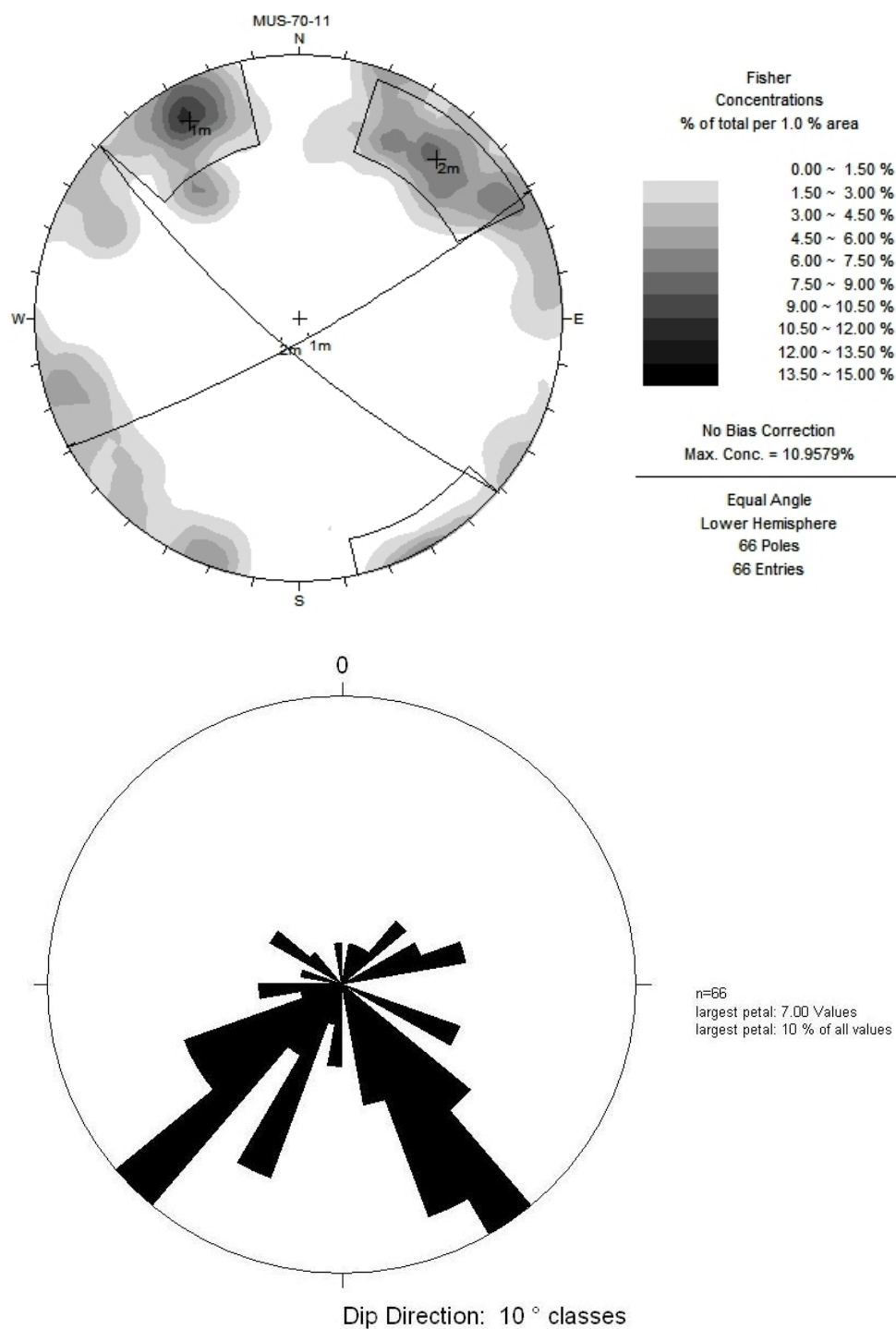
Figure 7B-21: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for MUS-70-11 site.
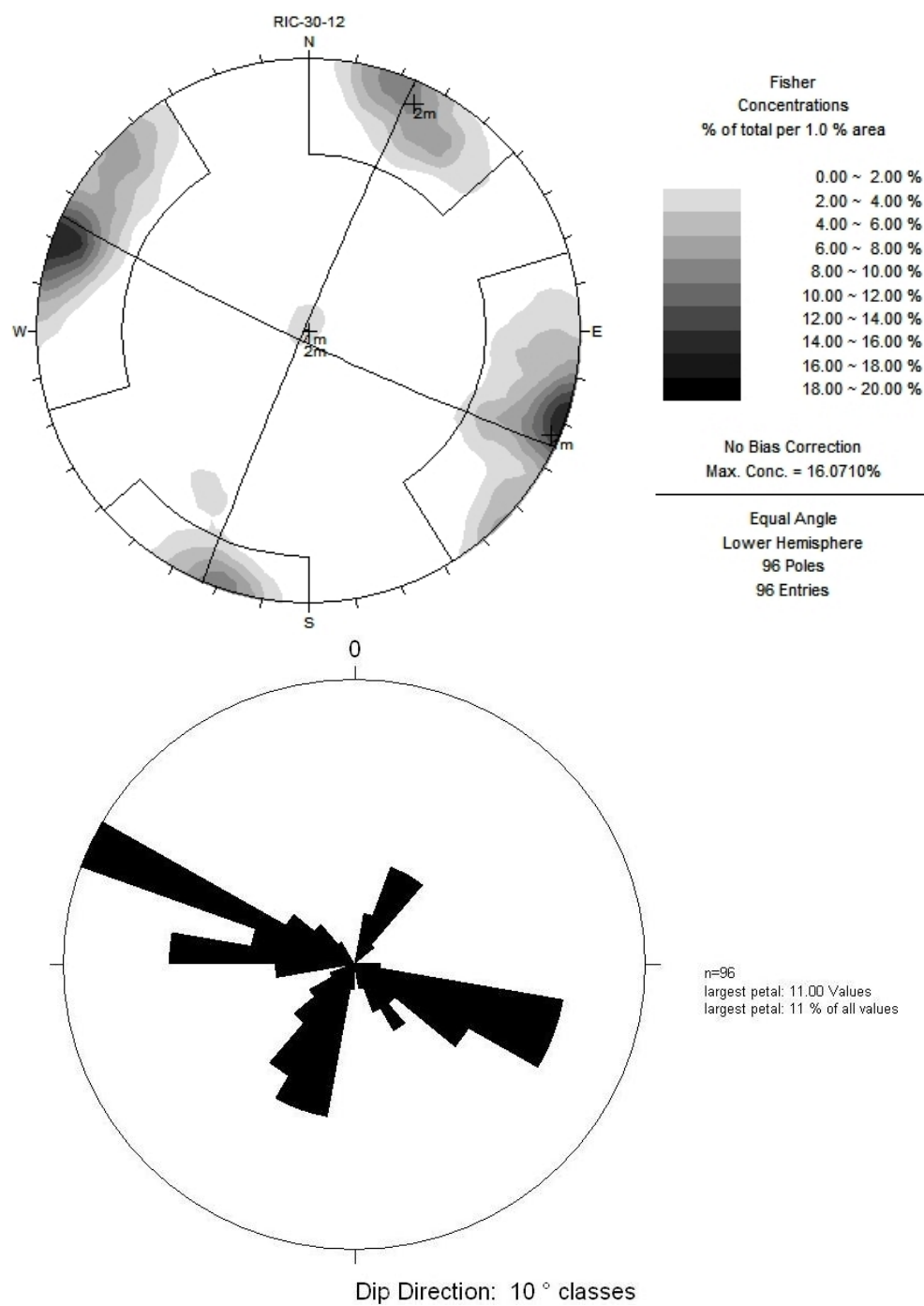
Figure 7B-22: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for RIC-30-12 site.
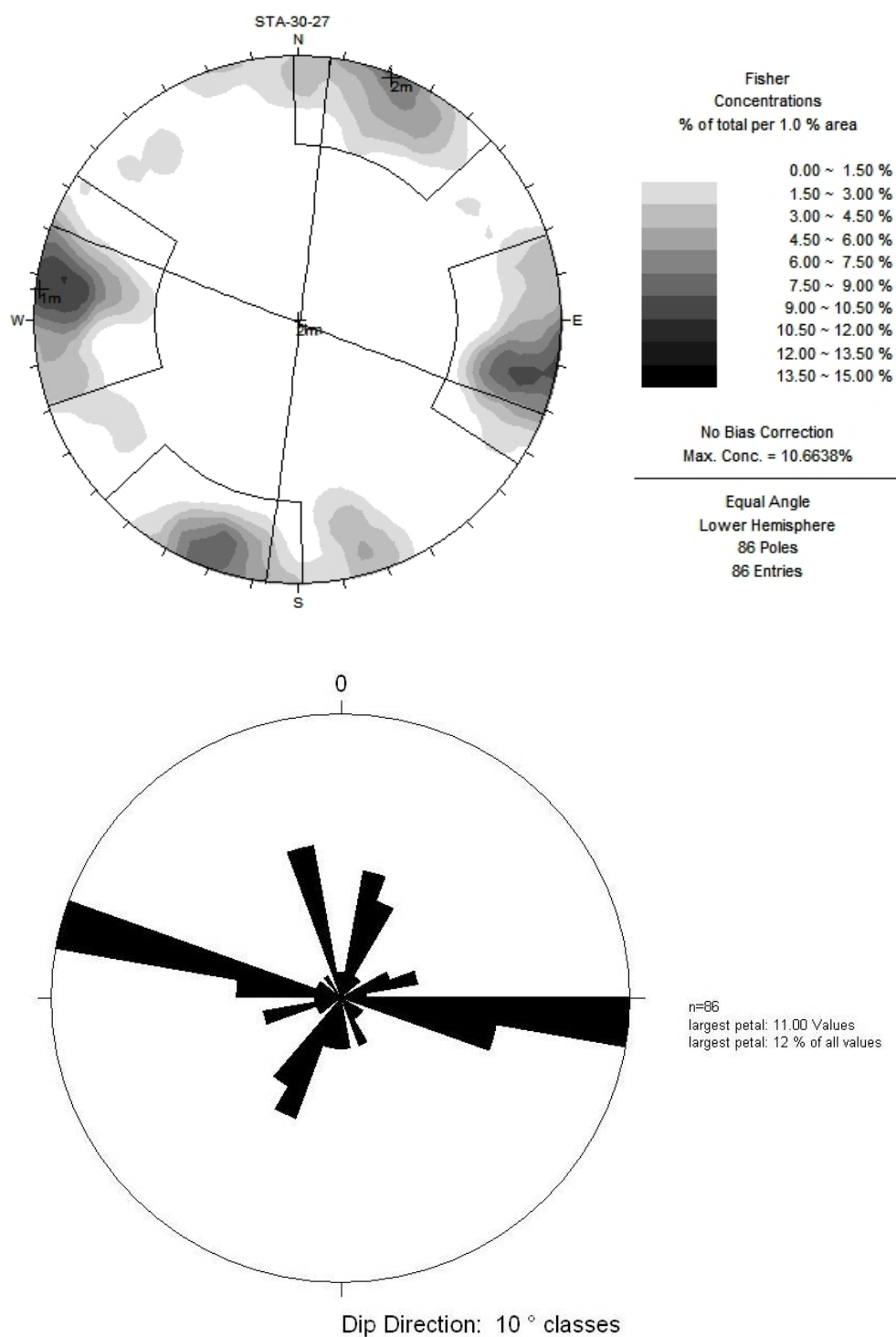
Figure 7B-23: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for STA-30-27 site.

WAS-7-18
N

Fisher
Concentrations
% of total per 1.0 % area

0.00 ~ 1.00 %
1.00 ~ 2.00 %
2.00 ~ 3.00 %
3.00 ~ 4.00 %
4.00 ~ 5.00 %
5.00 ~ 6.00 %
6.00 ~ 7.00 %
7.00 ~ 8.00 %
8.00 ~ 9.00 %
9.00 ~ 10.00 %

No Bias Correction
Max. Conc. = 8.1826%

Equal Angle
Lower Hemisphere
87 Poles
87 Entries

W

E

3m/1m

2m

1m

2m

S

0

n=86
largest petal: 5.00 Values
largest petal: 5 % of all values

Dip Direction: 10 ° classes
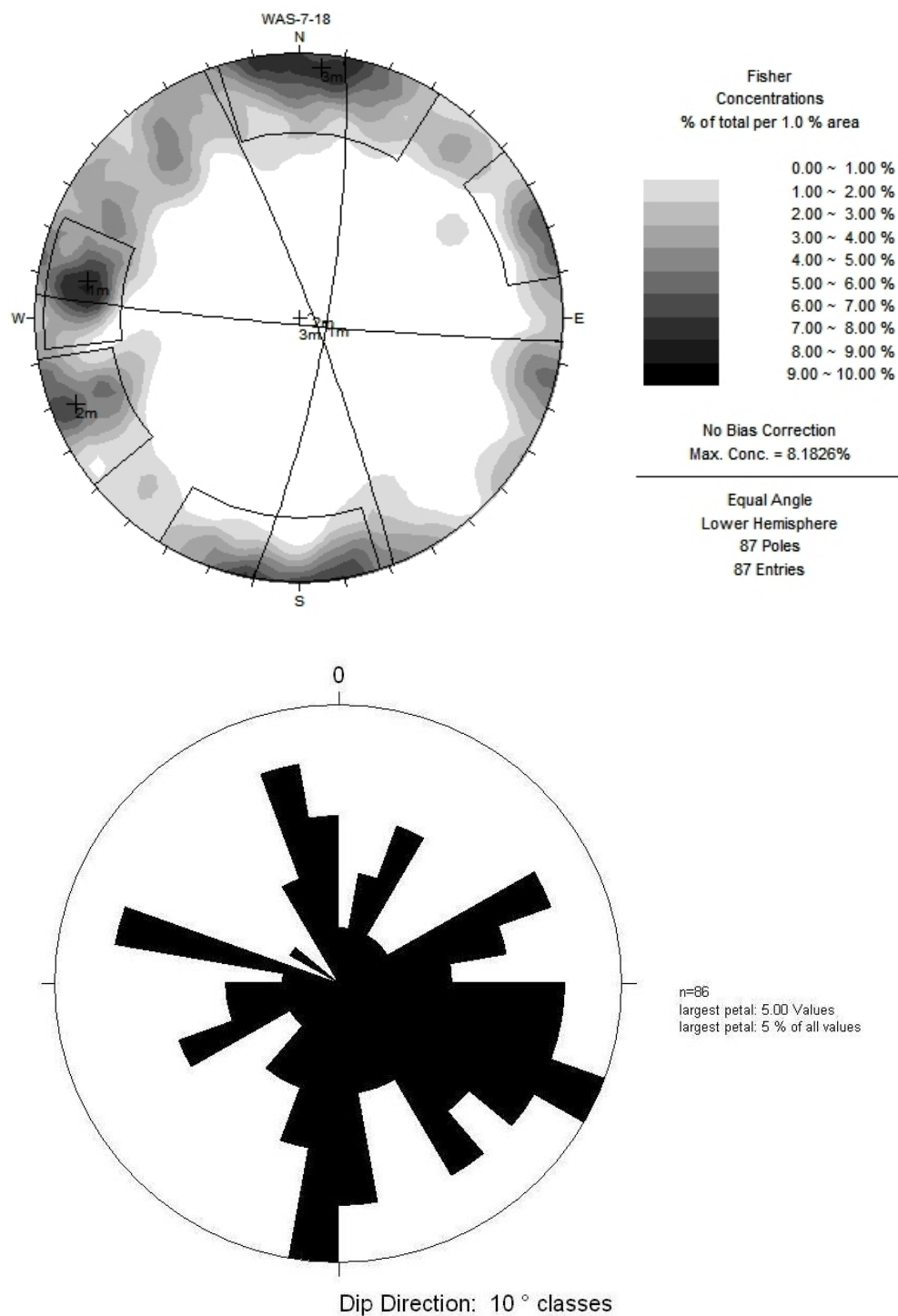
Figure 7B-24: Stereonet of contoured poles and rose diagram of dip directions of discontinuities for WAS-7-18 site.

APPENDIX 7-C

DISCONTINUITY SPACING AND BEDDING THICKNESS OF
UNDERCUT ROCK UNITS DATA

Table 7C-1: Average discontinuity spacing data for the 26 sites.

Site	Joint Spacing (ft)*
ADA-32-12	0.39-1.27
ADA-41-15	1.1
ATH-33-14	0.6
ATH-50-23	0.4
BEL-7-10	0.5
BEL-70-22	0.6
BEL-470-6	0.9
CLA-4-8	0.5
CLA-68-7	
CLE-275	0.3
COL-7-5	0.8
FRA-270-23	0.7
GUE-22-6	0.8
GUE-77-8	0.8
HAM-74-6	0.4
HAM-126-12	0.7
JEF-CR77-.38	0.7
LAW-52-11	2.0
LAW-52-12	
LIC-16-28	0.4
MEG-33-6	0.8
MEG-33-15	0.5
MUS-70-11	1.0
RIC-30-12	0.4
STA-30-27	0.6-1.5
WAS-7-18	1.0

Table 7C-1: Detailed Discontinuity spacing (by discontinuity type) and bedding thickness.

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
BEL-7-10	Sandstone	36		39	1.08	9.75
		54		39	0.72	14.63
		48		39	0.81	13
		35		39	1.11	9.48
		24		39	1.63	6.5
		31		39	1.26	8.4
		37		39	1.05	10.02
BEL-70-22	Sandstone	23		9	0.39	1.44
		18		3	0.17	0.38
		42		9	0.21	2.63
		35		12	0.34	2.92
		42		13	0.31	3.79
		32		15	0.47	3.33
		36		9	0.25	2.25
		37		11	0.3	2.83
		43		16	0.37	4.78
		37		10	0.27	2.57
		23		10	0.43	1.6
		48		15	0.31	5
		35		10	0.29	2.43
		28		10	0.36	1.94
		33		6	0.18	1.38
		33		13	0.39	2.98
		11		12	1.09	0.92
		41		16	0.39	4.56
		22	24	10	0.45	1.53
		8		11	1.38	0.61
		11		11	1	0.84
BEL-70-1.5	Sandstone	40	17	12	0.3	3.33
		27	20	5	0.19	0.94
		17	23	33	1.94	3.9
		22	5	11	0.5	1.68
		57	25	27	0.47	10.69

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
BEL-7-10	Sandstone	36		39	1.08	9.75
		54		39	0.72	14.63
		48		39	0.81	13
		35		39	1.11	9.48
		24		39	1.63	6.5
		31		39	1.26	8.4
		37		39	1.05	10.02
BEL-70-22	Sandstone	23		9	0.39	1.44
		18		3	0.17	0.38
		42		9	0.21	2.63
		35		12	0.34	2.92
		42		13	0.31	3.79
		32		15	0.47	3.33
		36		9	0.25	2.25
		37		11	0.3	2.83
		43		16	0.37	4.78
		37		10	0.27	2.57
		23		10	0.43	1.6
		48		15	0.31	5
		35		10	0.29	2.43
		28		10	0.36	1.94
		33		6	0.18	1.38
		33		13	0.39	2.98
		11		12	1.09	0.92
		41		16	0.39	4.56
		22	24	10	0.45	1.53
		8		11	1.38	0.61
		11		11	1	0.84
BEL-70-1.5	Sandstone	40	17	12	0.3	3.33
		27	20	5	0.19	0.94
		17	23	33	1.94	3.9
		22	5	11	0.5	1.68
		57	25	27	0.47	10.69
BEL-470-6	Limestone	13		12	0.92	1.08

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
BEL-470-6	Limestone	23		12	0.52	1.92
		16		12	0.75	1.33
		38		20	0.53	5.28
BEL-470-6	Limestone	17		20	1.18	2.36
		41		20	0.49	5.69
		31		20	0.65	4.31
		37		20	0.54	5.14
		34	19	17	0.5	4.01
		26	31	17	0.65	3.07
		10		17	1.7	1.18
		26		17	0.65	3.07
		42		17	0.4	4.96
		26		17	0.65	3.07
		26		17	0.65	3.07
		36		17	0.47	4.25
		21		17	0.81	2.48
		27		17	0.63	3.19
		21		17	0.81	2.48
		16		17	1.06	1.89
COL-7-3	Sandstone	49		39	0.8	13.27
		61		45	0.74	19.06
		28	19	7	0.25	1.36
		29		7	0.24	1.41
		10		10	1	0.69
		14		9	0.64	0.88
		13		5	0.38	0.45
		25	11	26	1.04	4.51
		25	12	43	1.72	7.47
		82		40	0.49	22.78
		13		17	1.31	1.53
		40		31	0.78	8.61
		21		8	0.38	1.17

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
COL-7-3	Sandstone	46		7	0.15	2.24
		70		7	0.1	3.4
		104		21	0.2	15.17
		27		8	0.3	1.5
		22		15	0.68	2.29
		52		5	0.1	1.81
		38		20	0.53	5.28
		35		9	0.26	2.19
COL-7-5	Sandstone	9	8	7	0.78	0.44
		115	11	46	0.4	36.74
		18	17	12	0.67	1.5
		13	18	9	0.69	0.81
		15		6	0.4	0.63
		11		9	0.82	0.69
		13		11	0.85	0.99
		40		29	0.73	8.06
		37		10	0.27	2.57
		8		14	1.75	0.78
		38		16	0.42	4.22
		46		25	0.54	7.99
HAM-74-6	Limestone	7		2	0.29	0.1
		10		2	0.2	0.14
		11		2	0.18	0.15
		18		2	0.11	0.25
		27		5	0.19	0.94
		12		5	0.42	0.42
		17		5	0.29	0.59
		15		3	0.2	0.31
		32		3	0.09	0.67
		26		3	0.12	0.54
		17		3	0.18	0.35

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
HAM-74-6	Limestone	18		3	0.17	0.38
		11		3	0.27	0.23
		25		3	0.12	0.52
		10		2	0.2	0.14
		13		2	0.15	0.18
HAM-74-6	Limestone	16		3	0.19	0.33
		8		3	0.38	0.17
		16		2	0.13	0.22
		27		2	0.07	0.38
		20		2	0.1	0.28
		21		3	0.14	0.44
		9		3	0.33	0.19
		16		3	0.19	0.33
		19		3	0.16	0.4
		21		3	0.14	0.44
JEF-7-6	Sandstone	104	28	16	0.15	11.56
		230	13	16	0.07	25.56
		256	16	10	0.04	17.78
JEF-7-23	Limestone	25	8	17	0.68	2.95
		17		16	0.94	1.89
		7		9	1.32	0.43
		17		13	0.76	1.53
		13		18	1.38	1.63
		10		12	1.2	0.83
		17		14	0.82	1.65
		67	32	5	0.07	2.33
		160	30	11	0.07	12.22
JEF-22-8(N-facing)	Sandstone	24	24	9	0.38	1.5
		43	13	15	0.35	4.48
		65	20	31	0.48	13.99
		59	71	11	0.19	4.51
		105	24	62	0.59	45.21

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
JEF-22-8(N-facing)	Sandstone	24	27	5	0.21	0.83
		25	40	42	1.68	7.29
		68	36	14	0.21	6.61
JEF-22-8(N-facing)	Sandstone	130	20	10	0.08	9.03
		32	17	13	0.41	2.89
JEF-22-8(S-facing)	Sandstone	64	33	4	0.06	1.78
		66	48	27	0.41	12.38
		94		21	0.22	13.71
JEF-CR77-0.4	Sandstone	112	48	12	0.11	9.33
		240	7	33	0.14	55
		127	44	28	0.22	24.69
		180	20	36	0.2	45
LAW-52-11	Limestone	360		45.6	0.13	114
		360		45.6	0.13	114
		360		45.6	0.13	114
		360		45.6	0.13	114
		360		45.6	0.13	114
		360		45.6	0.13	114
MUS-70-25	Limestone	22	15	21	0.95	3.21
		16	8	19	1.19	2.11
		22	14	21	0.95	3.21
		15	17	22	1.47	2.29
		18	14	22	1.22	2.75
		34	16	20	0.59	4.72
		10	18	15	1.5	1.04
		9	34	13	1.44	0.81
		3	21	16	5.33	0.33
WAS-77-15	Limestone	4		3	0.71	0.09
		6		4	0.67	0.17
		3		4	1.54	0.07
		4		3	0.75	0.08

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
WAS-77-15	Limestone	7		4	0.57	0.19
		5		4	0.84	0.13
		5		4	0.8	0.14
		11		13	1.18	0.99
		7		10	1.43	0.49
WAS-77-15	Limestone	6		5	0.86	0.2
		11		16	1.45	1.22
		15		14	0.95	1.43
		8		9	1.15	0.49
		7		10	1.39	0.5
		8		12	1.43	0.7
		11		14	1.27	1.07
		8		14	1.75	0.78
		5		5	1	0.17
		7		9	1.29	0.44
		9		11	1.27	0.66
		8		15	1.82	0.86
		10		7	0.72	0.47
		7		7	1.08	0.32
		8		7	0.84	0.41
		15		10	0.68	1.02
LAW-52-11	Sandstone	60	18	20	0.33	8.33
		48	24	20	0.42	6.67
		72		20	0.28	10
		840	19	74.4	0.09	434
		840	72	74.4	0.09	434
		840		74.4	0.09	434
		840		74.4	0.09	434
LAW-52-11	Sandstone	840	120	74.4	0.09	434
WAS-7-18	Sandstone	48		46	0.96	15.33
		36		58	1.61	14.5

Table 7C-1 (contd.).

Site	Rock Type	Spacing of Orthogonal Joints (in)	Spacing of Valley Stress Relief Joints (in)	Bedding Thickness (in)	Bedding Thickness/Spacing of Orthogonal Joints	Bedding Thickness Spacing of Orthogonal Joints (ft^2)
WAS-7-18	Sandstone	64		73	1.14	32.44
		38		30	0.79	7.92
		72		36	0.5	18
		52		18	0.35	6.5
		41		22	0.54	6.26
		43		26	0.6	7.76
WAS-77-15	Limestone	15		6	0.39	0.64
		11		6	0.53	0.47
		13		15	1.18	1.32
		9		7	0.81	0.42
		8		5	0.63	0.28
		10		3	0.3	0.21
		10		3	0.32	0.2
		9		6	0.65	0.39
		11		5	0.48	0.36
		20		5	0.25	0.68
		14		14	0.98	1.39
		10		10	0.98	0.71
		12		11	0.89	0.94
		23		13	0.57	2.08

APPENDIX 8

UNDERCUTTING DATA

APPENDIX 8-A

TOTAL AMOUNT OF UNDERCUTTING AND RATE OF
UNDERCUTING FOR THE 26 PROJECT SITES

Table 8A-1: Present and total amounts of undercutting for selected undercut layers from the 26 project sites.

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Age of Slope Cut	Rate of Undercutting (in/yr)
BEL-470-6	Limestone	37.2	20.8	82	30	2.7
	Limestone	21.9	11.2	63	30	2.1
	Limestone	22	0	76.8	30	2.6
	Limestone	38.3	24.7	49.8	30	1.7
BEL-70-22	Limestone	35.3	0	80.4	46	1.7
	Sandstone	52.8	27.8	43.3	46	0.9
	Sandstone	23.8	24	105.6	46	2.3
BEL-7-10	Limestone	164.3	9.4	73.8	35	2.1
	Limestone	72.4	0	55.9	35	1.6
	Sandstone	40	34.3	34.3	35	1.0
COL-7-5	Sandstone	175.8	10.5	20	19	1.1
	Sandstone	165	0	0	19	0.0
JEF-CR77-0.4	Sandstone	46.2	10.6	143.9	19	7.6
	Sandstone	38.3	18	72.9	19	3.8
	Sandstone	65.9	73.3	73.7	19	3.9
	Sandstone	25.1	40	43.2	19	2.3
LAW-52-11	Limestone	139	18	18	10	1.8
	Limestone	139.1	1.9	18	10	1.8
	Limestone	163.1	1.9	18	10	1.8
	Sandstone	122.5	0	0	10	0.0
	Sandstone	135.2	16.2	26.6	10	2.7
	Sandstone	135.2	8.8	26.6	10	2.7
	Sandstone	154.2	8.8	26.6	10	2.7
LAW-52-12	Sandstone	118.2	36.6	36.6	43	0.9
	Sandstone	126	36.6	36.6	43	0.9

Table 8A-1 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Age of Slope Cut	Rate of Undercutting (in/yr)
LAW-52-12	Sandstone	120.8	36.6	36.6	43	0.9
	Sandstone	118.2	31.4	31.4	43	0.7
LAW-52-12	Sandstone	126	31.4	31.4	43	0.7
	Sandstone	120.8	31.4	31.4	43	0.7

APPENDIX 8-B

TOTAL AMOUNT OF UNDERCUTTING AND RATE OF
UNDERCUTING FOR THE 23 ADDITIONAL SITES

Table 8B-1: Present and total amounts of undercutting for selected undercut layers from 23 additional sites.

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Age of Slope Cut	Rate of Undercutting (in/yr)
BEL-70-1.58	Sandstone	24.4	0	144	44	3.3
BEL-7-24	Sandstone	30.3	48	48		
COL-7-3	Sandstone	24.3	1.8	80.2	37	2.2
	Sandstone	60.4	39.8	39.8	37	1.1
	Sandstone	54.7	25.3	30.7	37	0.8
	Sandstone	60.4	0	39.8	37	1.1
JEF-22-8 (N-facing slope)	Sandstone	38.1	19.7	34.5	22	1.6
	Sandstone	25.8	79	74.3	22	3.4
	Sandstone	26.6	1.9	73.2	22	3.3
	Sandstone	19.3	27.6	72.3	22	3.3
JEF-22-8 (S-facing slope)	Sandstone	7.6	62.4	62.4	22	2.8
	Sandstone	16.2	23.9	23.9	22	1.1
JEF-7-23	Limestone	205.6	6.2	36.4	40	0.9
	Limestone	169.3	1.2	17.5	40	0.4
JEF-7-23	Limestone	189.7	26.3	38.4	40	1.0
	Limestone	140.2	6.8	48	40	1.2
	Sandstone	130.5	39.7	39.7	40	1.0
	Sandstone	197.9	21.6	21.6	40	0.5
	Sandstone	160.4	11.8	11.8	40	0.3
	Sandstone	183.8	7.8	7.8	40	0.2
JEF-7-6	Sandstone	100.2	11.8	11.8	54	0.2
TUS-77-168	Sandstone	30.3	0	76.6	42	1.8
WAS-77-15 (799*)	Limestone	113.6	12.8	56	42	1.3
	Limestone	103.5	12	85.3	42	2.0
	Limestone	74	21	118	42	2.8

Table 8A-1 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Age of Slope Cut	Rate of Undercutting (in/yr)
WAS-77-15 (801*)	Limestone	81.9	12.8	53.5	42	1.3
	Limestone	71.8	12	82.8	42	2.0
	Limestone	39.2	21	100.4	42	2.4
WAS-77-15 (810*)	Limestone	37.3	26.4	131.9	42	3.1
	Limestone	48	10.4	154.4	42	3.7

APPENDIX 8-C

TOTAL THICKNESS OF UNDERCUT ROCK UNIT DATA

Table 8C-1: Total thickness of undercut rock units.

Site	Rock type	Total Thickness (ft)
BEL-470-5B	Limestone	1.35
	Limestone	1.41
	Limestone	0.97
	Limestone	1.92
BEL-7	Limestone	0.9
	Limestone	1.1
	Limestone	1.68
	Sandstone	5
BEL-70-22	Sandstone	7
BEL-7-24	Sandstone	53.9
COL-7-3	Sandstone	24.21
	Sandstone	54.73
	Sandstone	60.37
	Sandstone	60.37
COL-7-5	Sandstone	1.6
MUS-70-25	Limestone	1.56
	Limestone	4
BEL-70-1.58	Sandstone	12
JEF-22-8N	Sandstone	19.34
	Sandstone	25.79
	Sandstone	26.57
	Sandstone	38.06
JEF-22-8S	Sandstone	7.61
	Sandstone	16.18
JEF-7-23-1	Limestone	2.39
	Sandstone	8.06
	Sandstone	10.69
	Limestone	2.19
	Limestone	2.14
	Sandstone	7.23
	Limestone	2.6
	Sandstone	2.49
JEF-7-6-1	Sandstone	2.84
	Sandstone	12.75
	Sandstone	42.56
JEF-CR77	Sandstone	5.9
	Sandstone	7.9
	Sandstone	14.7
	Sandstone	21.4
LAW-52-12	Limestone	3.8
	Limestone	3.8
	Limestone	2.7

Table 8C-1 (contd.).

Site	Rock type	Total Thickness (ft)
LAW-52-11	Sandstone	5.2
	Sandstone	6.2
	Sandstone	7.2
	Sandstone	9.4
	Sandstone	9.8
	Sandstone	10.4
LAW-52-12	Sandstone	0.76
	Sandstone	1
	Sandstone	1.35
	Sandstone	3.8
	Sandstone	6.72
	Sandstone	8.7
	Sandstone	45.61
	Sandstone	45.61
	Sandstone	45.77
	Sandstone	45.77
	Sandstone	54.35
	Sandstone	54.35
TUS-77-03	Sandstone	21
WAS-7-18	Sandstone	7.29
WAS-77-15	Limestone	1.12
	Limestone	2.64
	Limestone	4.17
	Limestone	4.07
	Limestone	0.49
	Limestone	3.06
	Limestone	1.95
	Limestone	2.12
	Limestone	2.88
	Limestone	2.66

APPENDIX 9

CATCHMENT DITCH DATA
(WIDTH AND DEPTH)

Table 9-1: Catchment ditch dimensions for the 26 selected sites. Values reported are average of five measurements of width and depth.

Site	Catchment Ditch	
	Width (ft)	Depth (ft)
ADA-32-12	12	2.2
ADA-41-15	25	1.8
ATH-33-14	28	2.2
ATH-50-23	40	2.5
BEL-7-10	21	2.8
BEL-70-22	7	1.9
BEL-470-6	32	2.3
CLA-4-8	15	2
CLA-68-7	20	1.3
CLE-275	17	2.5
COL-7-5	31	1.8
FRA-270-23	16	0.5
GUE-22-6	No catchment ditch	
GUE-77-8	21	2.4
HAM-74-6	24	1.9
HAM-126-12	12	1.6
JEF-CR77-.38	11	2
LAW-52-11	70	2.5
LAW-52-12	No measurement taken	
LIC-16-28	28	1.8
MEG-33-6	12	2
MEG-33-15	35	1.6
MUS-70-11	25	1.4
RIC-30-12	26	3
STA-30-27	12	0.8
WAS-7-18	24	1.9

APPENDIX 10

UNCONFINED COMPRESSIVE STRNGTH AND SLAKE DURABILITY
INDEX DATA

APPENDIX 10-A

UNCONFINED COMPRESSIVE STRNGTH AND SLAKE DURABILITY
INDEX DATA FOR OUTCROP SAMPLES

Table 10A-1: Unconfined compressive strength and slake durability index data for outcrop samples.

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
ADA-32-12	1	Claystone/mudstone	283	1.6
	2	Limestone	17285	99.5
	3	Claystone/mudstone	1214	2.3
	3A	Claystone/mudstone	324	8.9
	4	Limestone	10411	99.1
	5	Claystone/mudstone	381	2.2
	6	Limestone	10958	99.4
ADA-32-12B	1	Arenaceous Limestone	3010	90.7
	2	Limestone	65014	98.2
	3	Arenaceous Limestone	9048	95.3
	4	Limestone	10106	98.3
ADA-41-15	1	Limestone	13875	99.1
	2	Claystone/mudstone	703	20.5
	3	Claystone/mudstone	1452	22.5
	4	Limestone	20789	99.2
	5	Claystone/mudstone	933	9.8
	6	Fossiliferous Limestone	9822	99
	7	Limestone	22710	99
ATH-33-14	1	Sandstone	2768	88.2
	2	Sandstone	1454	60.3
	3	Sandstone	1428	63.6
	4	Sandstone	3018	87.4
	5	Sandstone	4229	88.1
ATH-33-26		Claystone/mudstone		3.8
ATH-50-22	1	Claystone/mudstone	498	5.4
	2	Limestone	9986	99.3
	3	Claystone/mudstone	667	8.9
	4	Limestone	8530	99.3
	5	Claystone/mudstone	393	9.1
	6	Limestone	13387	99.5
	7	Limestone	18240	98.8
	8	Claystone/mudstone	785	43.3
	9	Siltstone	8380	97.5
	10	Sandstone	8345	94.1
	11	Green Shale	5835	97.8
ATH-50-28	1	Claystone/mudstone		3.2

Table 10A-1 (contd.).

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
ATH-50-28	2	Claystone/mudstone		29.5
	3	Claystone/mudstone		35.8
	1	Underclay	218	30.1
	2	Limestone	6566	99.2
	4	Claystone/mudstone	392	64.9
	5	Limestone	9848	99.1
	6	Green Shale	2235	91.5
	7	Limestone	15345	99.5
	8	Limestone	19300	98.7
	1-A	Underclay	237	0
	1-B	Underclay	192	0
	2-A	Limestone	18786	99.4
	2-B	Limestone	12477	99.4
	4A	Claystone/mudstone	716	35.4
	4B	Claystone/mudstone	413	50.3
	5A	Limestone	11350	99.3
	5B	Limestone	12708	98.9
	6A	Green Shale	761	90.8
	6B	Green Shale	2332	77.2
	7A	Limestone	14247	99.4
BEL-470-6	7B	Limestone	14256	99.4
	8A	Limestone	20600	99.1
BEL-70-1.58	1	Shale		87.1
	2	Claystone/mudstone		5.1
	1	Dark Grey Shale	2127	93.3
	2	Sandstone	16704	98.5
	4	Sandstone		94.7
	3A	Claystone/mudstone	1612	0
	3B	Claystone/mudstone	454	58
BEL-70-22	4A	Sandstone	16365	96
	4B	Sandstone	14963	95.6
	1	Limestone	12479	99.2
	2	Limestone	6860	99.1
	3	Underclay	310	0
	4	Limestone	11912	99.2
	5	Limestone	6553	97
	6	Limestone	15046	99.3
BEL-7-10	7	Limestone	15832	99.4

Table 10A-1 (contd.).

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id$_2$ (%)
BEL-7-10	10	Dark Grey Shale		91.8
	1	Limestone	10799	98.2
	2	Limestone	13459	99.2
	3	Limestone	17614	99.3
	4	Limestone	14385	99.2
	5	Limestone	20565	99.5
CLA-4-8	6	Limestone	17690	99.3
	1	Limestone	15675	99.1
CLA-68-7	2	Limestone	8004	98.6
	3	Limestone	10701	98.3
	1	Limestone	20355	98.2
	2	Claystone/mudstone	540	56.6
	3	Limestone	18367	99.2
	4	Limestone	15633	98.7
	5	Claystone/mudstone	887	51.4
	6	Limestone	24542	99
	7	Limestone	21014	99.2
CLE-275-5	8	Claystone/mudstone	469	41.6
	9	Limestone	14600	98.8
COL-11-16		Dark Grey Shale		91.2
COL-30-30		Dark Grey Shale		96.8
	1	Sandstone		98.5
COL-7-3	2	Claystone/mudstone		48.9
	1	Dark Grey Shale	1749	97.8
	2	Sandstone	6221	97.5
	3	Dark Grey Shale	3286	97.8
	4	Dark Grey Shale	4518	98
	5	Dark Grey Shale	1960	92.1
	#1	Sandstone		97.3
	#3	Sandstone		98.5
	#4	Dark Grey Shale		90.1
COL-7-5	1A	Dark Grey Shale		97.6
FRA-270-23	1	Dark Shale	3854	99.3
GUE-22-6.9	1	Siltstone	8279	97.2
	2	Dark Grey Shale	3302	95.8

Table 10A-1 (contd.).

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
GUE-22-6.9	3	Sandstone	2752	97
GUE-70-12.9	1	Dark Grey Shale		96.4
GUE-77-21	1	Dark Grey Shale		94
GUE-77-8	1	Underclay	431	0
	2	Siltstone	5553	96.5
	3	Sandstone	6098	96.9
HAM-126-12	1	Fossileferous Limestone	9226	96.7
	2	Fossileferous Limestone	10160	94.7
	3	Fossileferous Limestone	12872	99.1
	4	Fossileferous Limestone	18247	97.8
	5	Fossileferous Limestone	12497	96.6
	6	Fossileferous Limestone	17720	99
	7	Fossileferous Limestone	9366	90.8
	8	Fossileferous Limestone	17114	98.5
	9	Claystone/mudstone	5618	81
HAM-74-6	1	Claystone/mudstone	613	64.2
	2	Fossileferous Limestone	17240	99
	3	Claystone/mudstone	493	73.4
	4	Fossileferous Limestone	14605	99.1
	5	Claystone/mudstone	577	60.5
	6	Fossileferous Limestone	17753	99
JEF-22-8	1	Dark Grey Shale		99.1
	1	Shale		86.3
	2	Dark Grey Shale		30.5
	3	Shale		76.6
	4	Shale		8.7

Table 10A-1 (contd.).

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
JEF-7-23	3	Sandstone		91.9
	5	Dark Grey Shale		84.9
JEF-7-6	1	Sandstone		97.3
	2	Mudstone/claystone		89.5
	4	Mudstone/claystone		55.1
JEF-CR77-0.4	1	Sandstone	5011	97.7
	2	Grey Shale	2906	96.4
	3	Underclay		5.2
LAW-52-11	1	Claystone/mudstone	434	70
	2	Sandstone	8371	97.4
	3	Siltstone	8279	96.4
	4	Sandstone	8611	97
	5	Claystone/mudstone	1811	35.4
	6	Sandstone	3461	89.9
	7	Sandstone	8848	97.7
	8	Limestone	20745	98.8
	9	Sandstone	4066	89.5
	10	Claystone/mudstone	620	19.7
LAW-52-12	1	Sandstone	4762	93.8
	2	Claystone/mudstone	1926	87.1
	3	Claystone/mudstone	1386	92.5
	4	Sandstone	3580	90.5
	5	Sandstone	4086	93.3
	6	Claystone/mudstone	739	48.8
LIC-16-28	1	Sandstone	1400	30.6
MEG-33-15	1	Claystone/mudstone	107	0.9
	2	Sandstone	10326	97.5
	3	Sandstone	1902	81.5
	4	Sandstone	1682	68.3
	5	Sandstone	15564	99
	6	Claystone/mudstone	192	2.7
	7	Sandstone	4198	92.4
	8	Sandstone	3494	93
	9	Claystone/mudstone	172	3.8
	10	Claystone/mudstone	253	32
MEG-33-6	1	Claystone/mudstone	956	47.9
	2	Claystone/mudstone	204	6

Table 10A-1 (contd.).

Site	Sample No.	Rock Type	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
MEG-33-6	3	Siltstone	899	82.7
	4	Sandstone	6582	97.2
	5	Claystone/mudstone	236	2
	6	Sandstone	5541	94.6
	7	Sandstone	4777	94.2
	8	Siltstone	5288	94.3
	9	Siltstone	4747	91.8
MUS-70-11	1A	Dark Grey Shale	2818	73.9
	1	Dark Grey Shale	545	85.4
	2	Sandstone	4506	91.5
	3	Sandstone		85.9
	4	Dark Grey Shale	7094	48.6
		Dark Grey Shale	663	71.6
	6	Sandstone	4640	86.3
MUS-70-25	1	Claystone/mudstone		52.5
RIC-30-12	1	Sandstone	1686	52.7
	2	Sandstone	3455	84.6
STA-30-27	1	Dark Grey Shale	3835	93.4
	2	Sandstone	11395	98.6
	3	Sandstone	9709	97.7
TUS-77-03	1	Dark Grey Shale		87.2
	2	Dark Grey Shale		11.5
WAS-7-18	1	Sandstone	8131	97.1
	2	Claystone/mudstone	572	1.1
	3	Sandstone	12823	98.2
	4	Claystone/mudstone	298	0.7
	5	Sandstone	7481	97.1
	6	Claystone/mudstone	416	5.6
	7	Shale	2459	95.2
	8	Sandstone	4862	95.6
	9	Claystone/mudstone	768	81.4
	10	Claystone/mudstone	3499	97.8
	11	Sandstone	9732	98.7
WAS-77-15	2	Claystone/mudstone		18.4
	3	Claystone/mudstone		73.8

APPENDIX 10-B

RQD, UNCONFINED COMPRESSIVE STRENGTH, AND SLAKE
DURABILITY INDEX DATA FOR CORE SAMPLES

Table 10B-1: RQD, unconfined compressive strength, slake durability index data for core samples.

Site	Sample No.	Rock Type	RQD	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
ADA-32-12B	1	Redish Dolomite	77	4148	97
	2	Arenaceous Shale	98	8670	92.7
	3	Arenaceous Shale	100	10646	93.9
	4	Grey Dolomite	69	10322	98.9
ADA-41-15	1	Claystone/mudstone	60	222	6.7
	1A	Limestone	60	18681	98.5
	2	Limestone	82	15395	98.7
ATH-33-14	1	Sandstone	97	9084	98.4
	2	Sandstone	100	2581	86.6
	3	Sandstone	100	3314	89.5
	4	Sandstone	90	6047	95
	5	Sandstone	100	17931	
BEL-470-6	1	Limestone	100	20760	99.6
	2	Claystone/mudstone	100	2261	70.1
	3	Claystone/mudstone with clasts	81	3109	86.5
	4	Claystone/mudstone with clasts	100	2669	94.8
	5	Sandstone	100	17116	98.7
	6A	Dark Green Shale	100	1736	92.6
	6B	Dark Green Shale	100	1157	92.6
	7	Sandstone	100	18384	97.6
	8	Dark Grey Shale	90.4	1719	70.1
	9	Dark Grey Shale	84	1796	77
	10	Green Shale	84		67.8
	11	Green Shale	84	1245	84.7
	12	Green Shale	100		97.1
	13	Green Shale	100	2241	93.6
	14	Green Shale	100	2999	77.4
	15	Dark Green Shale	100	4337	98.5
	16	Green Shale	46	1276	16.5
	17	Limestone	100	15670	99.4
	18	Limestone	100	11572	94.6
	19	Claystone/mudstone		2156	65.5
	20	Claystone/mudstone	100	1384	23.8
	21	Green Shale	100	2692	96.8
BEL-7-10	2	Underclay	0		23

Table 10B-1(contd.).

Site	Sample No.	Rock Type	RQD	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
BEL-7-10	3	Sandstone	100		98.3
	4	Shale	100	1795	95.2
	5	Limestone	94.1	12479	99.2
BEL-7-10	6	Claystone/mudstone with clasts	100	2410	57
	7	Claystone/mudstone with clasts	94	2412	92.3
	8	Sandstone	100	21507	99
	9	Shale		1404	90.6
	10	Shale	98	1606	83.9
	11	Claystone/mudstone	85	863	33.9
	12	Claystone/mudstone	67	2897	60.4
	13	Green Shale	100	6292	46.4
	14	Claystone/mudstone			19.9
	15	Green Shale	100	1381	86.5
	16	Limestone	100	20588	99.7
	17	Dark Grey Shale		3811	95.4
	18	Limestone	40	13612	98.4
	19	Claystone/mudstone	73	2139	4.8
	20	Sandstone	100	18087	99.1
	21	Dark Grey Shale		2660	87.4
	22	Green Shale	94	4204	88.6
	23	Green Shale	92	4444	97.9
	24	Claystone/mudstone	93	2492	71.3
	25	Sandstone	100	15520	98.9
	26	Green Shale		3099	97.2
	27	Claystone/mudstone	100	1013	33.4
	28	Limestone Dark	100	16829	99.5
	29	Green Shale		3038	70.6
	30	Limestone	100	25669	99.5
	31	Claystone/mudstone	48	2411	72.2
	32	Limestone	100	12566	99.1
	33	Limestone	100	8036	99
BEL-70-22	1	Sandstone	62	11225	98.4
	2	Sandstone	62	6518	95.9
	3	Clayey Material	0		31
	4	Dark Grey Shale	65	667	62.5
	5	Dark Grey Shale	70	417	97.2
	6	Limestone		23113	99.7

Table 10B-1(contd.).

Site	Sample No.	Rock Type	RQD	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
BEL-70-22	7	Underclay			11.1
	8	Grey Shale	76	1732	93.2
	9	Limestone		11508	85.5
	10	Limestone	68	16619	
	11	Claystone/mudstone	82	2043	
BEL-70-22	12	Siltstone	100	11809	98.3
	13	Grey Shale	96	2019	
	14	Siltstone	100	4036	98.1
	15	Dark Grey Shale	48	1520	87.7
CLA-68-7	1	Limestone	70	9568	98.6
	2	Limestone	95	10697	99
	3	Limestone	94	18926	99.4
CLE-275-5	1	Claystone/mudstone	76	298	27.7
	1A	Limestone		24413	
	2	Claystone/mudstone	76	694	31.6
GUE-77-8	1	Claystone/mudstone	0	332	44.7
	2	Clayey Material			0.1
	3	Claystone/mudstone	61		2.2
	4	Dark Grey Shale	65	909	88.5
	5	Claystone/mudstone	81	616	19.2
	6	Dark Grey Shale	98	848	86.5
	7	Sandstone	100	6433	96.7
	8	Sandstone	100	6760	96
	9	Clayey Material			0.1
	10	Sandstone	97	6538	96.8
HAM-126	1	Claystone/mudstone	54	426	20.8
	1A	Limestone		20563	
	2	Claystone/mudstone	24	1475	65.9
	2A	Limestone		11616	
	3	Claystone/mudstone		1956	23.8
	3A	Limestone	49	17496	
	4	Claystone/mudstone		1316	23.6
	4A	Limestone	79	15849	
LAW-52-11	1	Claystone/mudstone	96	833	12.2
	2	Claystone/mudstone	100	1651	69.4
	3	Claystone/mudstone	21	1263	73.3
	4	Grey Shale	83	2102	80.6
	5	Sandstone	100	12097	96.2
	6	Grey Shale	100	1341	84

Table 10B-1(contd.).

Site	Sample No.	Rock Type	RQD	Unconfined Compressive Strength from Point Load Test (psi)	Slake Durability Index, Id_2 (%)
LAW-52-11	7	Sandstone	100	16719	98.1
	8	Grey Shale	92	1498	75.8
	9	Grey Shale	100	1629	89.4
	10	Grey Shale	85	1373	81.8
	11	Grey Shale		1630	92.8
	12	Sandstone	100	12233	96.9
	13	Grey Shale	79	1710	89
	14	Grey Shale	100	1454	88.8
	15	Sandstone		7440	92.3
LAW-52-11	16	Sandstone	100	7192	94.4
	17	Claystone/mudstone	74	1454	16.8
	18	Grey Shale	100	2855	85.1
	19	Siltstone		10718	96.5
	20	Grey Shale	100	1705	85.5
	21	Claystone/mudstone	100	703	0
LIC-16-28	1	Sandstone	21	2064	69.3
	2	Sandstone	11	1179	37.8
	3	Sandstone	43	5140	92.7
	4	Sandstone	68	3318	85.4
MEG-33-6	1	Sandstone	82	4689	96.3
	3	Sandstone	98	11600	98.6
	6	Claystone/mudstone	74	437	23.7
RIC-30-12	1	Sandstone	50	4414	92
	2	Sandstone	46	3019	86.8
	3	Sandstone	67	2202	72.6
STA-30-27	1	Interbedded Siltstone/Shale	0		82.2
	2	Sandstone	0	2240	67.6
	3	Dark Grey Shale	24	804	79.8
	4	Dark Grey Shale	24	2394	86.3
	5	Sandstone	34	9259	96.5
	6	Sandstone	63	10238	95.5

APPENDIX 10-C

CORRELATIONS BETWEEN UNCONFINED COMPRESSIVE
STRENGTH, SLAKE DURABILITY INDEX AND RQD
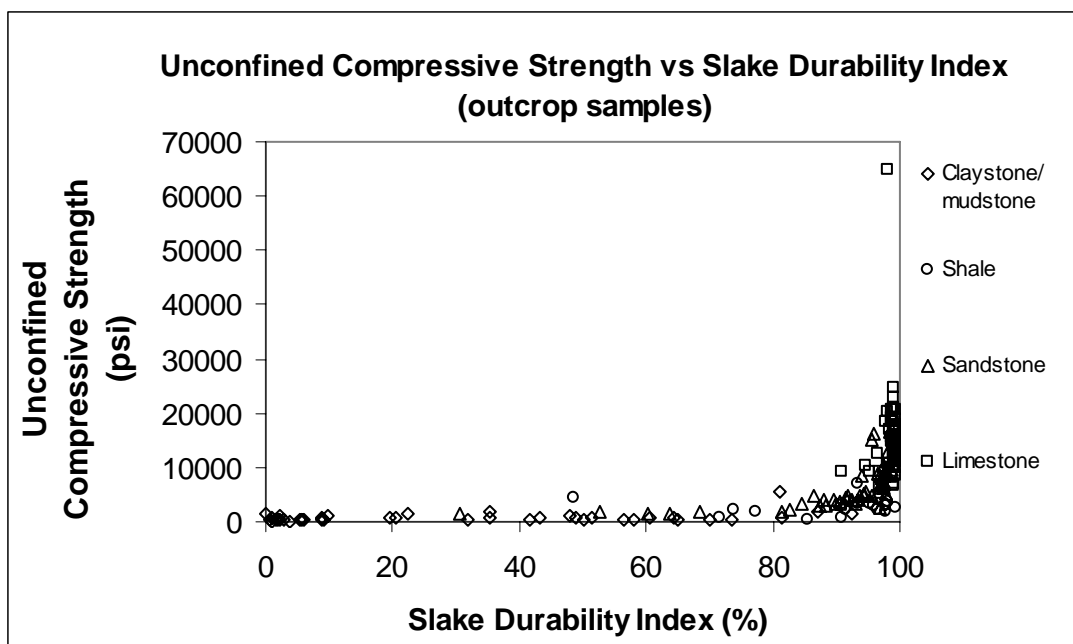
Figure 10C-1: Correlation between unconfined compressive strength and slake durability index for all rock types (outcrop samples).
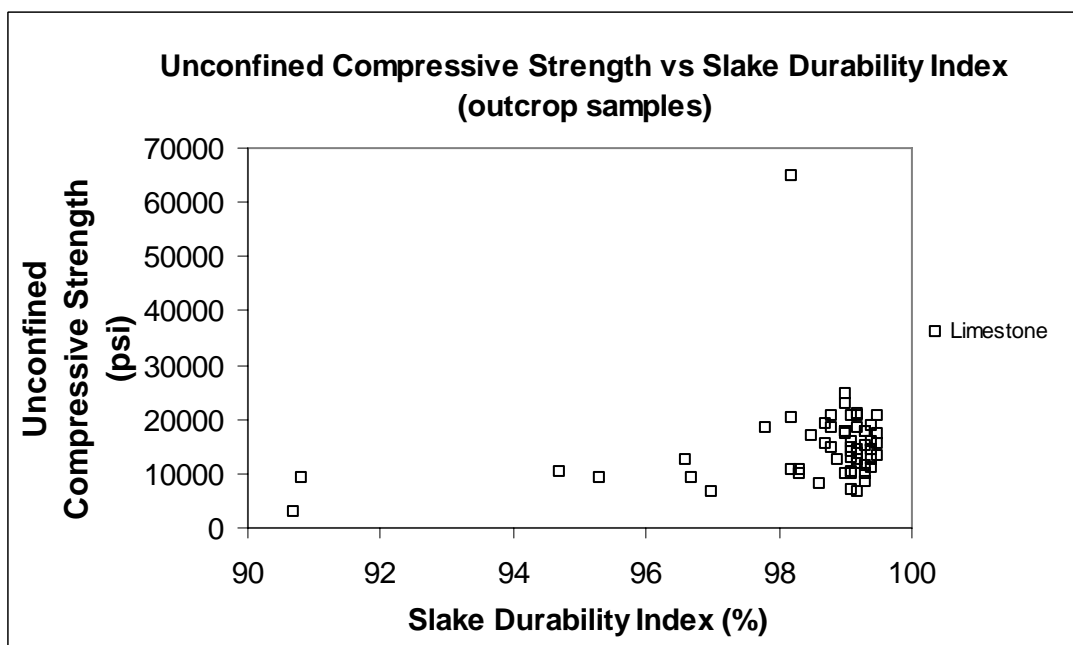
Figure 10C-2: Correlation between unconfined compressive strength and slake durability index for limestone units (outcrop samples).
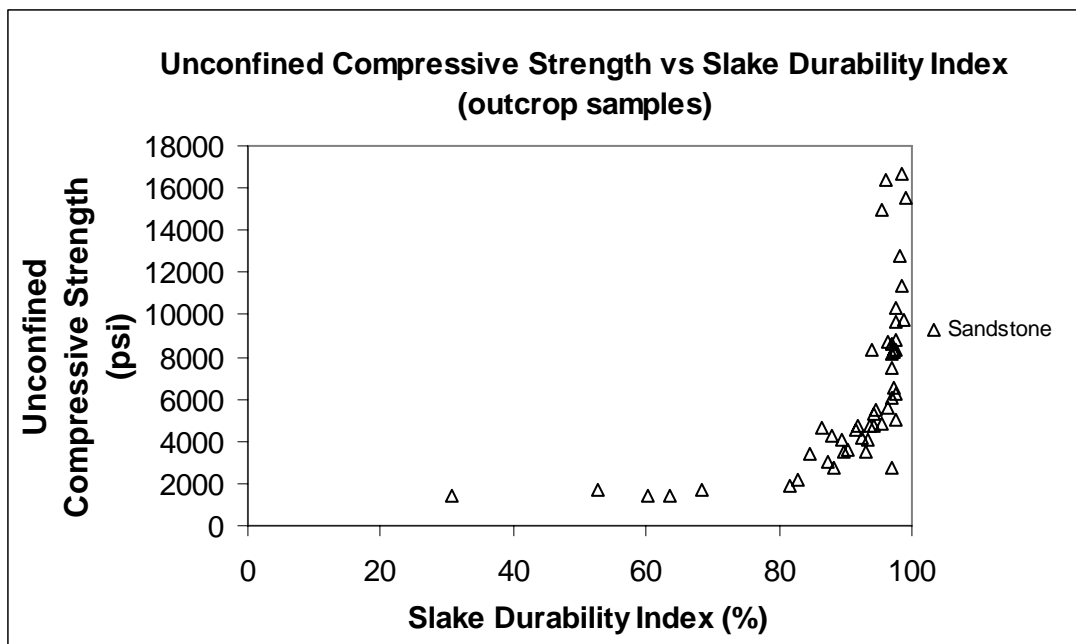
Figure 10C-3: Correlation between unconfined compressive strength and slake durability index for sandstone units (outcrop samples).
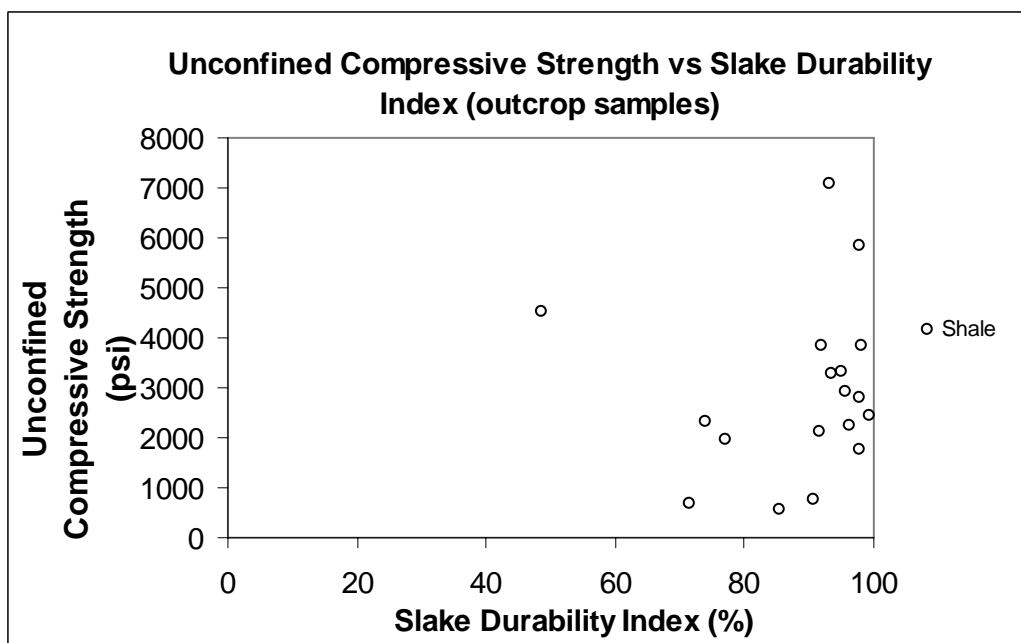
Figure 10C-4: Correlation between unconfined compressive strength and slake durability index for shale units (outcrop samples).
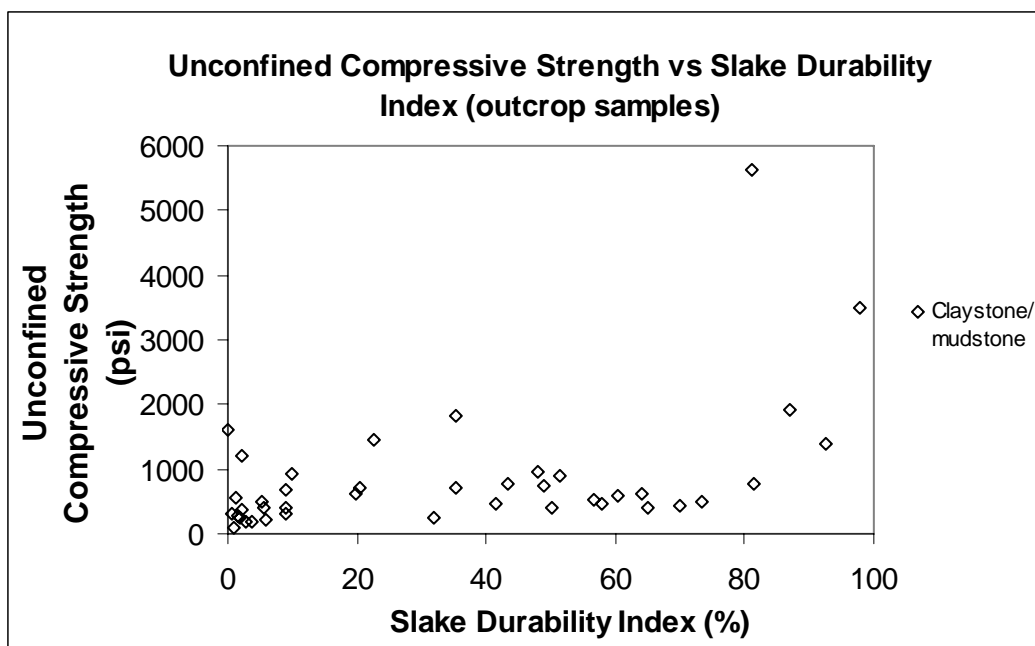
Figure 10C-5: Correlation between unconfined compressive strength and slake durability index for claystone/mudstone units (outcrop samples).
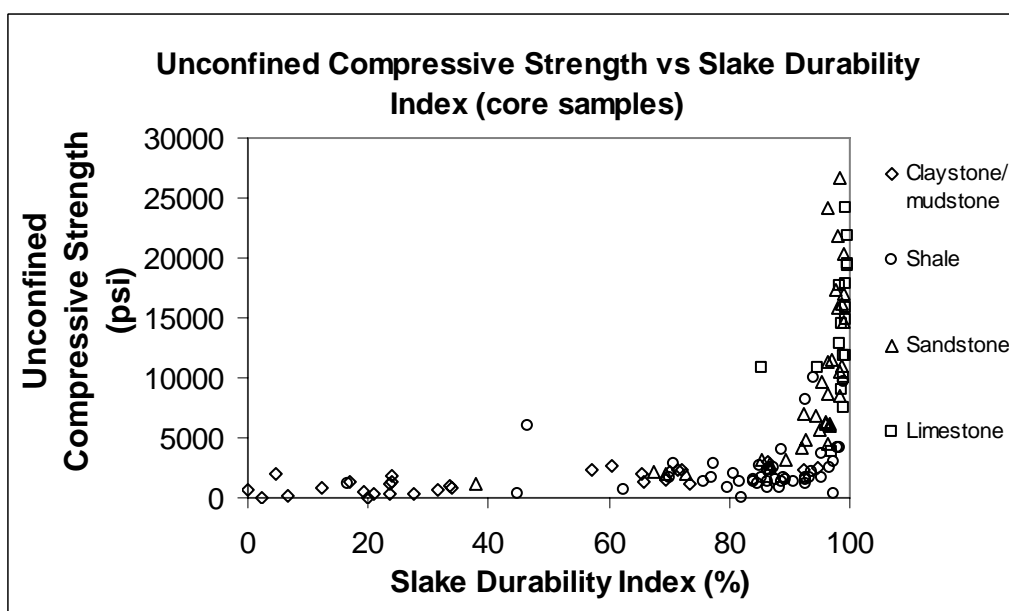
Figure 10C-6: Correlation between unconfined compressive strength and slake durability index for all rock types (core samples).
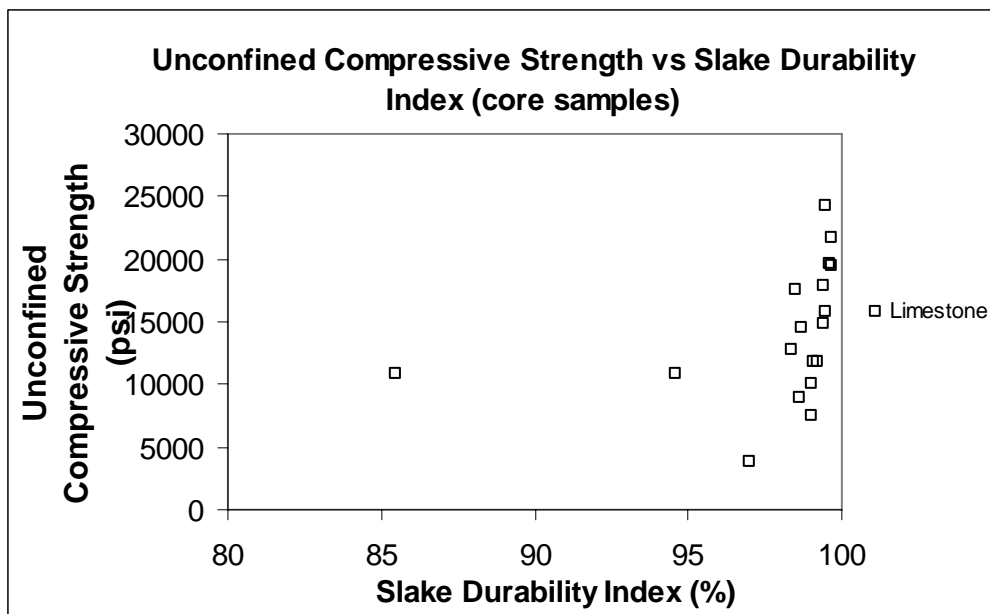
Figure 10C-7: Correlation between unconfined compressive strength and slake durability index for limestone units (core samples).
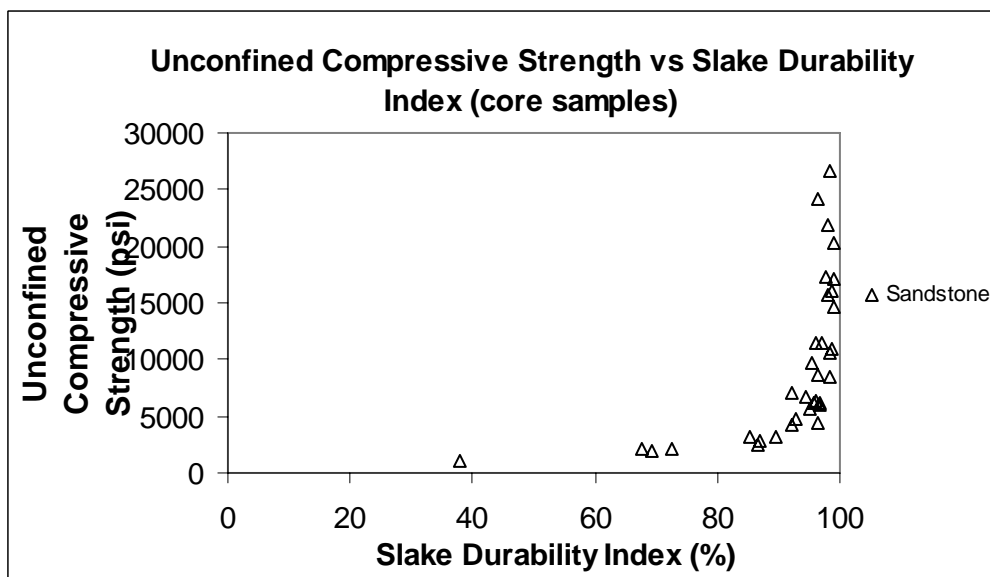
Figure 10C-8: Correlation between unconfined compressive strength and slake durability index for sandstone units (core samples).
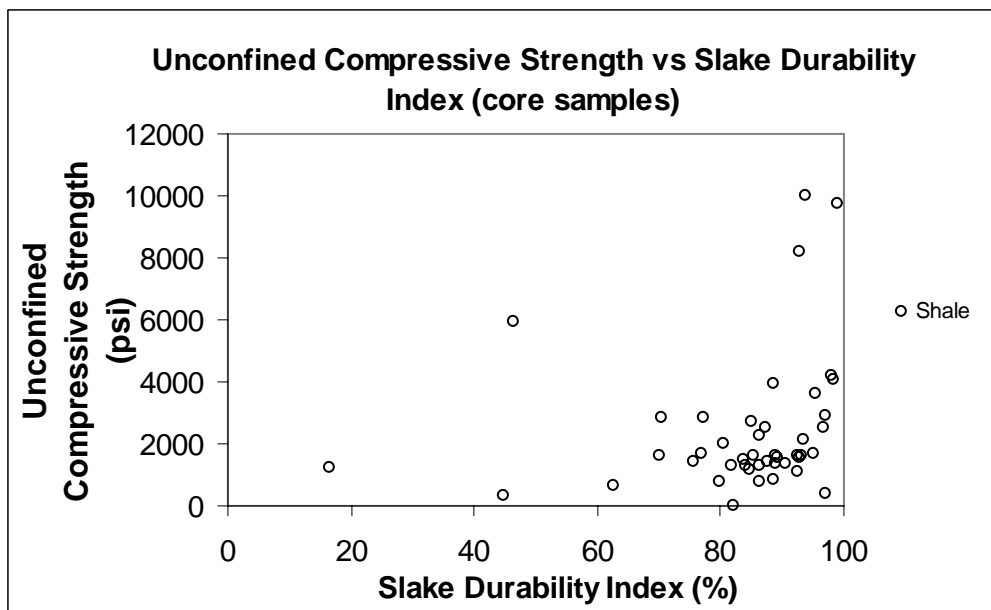
Figure 10C-9: Correlation between unconfined compressive strength and slake durability index for shale units (core samples).
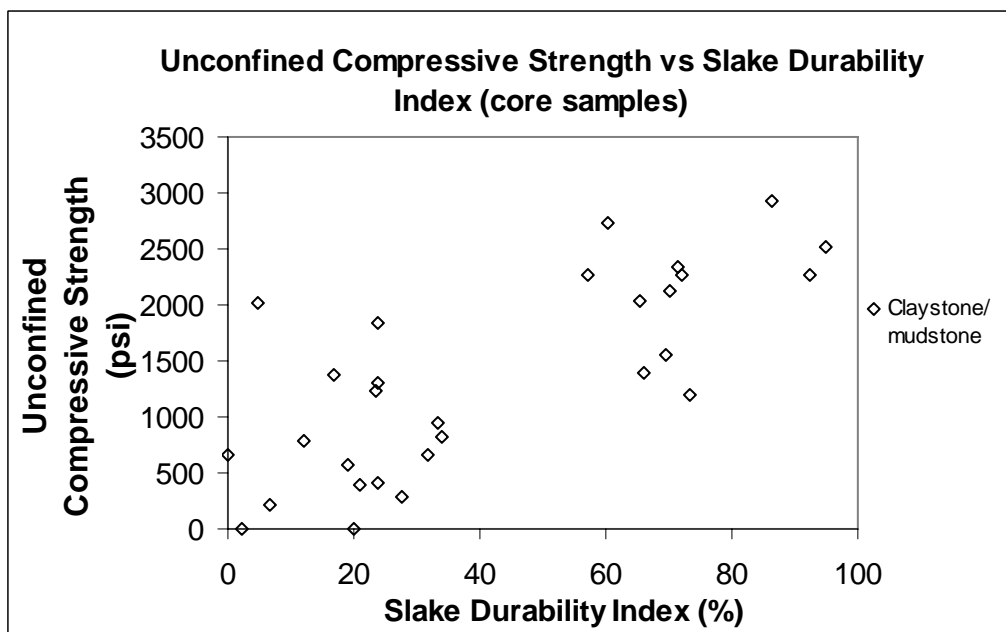
Figure 10C-10: Correlation between unconfined compressive strength and slake durability index for claystone/mudstone units (core samples).
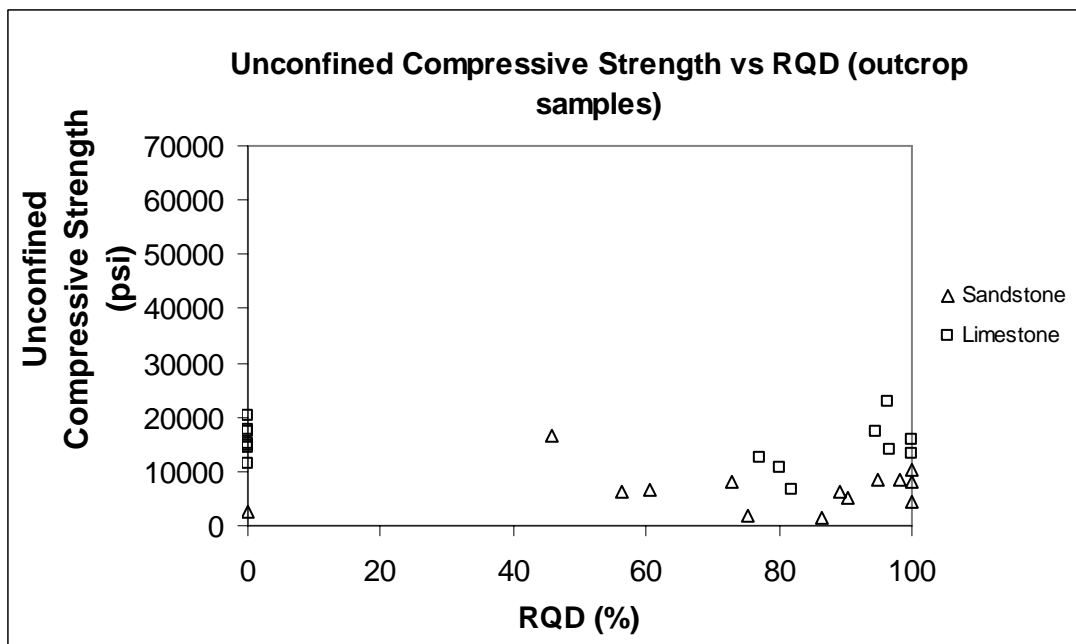
Figure 10C-11: Correlation between unconfined compressive strength and RQD for sandstone and limestone units (outcrop samples).
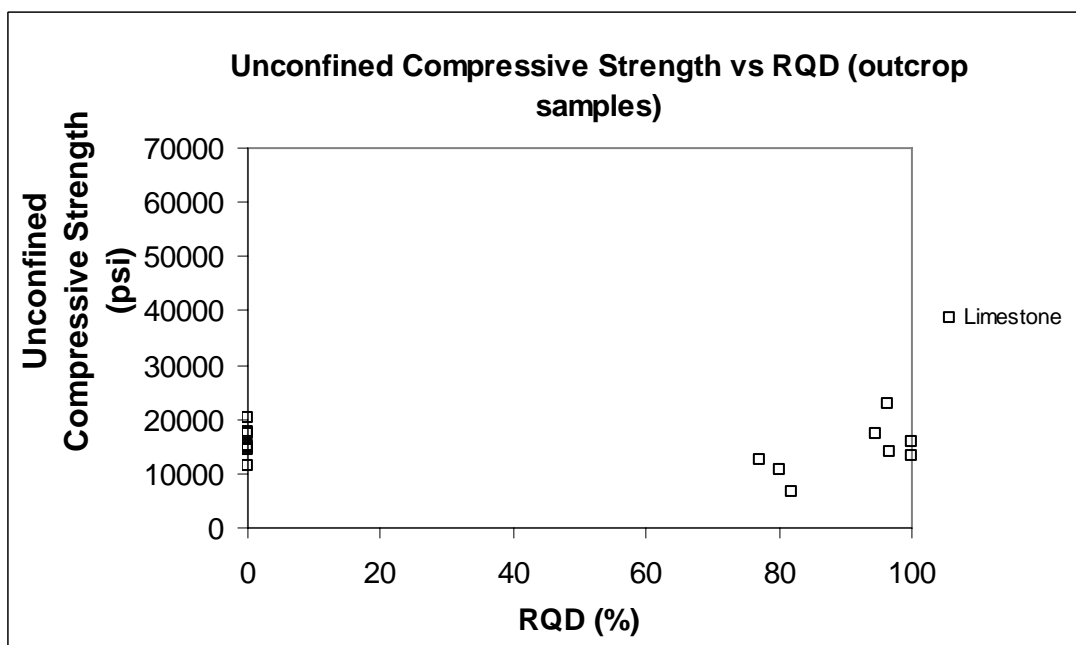
Figure 10C-12: Correlation between unconfined compressive strength and RQD for limestone units (outcrop samples).
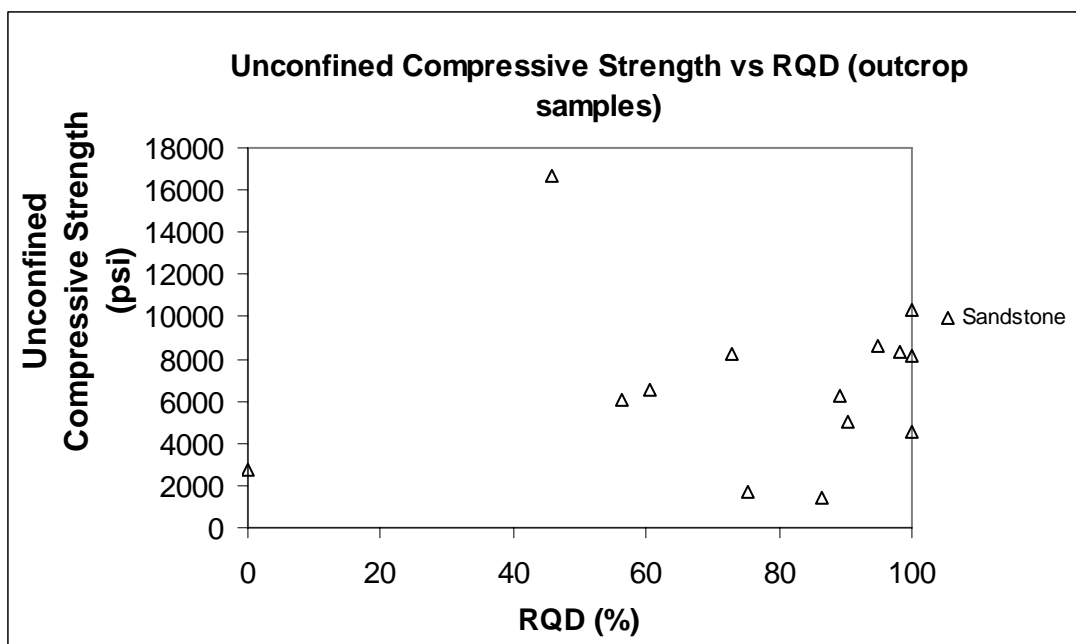
Figure 10C-12: Correlation between unconfined compressive strength and RQD for sandstone units (outcrop samples).
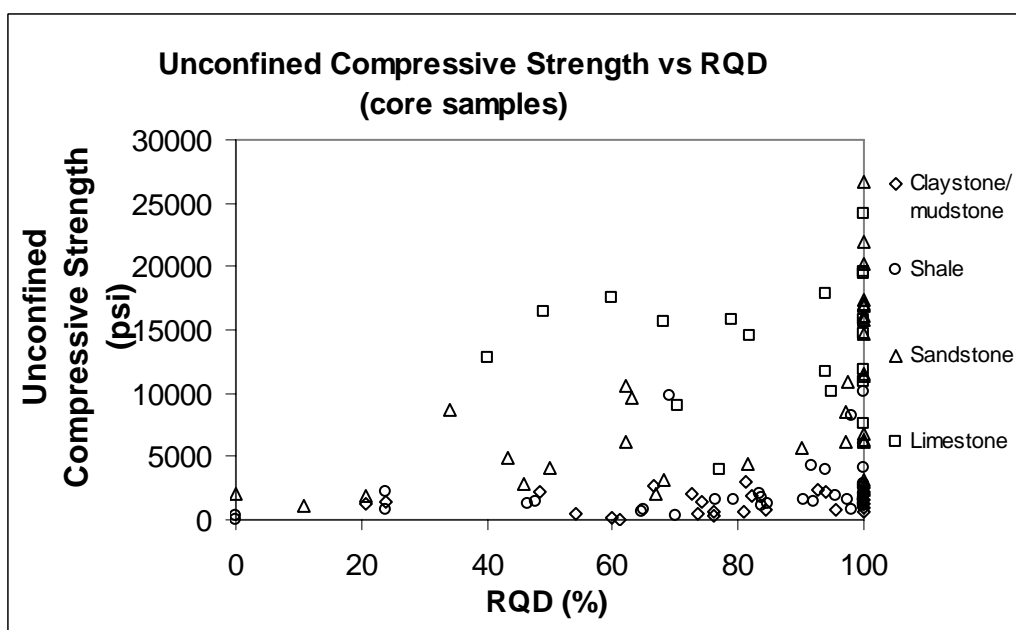
Figure 10C-13: Correlation between unconfined compressive strength and RQD for all rock types (core samples).
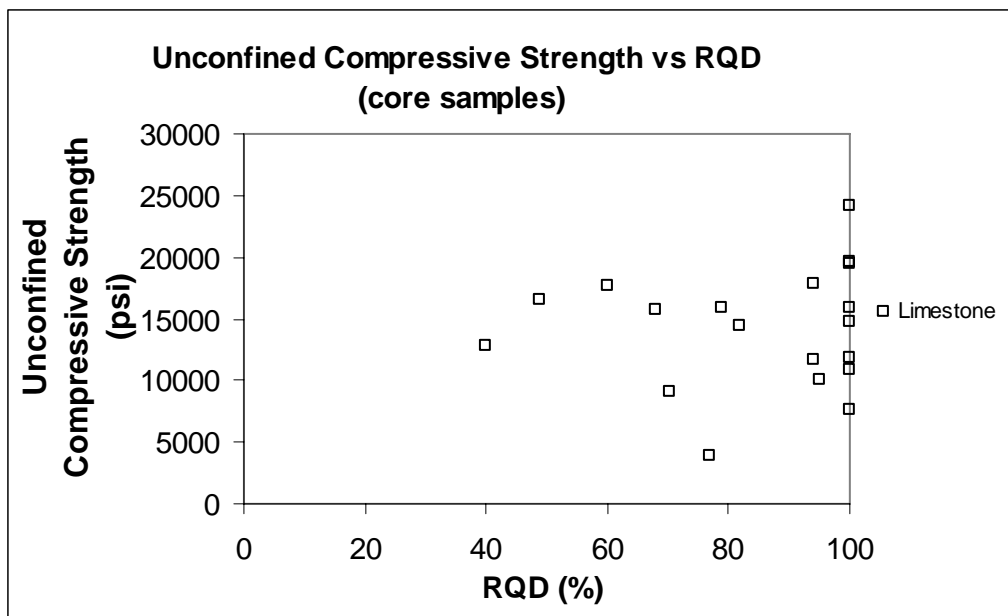
Figure 10C-14: Correlation between unconfined compressive strength and RQD for limestone units (core samples).
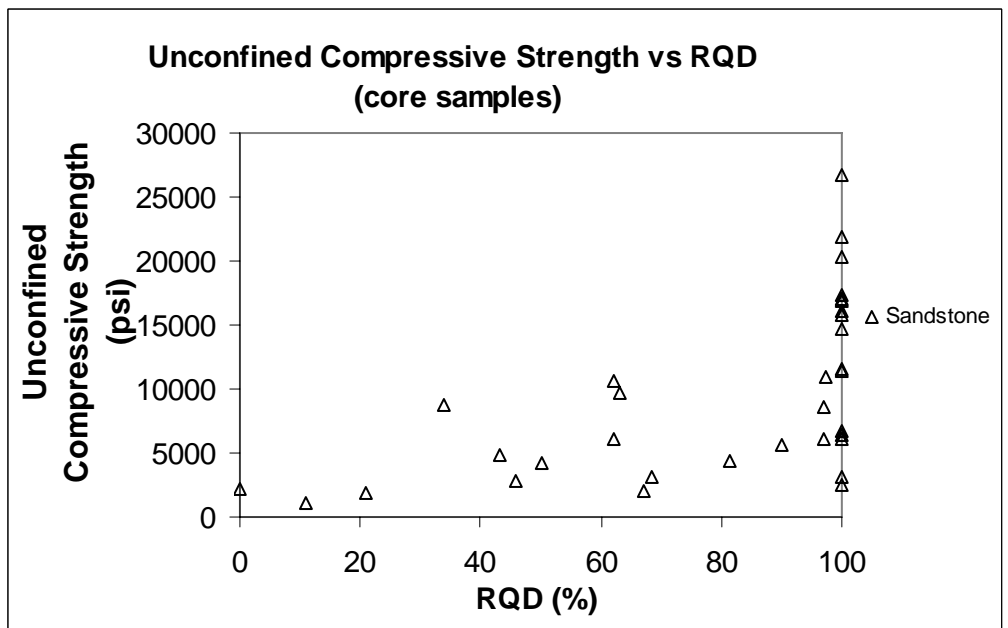
Figure 10C-14: Correlation between unconfined compressive strength and RQD for sandstone units (core samples).
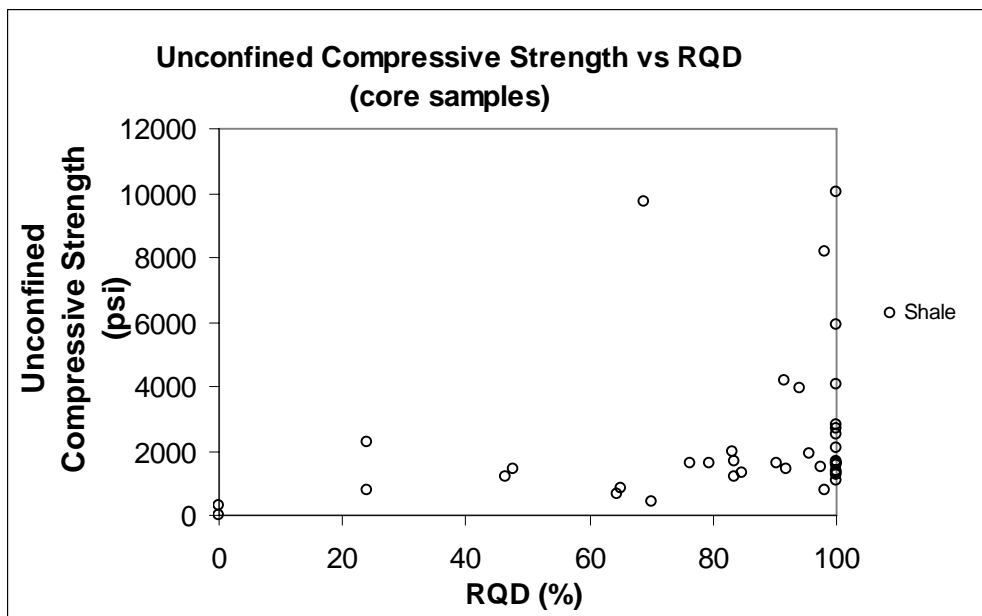
Figure 10C-15: Correlation between unconfined compressive strength and RQD for shale units (core samples).
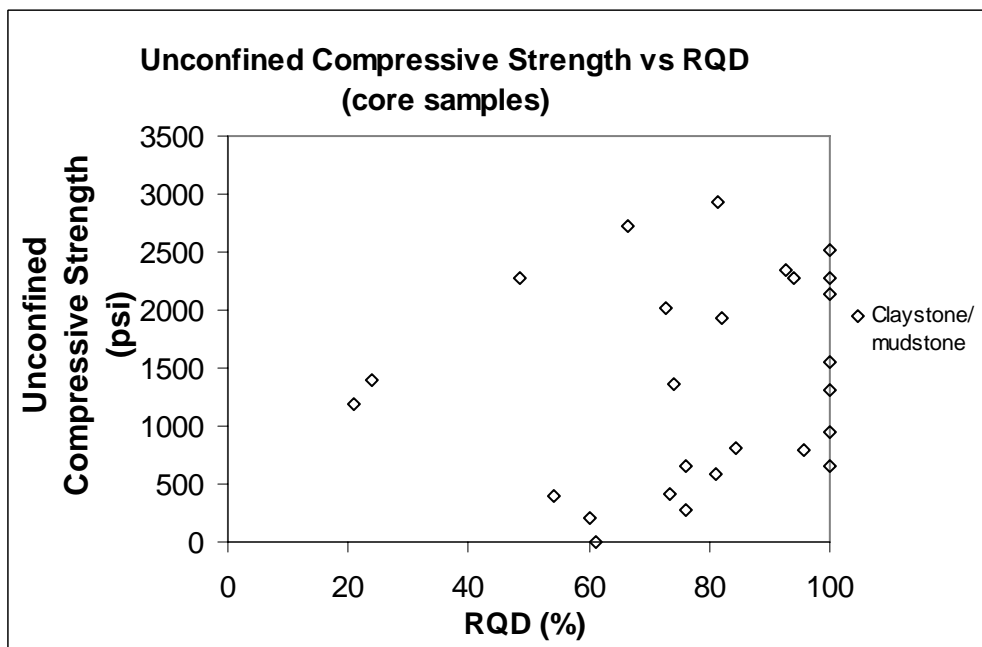
Figure 10C-16: Correlation between unconfined compressive strength and RQD for claystone/mudstone units (core samples).
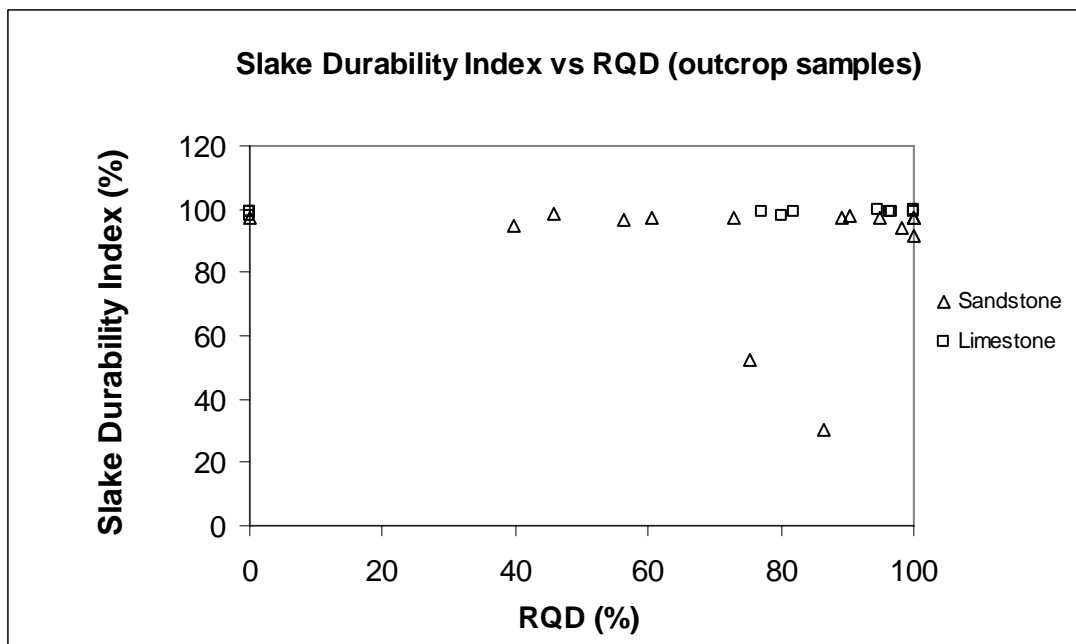
Figure 10C-17: Correlation between slake durability index and RQD for sandstone and limestone units (outcrop samples).
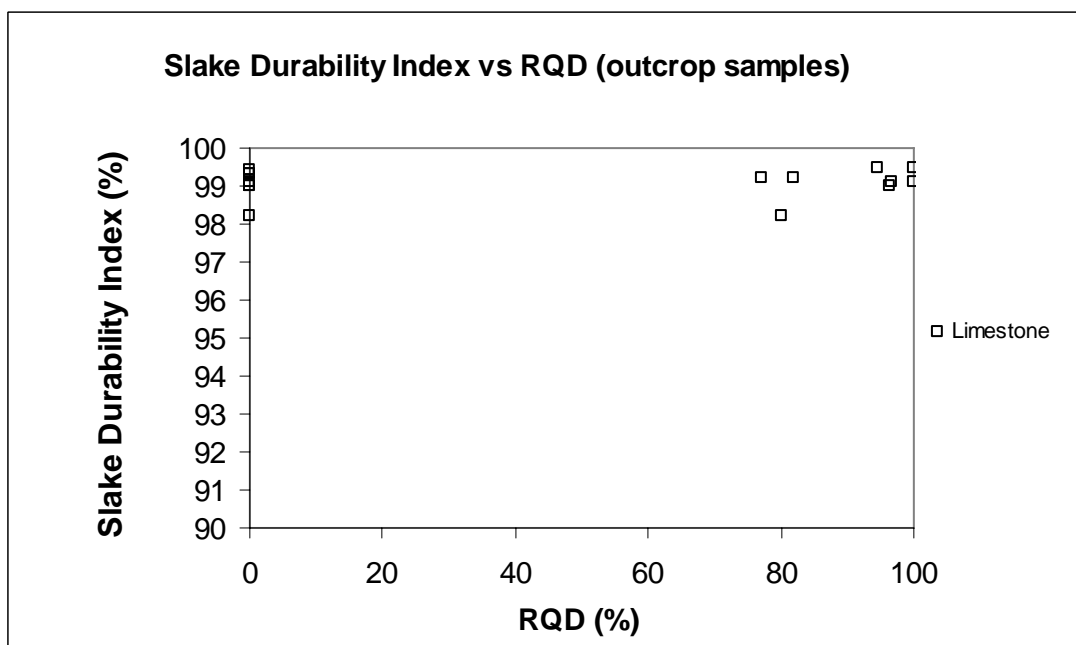
Figure 10C-17: Correlation between slake durability index and RQD for limestone units (outcrop samples).
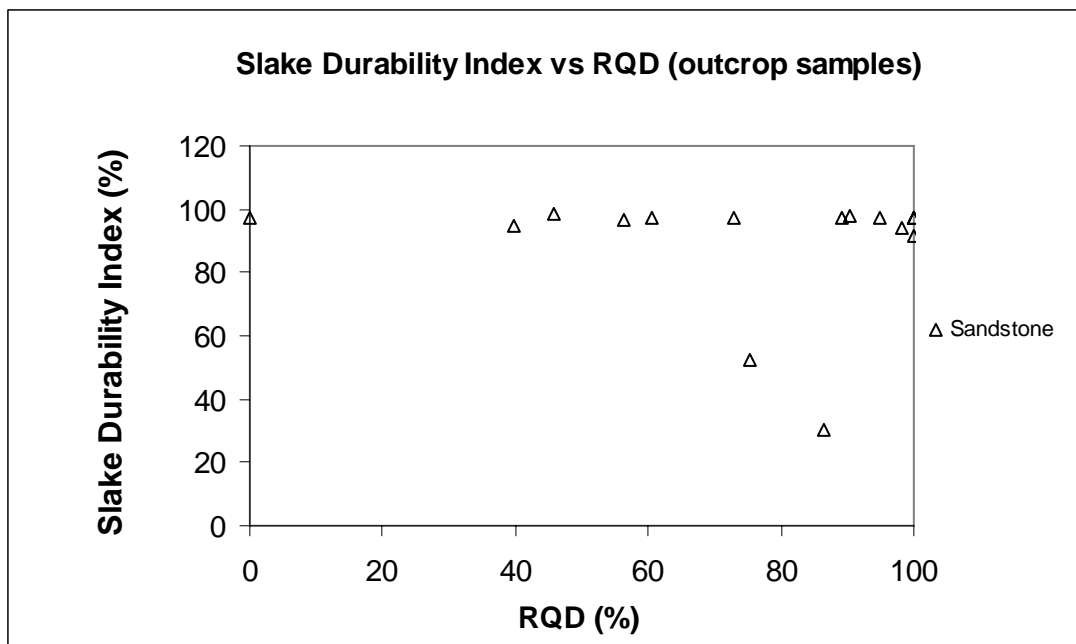
Figure 10C-18: Correlation between slake durability index and RQD for sandstone units (outcrop samples).
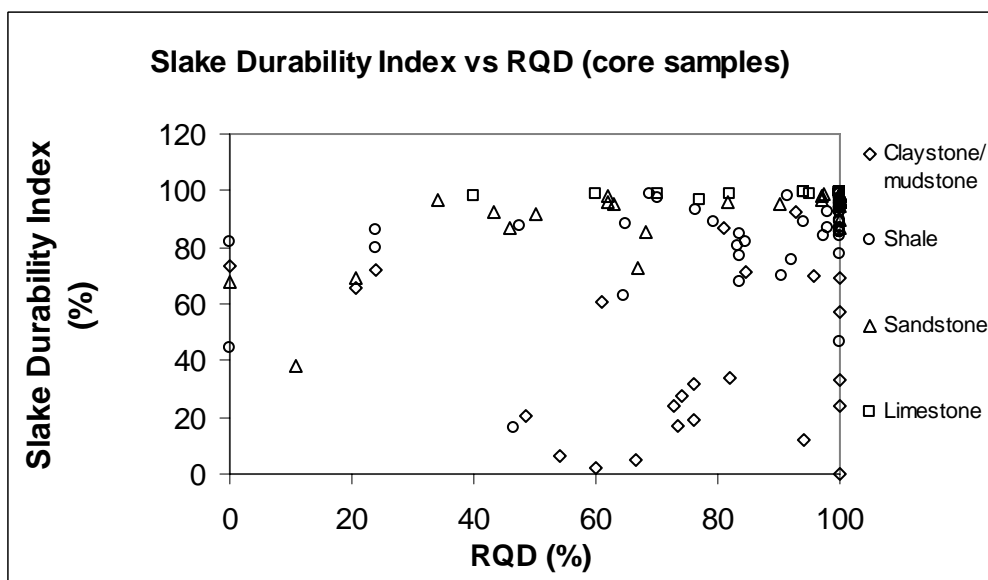
Figure 10C-19: Correlation between slake durability index and RQD for all rock types (core samples).
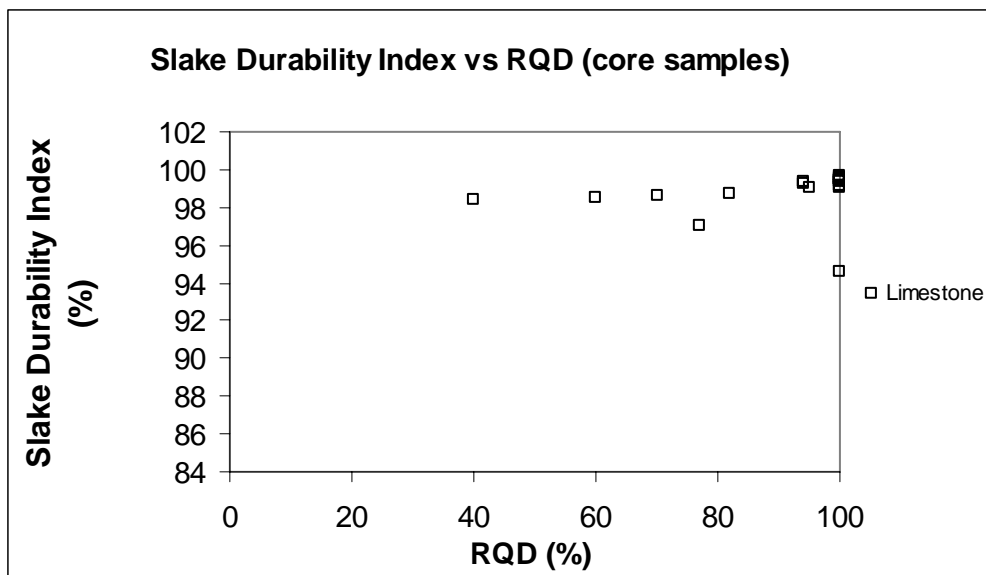
Figure 10C-20: Correlation between slake durability index and RQD for limestone units (core samples).
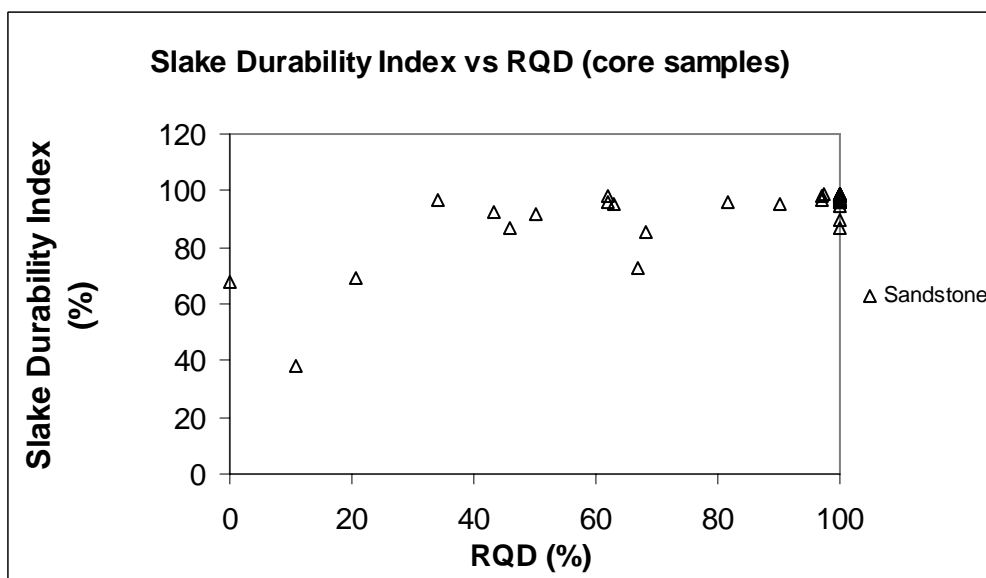
Figure 10C-21: Correlation between slake durability index and RQD for sandstone units (core samples).
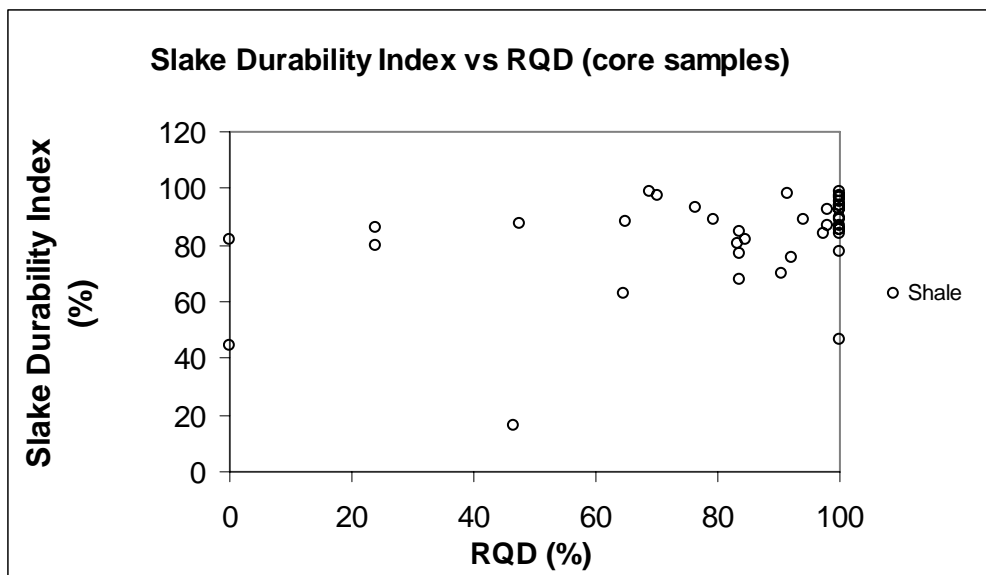
Figure 10C-22: Correlation between slake durability index and RQD for shale units (core samples).
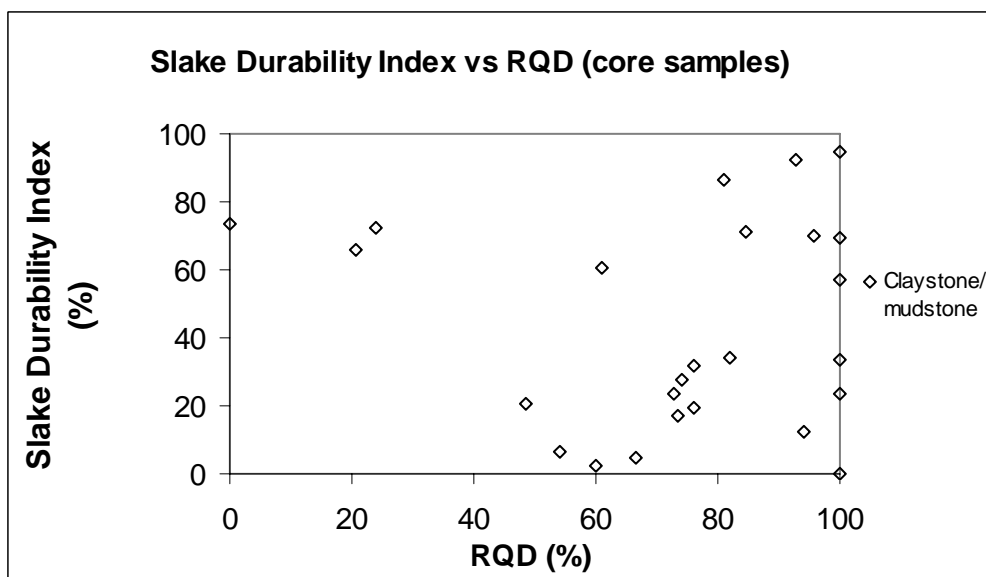
Figure 10C-23: Correlation between slake durability index and RQD for claystone/mudstone units (core samples).

APPENDIX 11

INDEX PROPERTIES

APPENDIX 11-A

DRY DENSITY DATA

Table 11A-1: Dry density values for selected core samples.

Sample	Lithology	Density (pcf)
CLA-68-9(32'-34')	Limestone	156.9
CLA-68-9(34'-36')	Limestone	155.3
CLA-68-9(36'-38')	Limestone	159.8
CLA-68-9(38'-40')	Limestone	161.0
ATH-33-14(100'-102')	Sandstone	140.1
MEG-33-6(25'-27')	Sandstone	156.5
MEG-33-6(36'-38')	Sandstone	158.8
MEG-33-6(27'-29')	Sandstone	151.6
MEG-33-6(32'-34')	Sandstone	156.1
LIC-16-28(41'-43')	Sandstone	120.4
RIC-30-12(36'-38')	Sandstone	128.4
ATH33(117'-118')	Claystone/Mudstone	161.0
GUE-77-8#5	Claystone/Mudstone	170.8
GUE-77-8 #2	Claystone/Mudstone	156.6
GUE-77-8 #5	Claystone/Mudstone	162.2
GUE-77-8 #9	Claystone/Mudstone	164.3
LAW52-11-#17	Claystone/Mudstone	166.4
LAW-52-11-#2	Claystone/Mudstone	165.3
LAW-52-11-#3	Claystone/Mudstone	163.5
ADA-32-12 #2	Shale	162.7
BEL-470-6-#12	Shale	172.5
BEL-470-6#13	Shale	175.9
BEL-470-6#14	Shale	168.7
BEL-470-6#15	Shale	168.5
BEL-470-6#15	Shale	172.4
BEL-470-6#19	Claystone/mudstone	169.1
BEL-70-22#8	Shale	168.5
GUE-77-8 #1	Claystone/mudstone	145.9
LAW-52-11#11	Shale	169.2
LAW-52-11#14	Shale	164.5
LAW-52-11-#20	Shale	161.1
LAW-52-11-#9	Shale	154.9
BEL-70-22#14	Siltstone	170.9
LAW-52-11#19	Siltstone	168.4

APPENDIX 11-B

ATTERBERG LIMITS DATA
(OUTCROP AND CORE SAMPLES)

Table 11B-1: Atterberg limits for outcrop samples

Site	No.	Liquid Limit	Plasticity Limit	Plasticity Index
ADA-32-12	5	38.1	23.22	14.88
	1	40.7	23.42	17.28
ADA-41-15	3	40.2	26.25	13.95
ATH-50-22	5	35.2	32.82	2.38
	8	29.16	19.7	9.46
BEL-470-6	4A	32.1	20.58	11.52
	1	34.71	25.31	9.4
BEL-70-22	3	30.2	18.29	11.91
	3A	37.9	17.07	20.83
	3	38	25.04	12.96
CLE-275-5	5	38.1	20.79	17.31
HAM-126-12	9	32.38	15.21	17.17
HAM-74-6	3	29.1	16.81	12.29
	5	31.3	18.28	13.02
	1	31.8	23.33	8.47
LAW-52-11	1	23.3	19.99	3.31
	10	23.3	16.28	7.02
	5	23.6	19.52	4.08
LAW-52-12	6	25.9	16.45	9.45
MEG-33-15	10	31.04	20.9	10.14
	9	31.8	23.63	8.17
MEG-33-6	1	37.9	16.88	21.02
	2	36.8	23.86	12.94
MUS-70-11	5	39.4	25.89	13.51
WAS-7-18	4	28.2	16.63	11.57

Table 11B-2: Atterberg limits for core samples

Sample	Sample No.	Liquid Limit	Plastic Limit	Plasticity Index
ADA-41-15	1	31.99	24.3	7.69
BEL-470-6	16	36.37	25.8	10.57
BEL-470-6	20	31.82	25.04	6.78
BEL-70-22	11	27.11	23.45	3.66
BEL-70-22	3	30.96	23.93	7.03
BEL-70-22	7	29.46	23.59	5.87
BEL-70-22	7	28.49	23.05	5.44
BEL-7-10	19	29.58	24.17	5.41
CLE-275-5	1	33.87	23.54	10.33
CLE-275-5	2	30.57	23.58	6.99
GUE-77-8	2	27.48	21.18	6.3
GUE-77-8	5	27.87	23.68	4.19
GUE-77-8	9	24.58	21.23	3.35
HAM-126-12	1	32.27	23.91	8.36
HAM-126-12	3	28.03	20.97	7.06
HAM-126-12	4	30.82	21.82	9
LAW-52-11	1	24.95	21.6	3.35
LAW-52-11	17	36.69	21.46	15.23
LAW-52-11	21	29.31	24.14	5.17
MEG-33-6	1	27.93	21.67	6.26

APPENDIX 12

DESCRIPTIVE STATISTICS OF DATA

APPENDIX 12-A

DESCRIPTIVE STATISTICS FOR GEOMETRICAL DATA
(SLOPE ANGLE, SLOPE HEIGHT, CATCHMENT DITCH WIDTH,
CATCHMENT DITCH DEPTH, TOTAL AMOUNT OF
UNDERCUTTING, AND RATE OF UNDERCUTTING)

Table 12A-1: Descriptive statistics for geometrical data.

Type of Data	Mean	Median	Mode	Standard Deviation	Kurtosis	Skewness	Range	Count
Slope Angle for Competent Units	68	73	75	10.54	-0.04	-0.95	45-80	17.00
Slope Angle for Incompetent Units	45	40	27	17.17	0.80	1.02	27-80	9.00
Slope Angle for Inter-layered units	49	44	42	12.35	-0.20	0.86	33-71	12.00
Slope Height	75	61	#N/A	40.63	0.29	0.97	21-169	25.00
Catchment Ditch Width (ft)	21	21	12	8.64	-0.59	0.269804	7-40	23
Catchment Ditch Depth (ft)	2	2	1.8	0.63	0.9	-0.6	0.5-3	24
Total Amount of Undercutting	54	43	18	36.20	0.70	1.00	0-154.4	59.00
Rate of Undercutting	2	2	1	1.04	-0.82	0.35	0-3.878947	57.00

APPENDIX 12-B

DESCRIPTIVE STATISICS FOR DISCONTINUITY ORIENTATION,
SPACING, APERTURE, CONTINUITY, DISCONTINUITY
GROUNDWATER CONDITIONS; BEDDING THICKNESS OF
UNDERCUT ROCK UNITS, AND TOTAL THICKNESS OF UNDERCUT
ROCK UNITS

Table 12B-1: Descriptive statistics for discontinuity orientation.

Site	Set	K	Dip	Dip Direction	Variability Interval		Confidence interval		Count	Intersecting Sets	Intersection Azimuth	Intersection Plunge
					68.26 %	95.44 %	68.26 %	95.44 %				
ADA-32-12	1	64.5	88.49	313.2	10.8	17.79	1.89	3.1	33	2/1	16	87
	2	79.8	86.86	31.19	9.73	15.99	3.25	5.34	9			
ADA-41-15	1	103	87.29	138.66	8.57	14.08	1.59	2.62	29			
	2	186	89.1	51.33	6.36	10.4	2.12	3.48	9			
ATH-33-14	1	52.8	71.4	23.85	11.96	19.68	6.01	9.87	4	3/1	18	72
	2	216	86.9	22.49	5.9	9.7	4.18	6.86	2	3/2	78	83
	3	51.1	82.7	88.44	12.16	20.01	5.47	8.98	5			
ATH-50-23	1	31.6	87.7	119.69	15.48	25.33	3.2	5.25	24			
	2	19.6	79.57	205.87	19.69	32.57	3.55	5.83	32			
BEL-7-10	1	34.9	83.1	73.2	14.7	24.27	3.33	5.46	20	2/1	113	80
	2	21.4	79.9	131.27	18.82	31.12	3.24	5.32	35			
BEL-70-22	1	188	82.83	16.5	6.32	10.39	1.38	2.27	21			
	2	61.3	83.24	289.45	11.09	18.25	2	3.29	31	2/1	331	81
BEL-470-6	1	65.5	78.9	0.45	10.73	17.65	1.45	2.38	55	2/1	13	80
	2	27.9	89.06	287	16.48	27.2	2.55	4.18	43	2/1	318	85
CLA-4-8	1	146	85.48	278.59	7.17	11.78	1.53	2.51	22			
	2	51.5	86.25	0.46	12.11	19.94	2.73	4.47	20	2/1	341	86
CLE-275-5	1	99.8	86.53	216.107	8.69	14.29	2.18	3.58	16	3/1	279	83
	2	78.7	88.23	280.77	9.79	16.09	2.84	4.66	12	2/1	206	87
	3	193	86.27	341.43	6.25	10.29	2.36	3.88	7			

Table 12B-1 (contd.).

Site	Set	K	Dip	Dip Direction	Variability Interval		Confidence interval		Count	Intersecting Sets	Intersection Azimuth	Intersection Plunge
					68.26 %	95.44 %	68.26 %	95.44 %				
COL-7-5	1	27.3	73.29	169.02	16.65	27.49	2.34	3.84	52			
FRA-270-24	1	71.9	89.14	218.57	10.25	16.85	2.36	3.87	19	2/1	132	73
	2	27.7	72.5	133.45	16.53	27.29	3.66	6	21			
GUE-77-8	1	19.5	82.7	270.7	19.77	32.71	3.81	6.25	28	2/1	335	76
	2	135	74.69	334.78	7.48	12.29	2.65	4.35	8	3/1	345	67
	3	45.5	68.88	5.58	12.9	21.24	4.33	7.11	9			
GUE-22-6	1	14.5	87.19	48.2	22.92	38.04	4.45	7.3	28	3/1	134	64
	2	131	75.7	175.8	7.58	12.45	3.1	5.09	6	2/1	130	70
	3	98.7	65	134.13	8.74	14.3	3.58	5.87	6	3/2	116	64
HAM-74-6	1	48.6	86.7	64.9	12.4	20.5	2.88	4.73	19	2/1	108	86
	2	48.4	88.47	166.54	12.51	20.58	3.36	5.52	14			
HAM-126-12	1	46	81.02	9.98	12.83	21.13	4.88	8.02	7	4/1	8	81
	2	97.2	84.98	344.5	8.81	14.48	3.95	6.49	5	4/3	8	81
	3	115	85.23	66.24	8.08	13.28	4.05	6.65	4	4/2	14	85
	4	141	89.33	93.33	7.32	12.01	4.23	6.94	3	3/2	21	83
										2/1	50	81

Table 12B-1 (contd.).

Site	Set	K	Dip	Dip Direction	Variability Interval		Confidence interval		Count	Intersecting Sets	Intersection Azimuth	Intersection Plunge
					68.26 %	95.44 %	68.26 %	95.44 %				
LAW-52.-11	1	112	78.23	225.45	8.23	13.5	2.48	4.07	11	3/2	342	56
	2	88.5	88.97	252.18	9.43	15.5	4.23	6.94	5	3/1	295	54
	3	37	56.71	321.667	14.31	23.58	5.89	9.68	6	2/1	165	37
LIC-16-28	1	40.5	58.44	169.21	13.67	22.53	4.87	8	8	3/1	100	32
	2	58.6	37.18	133.77	11.35	18.677	4.66	7.65	6	2/1	238	29
	3	659	85.99	150.99	3.38	5.54	2.39	3.92	2	2/3	61	12
MEG-33-15	1	42.8	87.92	35.8	13.29	21.88	3.46	5.68	15	2/1	105	81
	2	89.1	79.54	115.39	9.2	15.13	3.27	5.36	8	2/3	129	81
	3	40.8	81.3	148.74	13.6	22.42	4.34	7.12	10	3/1r	110	80
MUS-70-11	1	61.4	81.11	151.138	11.09	18.24	2.88	4.72	15	2/1	201	77
	2	30.1	76.69	220.74	15.86	26.16	3.78	6.21	18			
RIC-30-12	1	24	88.28	292.68	17.7	29.38	2.46	4.04	54	2/1	206	84
	2	51.2	85.23	205.17	12.14	24.9	2.49	4.09	24			
STA-30-27	1	26.3	89.1	97.38	16.98	28.04	2.69	4.41	41	2/1	90	90
	2	40.6	88.53	201.29	13.65	22.49	2.81	4.61	24			
WAS-7-18	1	110	83.1	115.77	8.26	13.58	2.93	4.81	8	3/1	109	82
	2	101	85.57	192.04	8.64	14.19	3.87	6.36	5	2/1	133	81
	3	98.5	83.64	67.02	8.76	14.38	5.01	8.31	3			

Table 12B-2: Descriptive statistics for discontinuity spacing (spacing of orthogonal joints) (in).

Lithology	Data Origin	General Description	Population	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	One Population With Some Outliers	Population 1	16.2	15	11	9.39	0.84	0.11	2.6-42	90
Sandstone Units	Outcrop	One Population With Some Outliers	Population 1	34.2	35	48	18.1	0.38	-0.77	8-72	103

Table 12B-3: Summary of average aperture, continuity and groundwater condition.

Site	Aperture (average numerical code: description)	Continuity (average numerical code: description)	Groundwater flow (average numerical code: description)
ADA-32-12	4: Open (0.5-2.5 mm, 0.02-0.1 in	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
ADA-41-15	5: Moderately wide (2.5 mm - 1 cm, 0.1 – 0.4 in)	1: Very low continuity < 3.3 ft (< 1 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
ATH-33-14	6: Wide (> 1 cm, >0.4 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
ATH-50-23	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
BEL-7-10	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	1: The discontinuity is dry with no evidence of water flow.
BEL-70-22	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
BEL-470-6	2: Tight (0.1-0.25 mm, 0.004-0.01in)	1: Very low continuity < 3.3 ft (< 1 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
CLA-4-8	6: Wide (> 1 cm, >0.4 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
CLE-275-5	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
COL-7-5	3: Partly open (0.25-0.5 mm, 0.01-0.02in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
FRA-270-5	5: Moderately wide (2.5 mm - 1 cm, 0.1 – 0.4 in)	1: Very low continuity < 3.3 ft (< 1 m)	1: The discontinuity is dry with no evidence of water flow
GUE-22-6	6: Wide (> 1 cm, >0.4 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
GUE-77-8	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	1: The discontinuity is dry with no evidence of water flow
HAM-74-6	4.: Open (0.5-2.5 mm, 0.02-0.1 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
HAM-126-12	4: Open (0.5-2.5 mm, 0.02-0.1 in)	1: Very low continuity < 3.3 ft (< 1 m)	3: The discontinuity is damp but no free water is present

Table 12B-3 (contd.).

Site	Aperture (average numerical code: description)	Continuity (average numerical code: description)	Groundwater flow (average numerical code: description)
JEF-CR77-0.4	2: Tight (0.1-0.25 mm, 0.004-0.01in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
LAW-52-11	5: Moderately wide (2.5 mm - 1 cm, 0.1 – 0.4 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining
LIC-16-28	3: Partly open (0.25-0.5 mm, 0.01-0.02in)	3: Medium continuity 10 ft - 33 ft (3 - 10 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
MEG-33-6	5: Moderately wide (2.5 mm - 1 cm, 0.1 – 0.4 in)	1: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
MEG-33-15	6:Wide (> 1 cm, >0.4 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
MUS-70-11	6: Wide (> 1 cm, >0.4 in))	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
RIC-30-12	2: Tight (0.1-0.25 mm, 0.004-0.01in)	1: Medium continuity 10 ft - 33 ft (3 - 10 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.
STA-30-27	3: Partly open (0.25-0.5 mm, 0.01-0.02in)	1: Medium continuity 10 ft - 33 ft (3 - 10 m)	3: The discontinuity is damp but no free water is present.
WAS-7-18	4: Open (0.5-2.5 mm, 0.02-0.1 in)	2: Low continuity 3.3 - 10 ft (1 - 3 m)	2: The discontinuity is dry but shows evidence of water flow. i.e. rust staining.

Table 12B-4: Descriptive statistics for bedding thickness (ft).

Lithology	Data Origin	General Description	Population	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	One Population With Some Outliers	Population 1	10.3	10.5	3	6.6	0.14	-1.46	2-22	90
Sandstone Units	Outcrop	One Population With Some Outliers	Population 1	21	14	10	17.6	1.60	2.17	3-74	121

Table 12B-5: Descriptive statistics for total thickness (ft).

Lithology	Data Origin	General Description	Population	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	One Population With Some Outliers	Population 1	2.28	2.14	3.8	1.08	0.34	-0.86	0.5-4.2	25
Sandstone Units	Outcrop	Two Populations	Population 1	9.7	7.61	NA	7.24	0.99	0.13	0.1-26.6	35
			Population 2	48.07	45.77	45.61	5.87	-0.16	-1.16	38.4-554.5	10

APPENDIX 12-C

DESCRIPTIVE STATISTICS FOR RQD, UNCONFINED
COMPRESSIVE STRENGTH, SLAKE DURABILITY INDEX,
PLASTICITY INDEX, AND DENSITY VALUES

Table 12C-1: Descriptive statistics for RQD.

Lithology	Data Origin	General Description	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	Two Populations	90.9	95.5	100.0	9.5	-0.6	-1.9	77.1-100	8.0
Sandstone Units	Outcrop	One Population with outliers	79.3	87.8	100.0	21.1	-0.7	-0.8	39.9-100	14.0
Limestone Units	Core	One Population	84.7	94.1	100.0	19.2	-1.1	0.2	40-100	19.0
Sandstone Units	Core	Two Populations	29.3	34.0	#N/A	19.1	-0.5	-1.4	0-50	7.0
			98.2	100.0	100.0	4.6	-3.1	9.9	81.5-100	20.0
Shale Units	Core	One Population with outliers	91.4	98.0	100.0	11.3	-1.2	0.2	64.5-100	35.0
Claystone/Mudstone Units	Core	One Population with outliers	82.2	81.7	100	16.3	-0.48	-0.8	48.4-100	24

Table 12C-2: Descriptive statistics for unconfined compressive strength (psi).

Lithology	Data Origin	General Description	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	One Population	14194	14252	#N/A	4626.5	-0.0011	-0.52	3010.1-24542	58
Sandstone Units	Outcrop	One Population	6371	5011	#N/A	4012.5	1.04	0.57	1400-16704	49
Limestone Units	Core	One Population	15331	15670	#N/A	5541.7	0.12	-0.55	4147.8-25669.2	23
Sandstone Units	Core	Two Populations	6696	6518	#N/A	3507.8	0.19	-1.24	1178.5-12232.6	27
Sandstone Units			17895	17931	#N/A	1868.8	1.14	2.42	15519.8-21506.9	7
Shale Units	Outcrop	One Population With Outliers	2904	2639	#N/A	1712	0.9	1.0	545-7049	18
Claystone/Mudstone Units	Outcrop	One Population	854	572	#N/A	98.6	3.5	14	107-5618	41
Shale Units	Core	One Population With Outliers	2399	1719	#N/A	2021.2	2.55	7.5	332.3-10645.6	43
Claystone/Mudstone Units	Core	One Population	1557	1465	#N/A	857.5	0.06	-1.24	221.6-3108.6	28

Table 12C-3: Descriptive statistics for slake durability index (%).

Lithology	Data Origin	General Description	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone Units	Outcrop	One Population	98.5	99.1	99.1	1.7	-3.4	12.5	90.7-99.5	59.0
Sandstone Units	Outcrop	One Population With Outliers	94.1	96	97.5	4.5	-1.2	0.65	81.5-99	51
Limestone Units	Core	One Population	98.0	99.1	99.0	3.4	-3.5	12.8	85.5-99.7	18.0
Sandstone Units	Core	One Population With Outliers	93.21	96.40	96.50	8.26	-2.18	4.17	67.6-99.1	34
Shale Units	Outcrop	One Population With Outliers	90.9	92.7	97.8	7.7	-1.2	0.7	71.6-99.3	30.0
Claystone/Mudstone Units	Outcrop	Two Populations	4.2	3.5	3.8	3.1	0.6	-0.8	0-9.8	20.0
			54.4	52.0	35.4	22.4	0.2	-0.8	18.4-97.8	32.0
Shale Units	Core	One Population With Outliers	87.1	88.5	86.5	8.8	-0.9	0.5	62.5-98.9	43.0
Claystone/Mudstone Units	Core	Two Populations	17.8	20.4	0.1	11.8	-0.3	-1.3	0-33.9	20.0
			73.2	70.7	#N/A	12.0	0.8	-0.3	57-94.8	12.0

Table 12C-3: Descriptive statistics for plasticity index.

Data Origin	General Description	Population 1	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Outcrop	One Population	Population 1	11.8	11.9	NA	4.8	-0.01	-0.1	2.38-21	25
Core	One Population	Population 1	6.9	6.5	3.4	2.8	1.3	2.7	3.3-15.2	20

Table 12C-4: Descriptive statistics for density values.

Lithology	Mean	Median	Mode	Standard Deviation	Skewness	Kurtosis	Range	Count
Limestone	158.3	158.4	#N/A	2.6	-0.1	-3.2	155.3-161	4
Sandstone	144.5	151.6	#N/A	15.2	-0.8	-1.1	120.4-158.8	7
Shale	165.7	168.5	#N/A	8.1	-1.3	1.9	145.9-175.9	13
Claystone/Mudstone	163.8	163.9	#N/A	4.1	-0.1	1.1	156.6-170.8	8

APPENDIX 13

STABILITY ANALYSIS FOR COMPETENT ROCK UNITS

APPENDIX 13-A

KINEMATIC ANALYSIS USING ROCKPACK SOFTWARE

<u>Using RockPack</u>
STEREONETT software program was used to contour poles. Principal discontinuity sets were identified using STEREONETT-drawn contours and their corresponding great circles were chosen manually on the RockPack stereonet output.

If the great circle representing discontinuity falls within the shaded zone, a plane failure is likely to occur based on Hoek and Bray's (1981) criteria.

If the intersection of two great circles representing discontinuities falls within the shaded zone, a wedge failure is likely to occur based on Hoek and Bray's (1981) criteria.

Type A toppling failure occurs when the great circle representing a discontinuity is sub-parallel, within 30 degrees to the great circle representing the slope face and its dip vector falls in the triangular shaded zone based on Goodman's, (1989) criteria.

Type B toppling occurs when two great circles representing discontinuities plunge at greater than 80 degrees.

ADA-32-12

Pole Plot

Dip Vector Plot
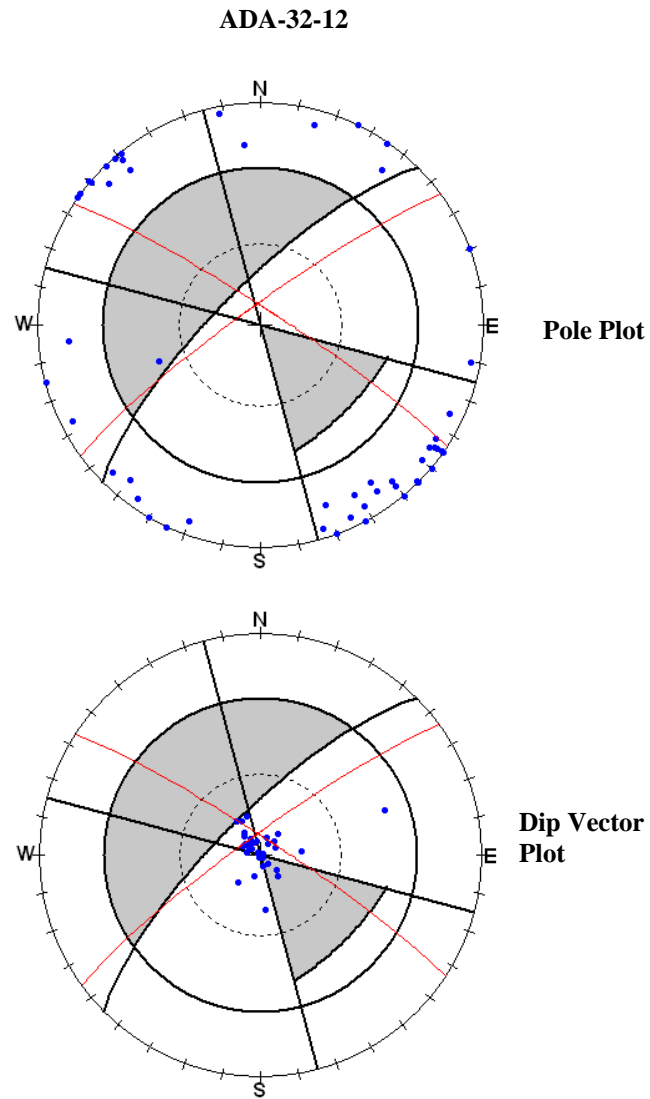
Figure 13A-1: Kinematic analysis for ADA-32-12 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
ADA-32-12-	Limestone	57	75	No	No	No	Yes

ATH-33-14

Pole Plot

Dip Vector Plot
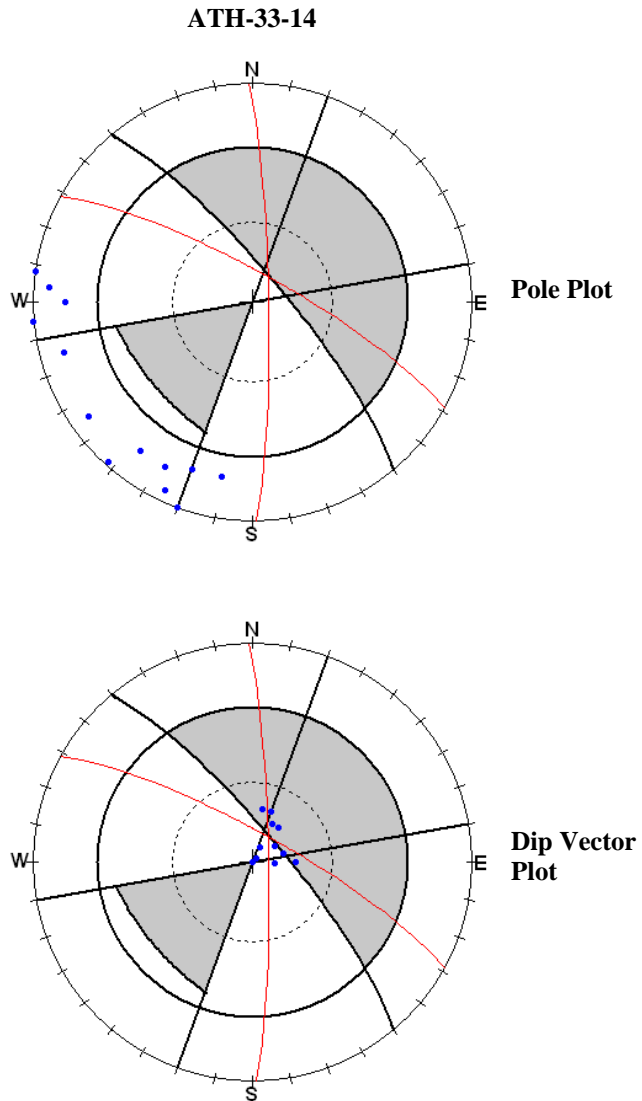
Figure 13A-2: Kinematic analysis for ATH-33-14 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
ATH-33-14	Sandstone	13	79	No	No	No	No

BEL-470-6

Pole Plot

Dip Vector
Plot
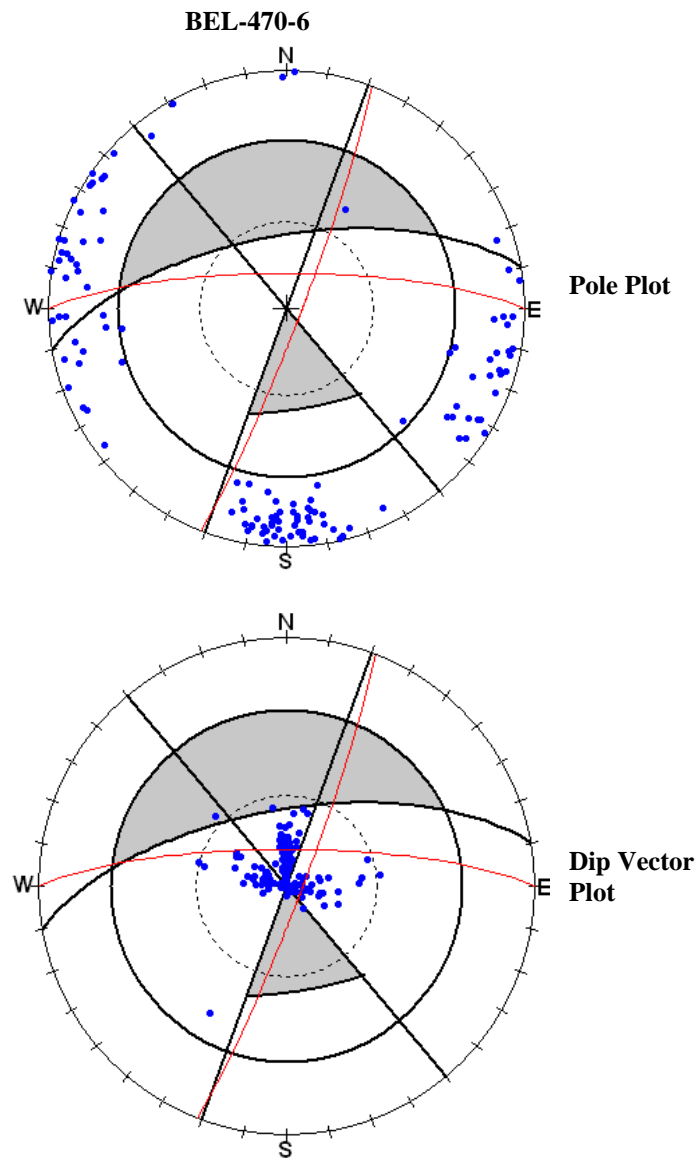
Figure 13A-3: Kinematic analysis for BEL-470-6 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
BEL-470-6	Limestone.	127	65	No	No	No	No

CLA-4-8

Pole Plot

Dip Vector Plot
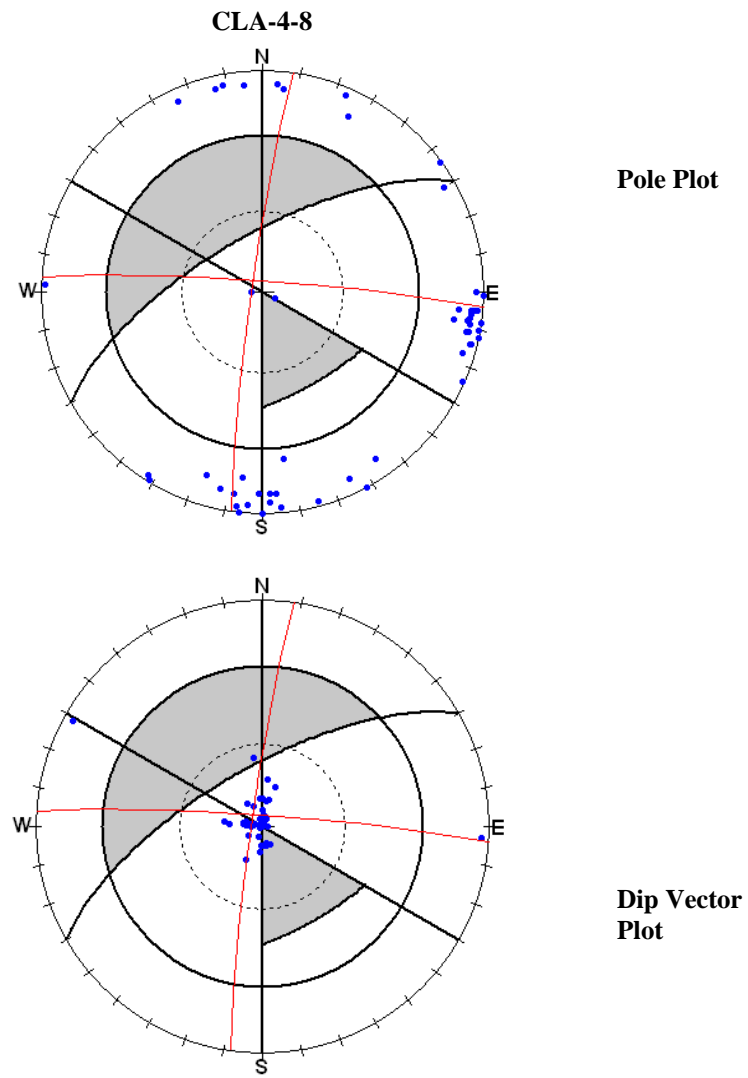
Figure 13A-4: Kinematic analysis for CLA-4-8 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
CLA-4-8	Limestone	55	69	No	No	No	Yes

COL-7-5

Pole Plot

Dip Vector
Plot
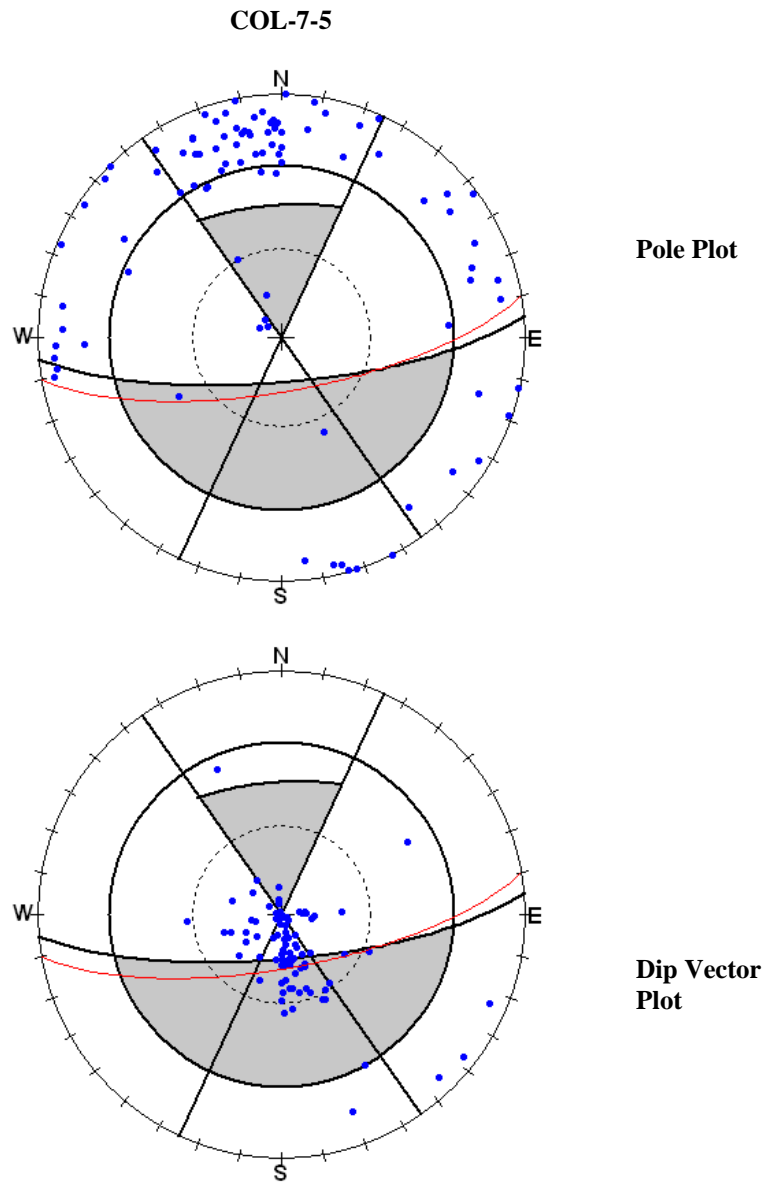
Figure 13A-5: Kinematic analysis for COL-7-5 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
COL-7-5	Sandstone	93	75	Yes	No	No	No

GUE-77-8

Pole Plot

Dip Vector Plot
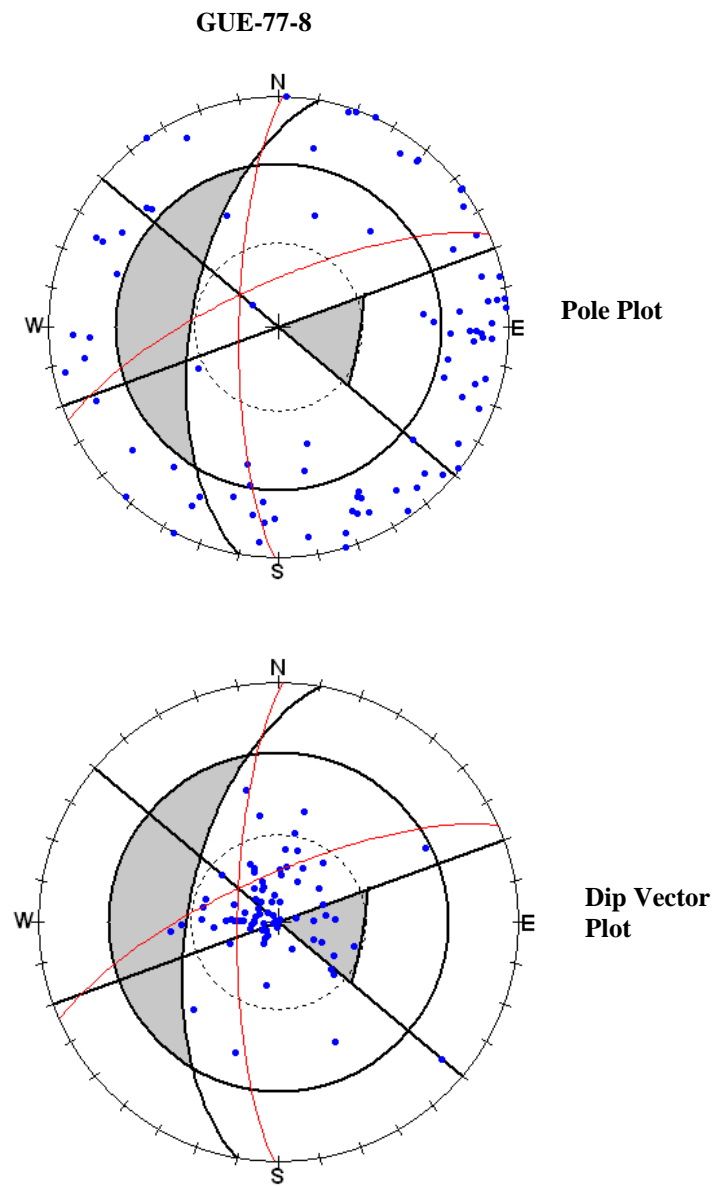
Figure 13A-6: Kinematic analysis for GUE-77-8 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
GUE-77-8	Sandstone	87	59	No	No	Yes	No

JEF-CR77-0.4

Pole Plot

Dip Vector
Plot
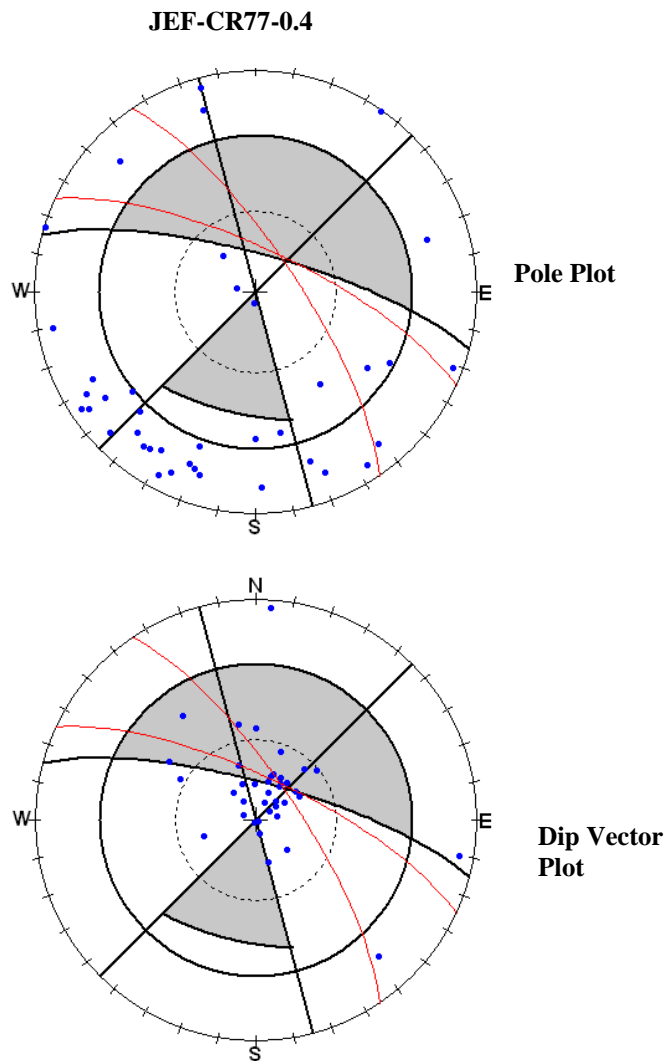
Figure 13A-7: Kinematic analysis for JEF-CR77-0.4 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
JEF-CR77 -0.38	Sandstone	39	76	No	No	No	No

LAW-52-11

Pole Plot

Dip Vector Plot
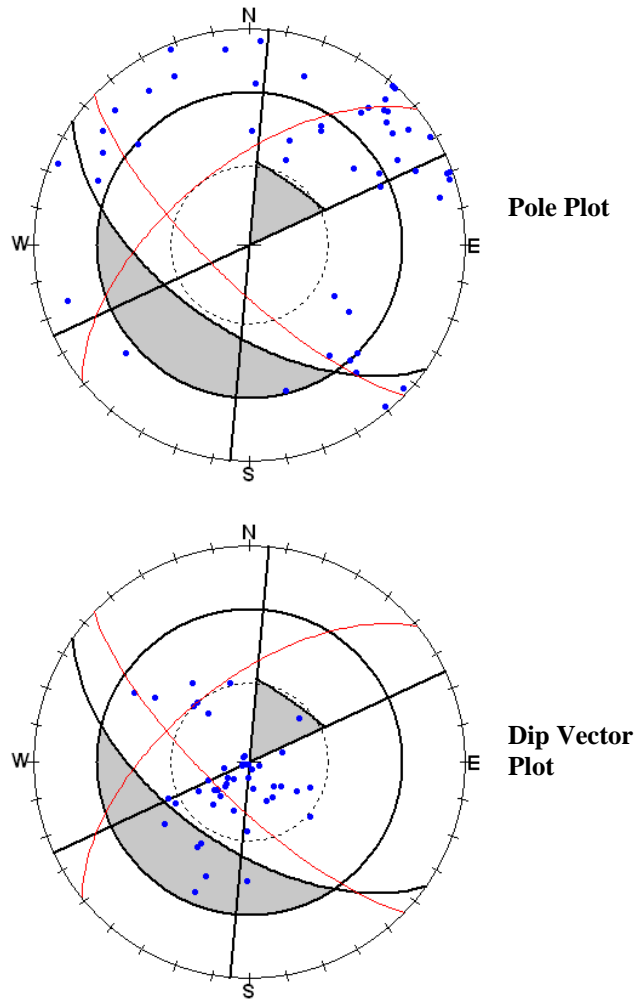
Figure 13A-8: Kinematic analysis for LAW-52-11 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
LAW -52- 11	Sandstone	51	58	No	No	No	No

LIC-16-28
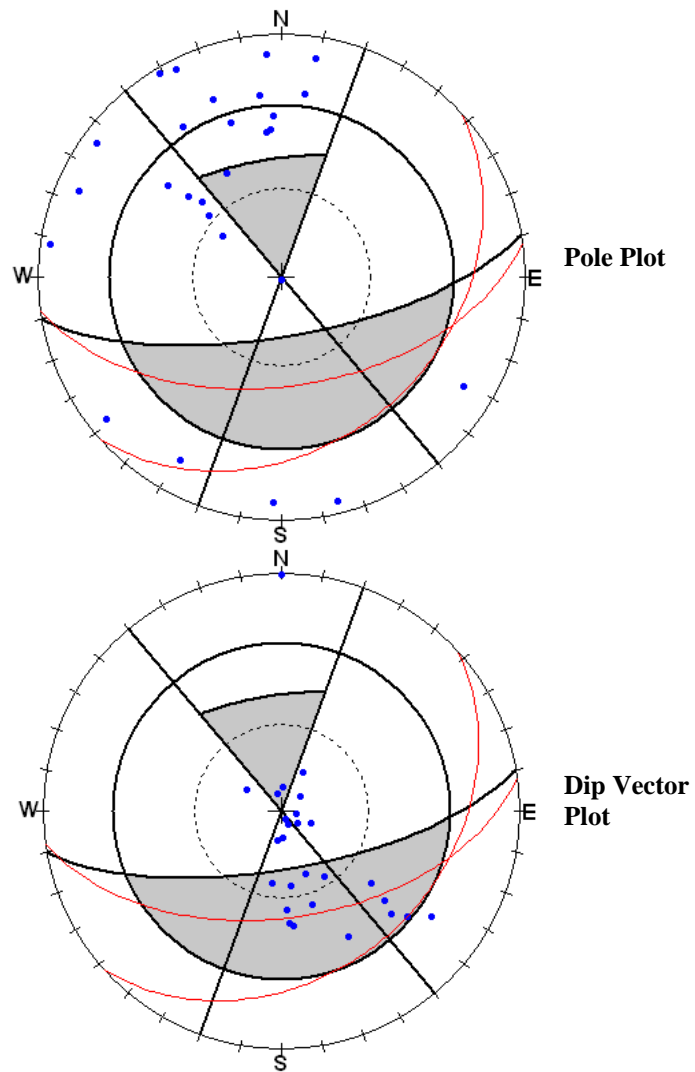
Figure 13A-9: Kinematic analysis for LIC-16-28 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
LIC-16-28	Sandstone	28	69	Yes	No	No	No

MUS-70-11

Pole Plot

Dip Vector
Plot
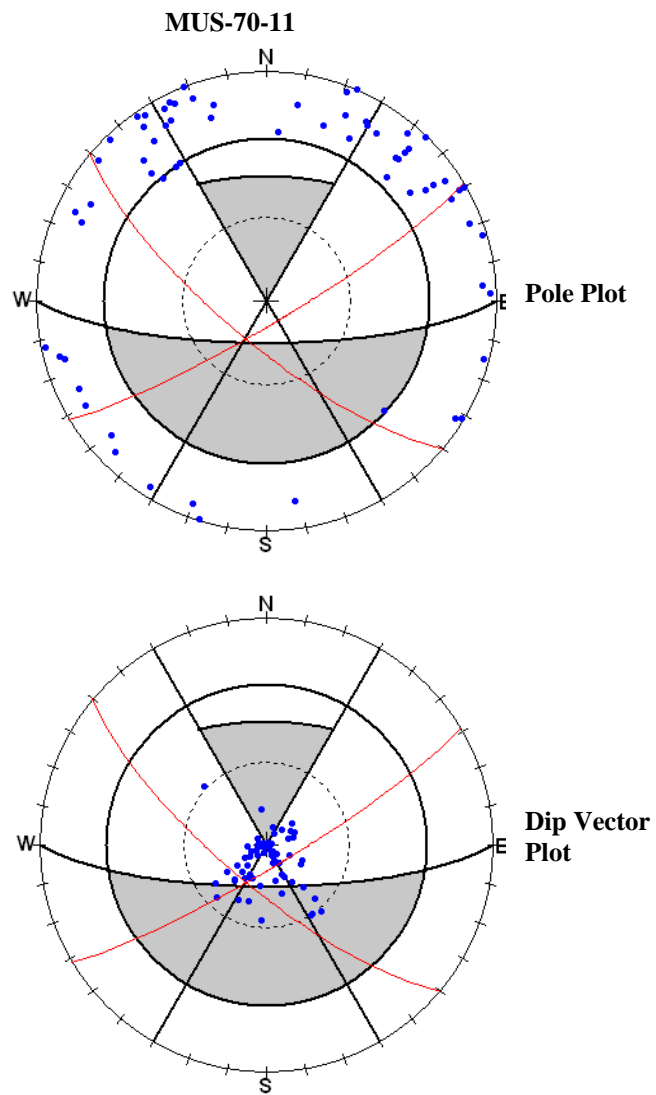
Figure 13A-10: Kinematic analysis for MUS-70-11 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
MUS-70-11	Sandstone	66	75	No	No	No	No

RIC-30-12

Pole Plot

Dip Vector Plot
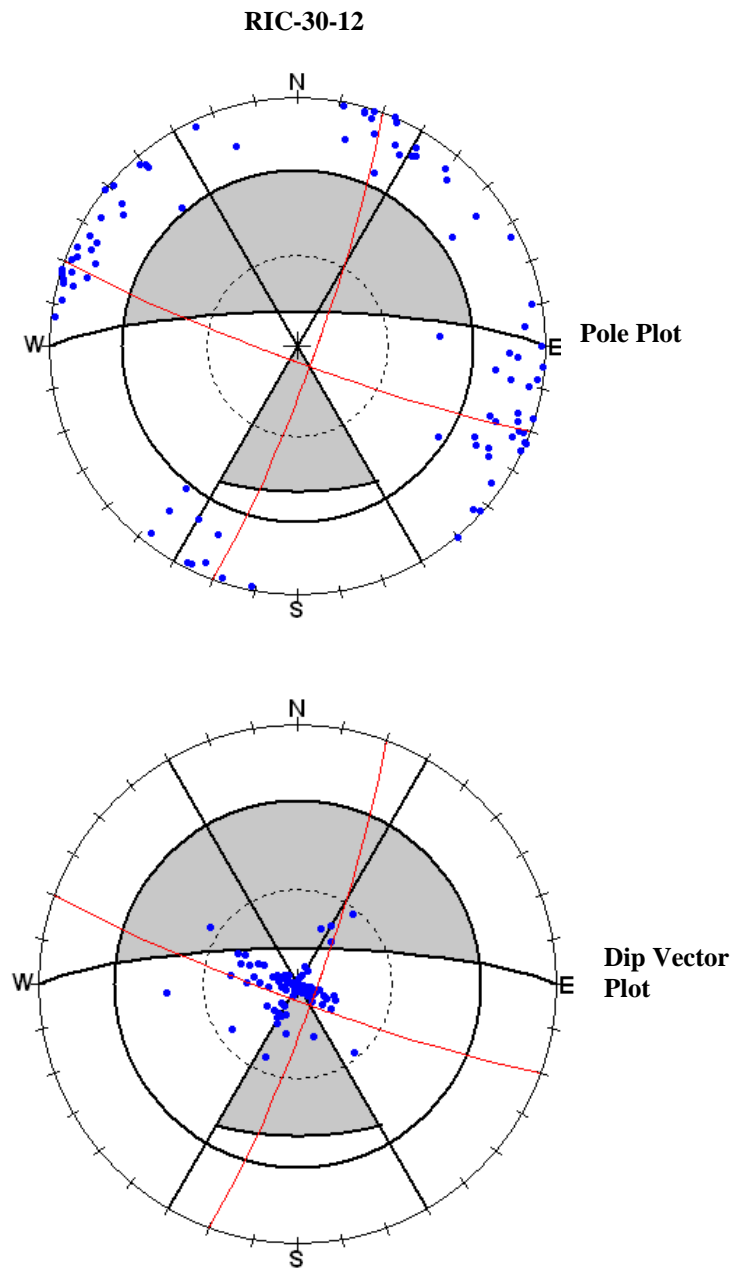
Figure 13A-11: Kinematic analysis for RIC-30-12 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
RIC-30-12	Sandstone	91	79	No	No	No	Yes

WAS-7-18

Pole Plot

Dip Vector Plot
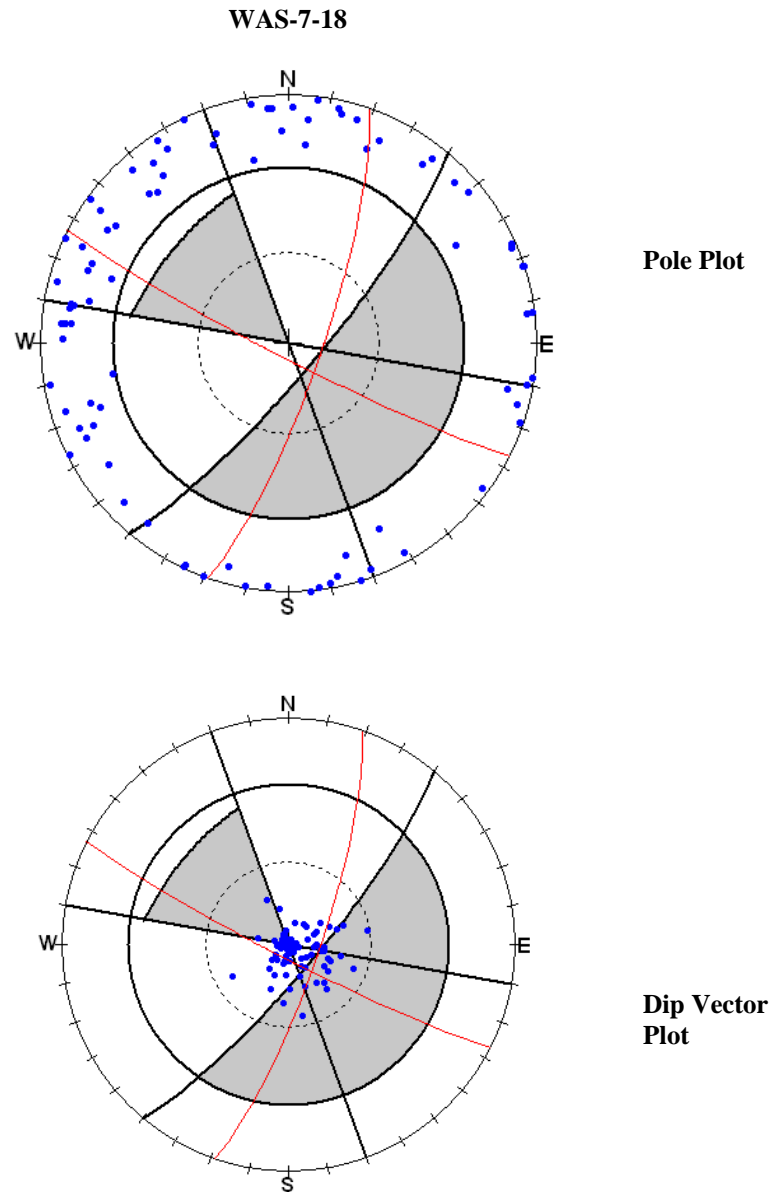
Figure 13A-12: Kinematic analysis for WAS-7-18 site.

Site	Rock Unit	No. of Discontinuities	Existing Slope Angle (Degrees)	Plane Failure Potential	Wedge Failure Potential	Type A Toppling Potential	Type B Toppling Potential
WAS-7-18	Sandstone	87	80	No	Yes	No	No

APPENDIX 13-B

KINEMATIC ANALYSIS USING DIPS SOFTWARE
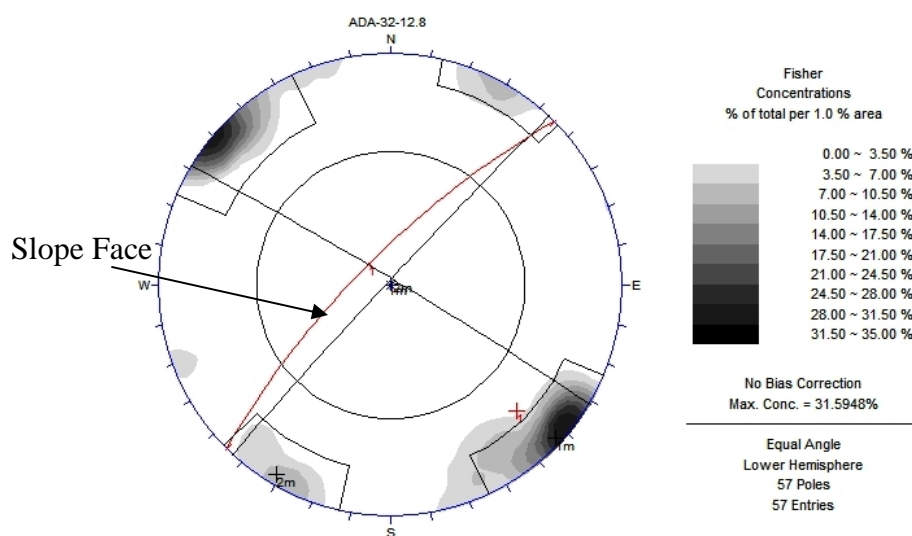
Figure 13B-1: Kinematic analysis for ADA-32-12.8 site.
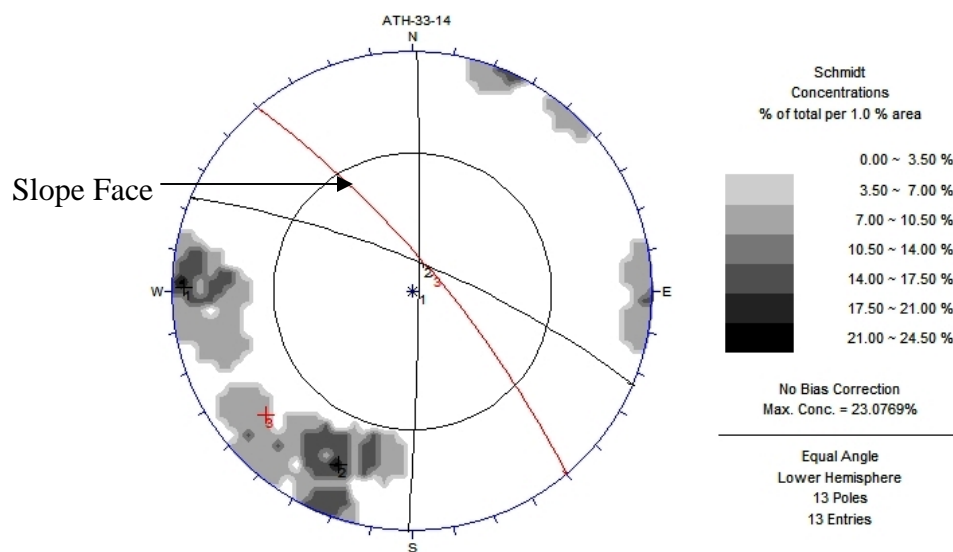
Figure 13B-2: Kinematic analysis for ATH-33-14 site.
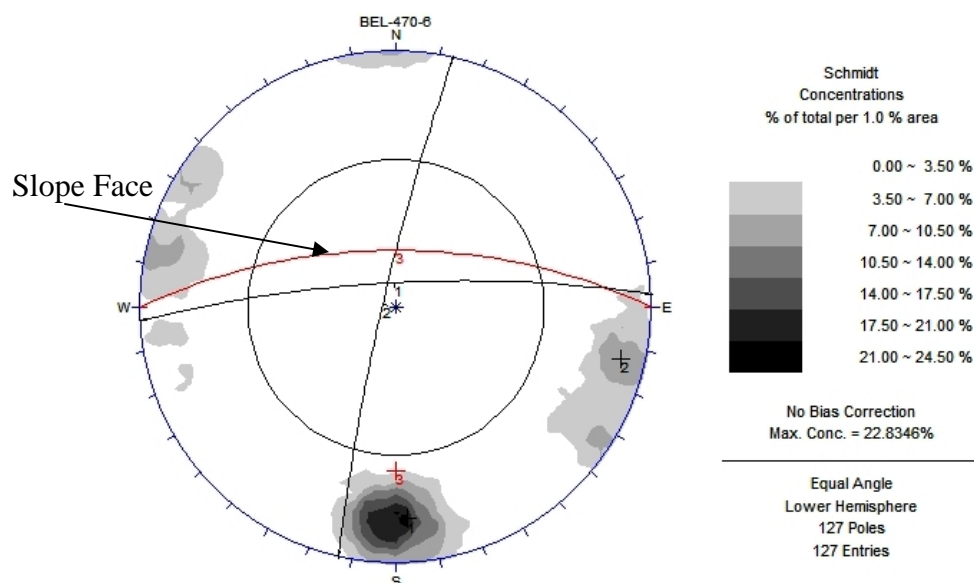
Figure 13B -3: Kinematic analysis for BEL-470-6 site.
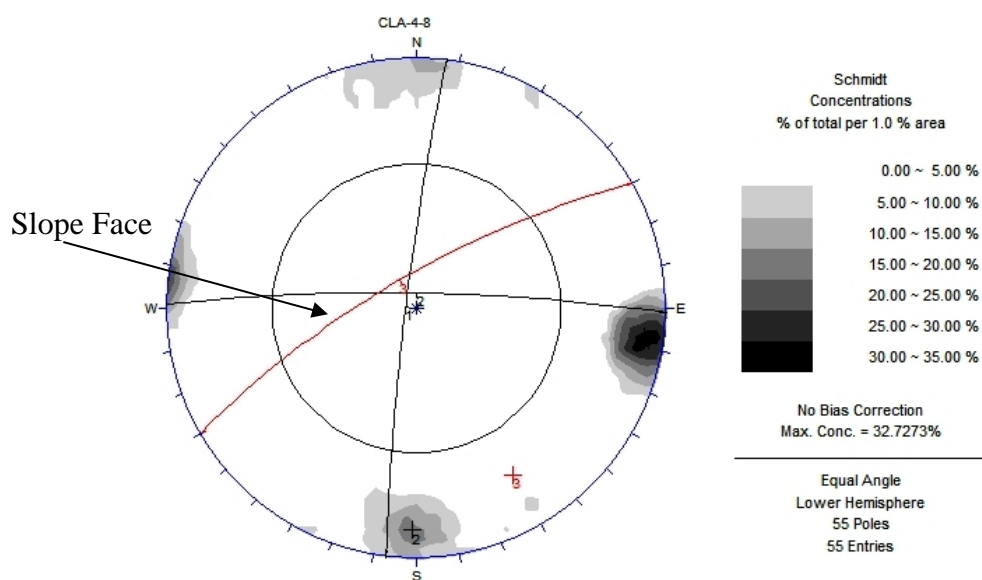
Figure 13B-4: Kinematic analysis for CLA-4-8 site.
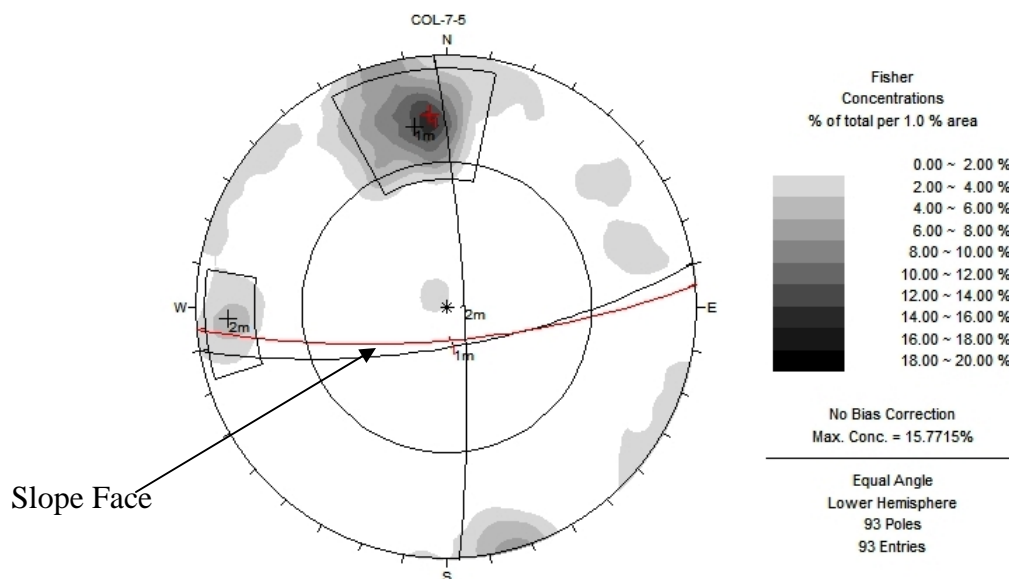
Figure 13B-5: Kinematic analysis for COL-7-5 site.
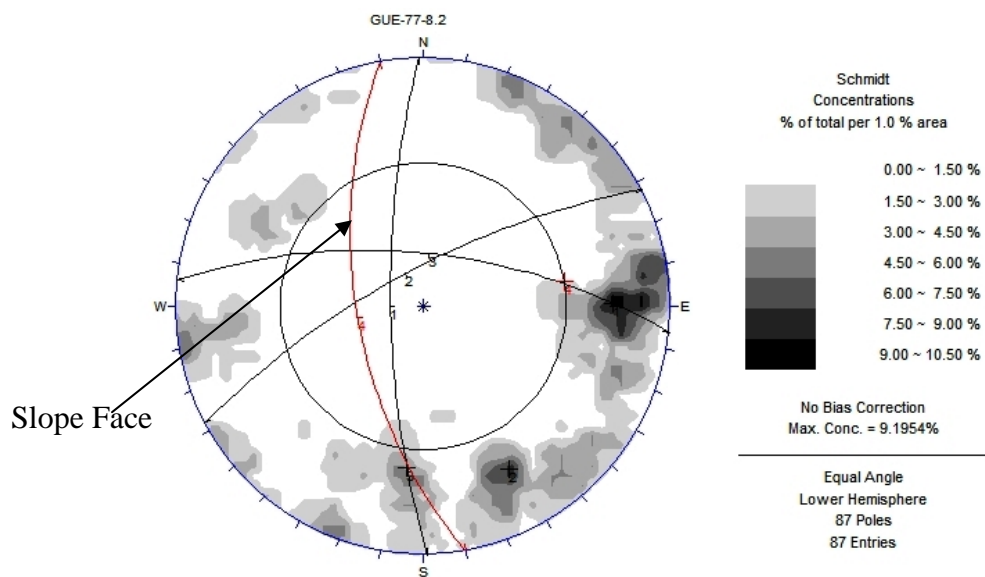
Figure 13B-6: Kinematic analysis for GUE-77-8.2 site.
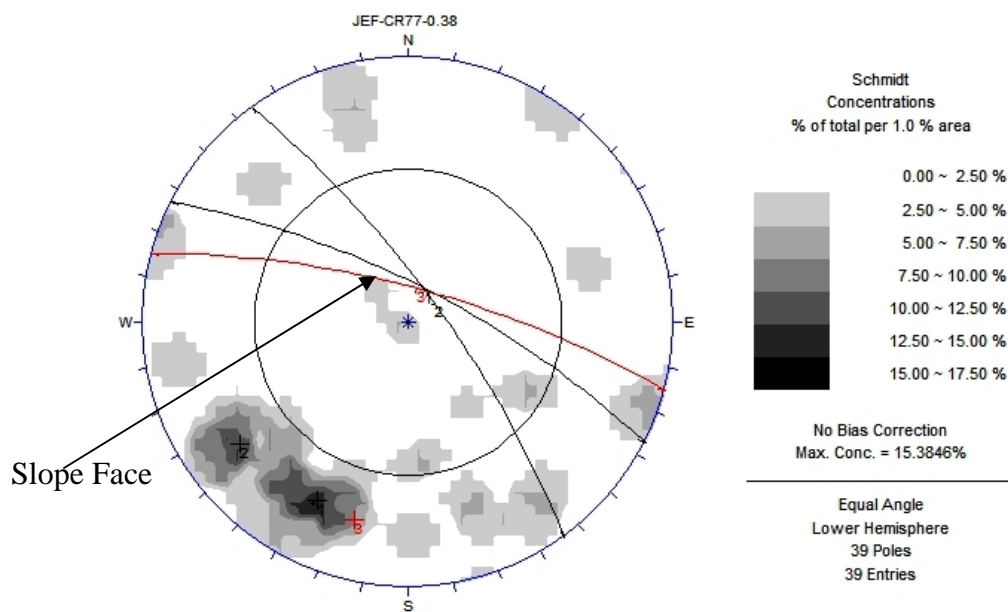
Figure 13B-7: Kinematic analysis for JEF-CR77-0.38 site.
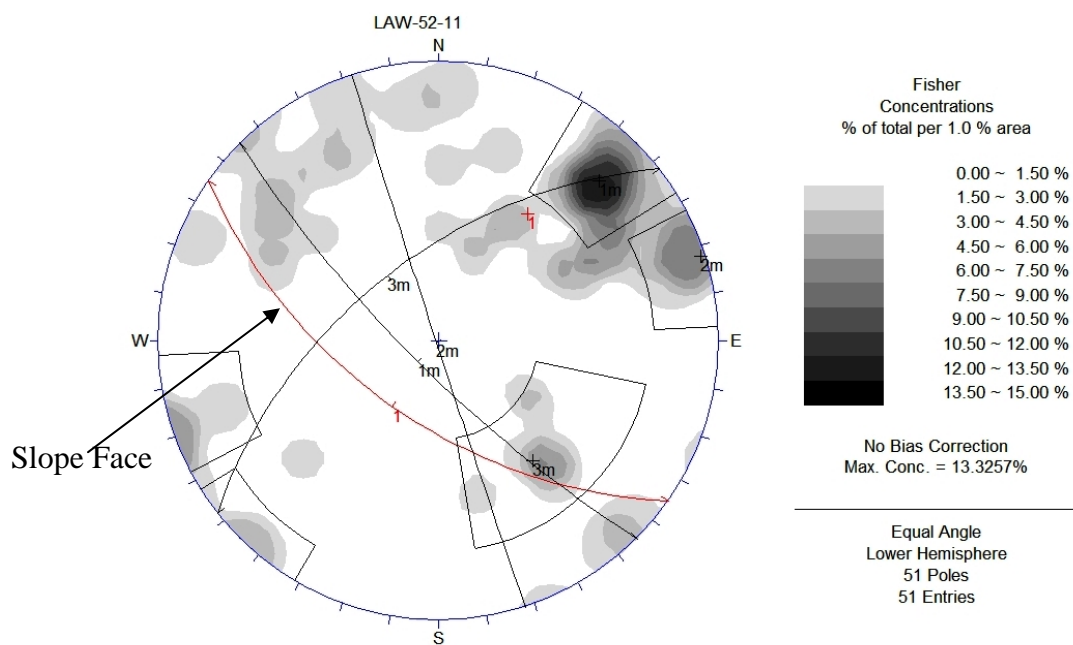
Figure 13B -8: Kinematic analysis for LAW-52-11 site.
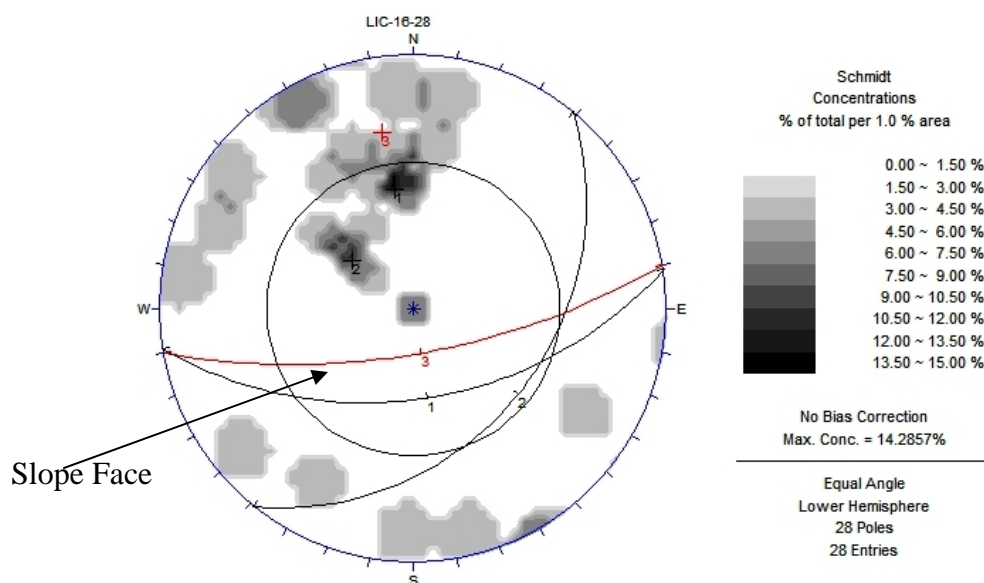
Figure 13B -9: Kinematic analysis for LIC-16-28 site.
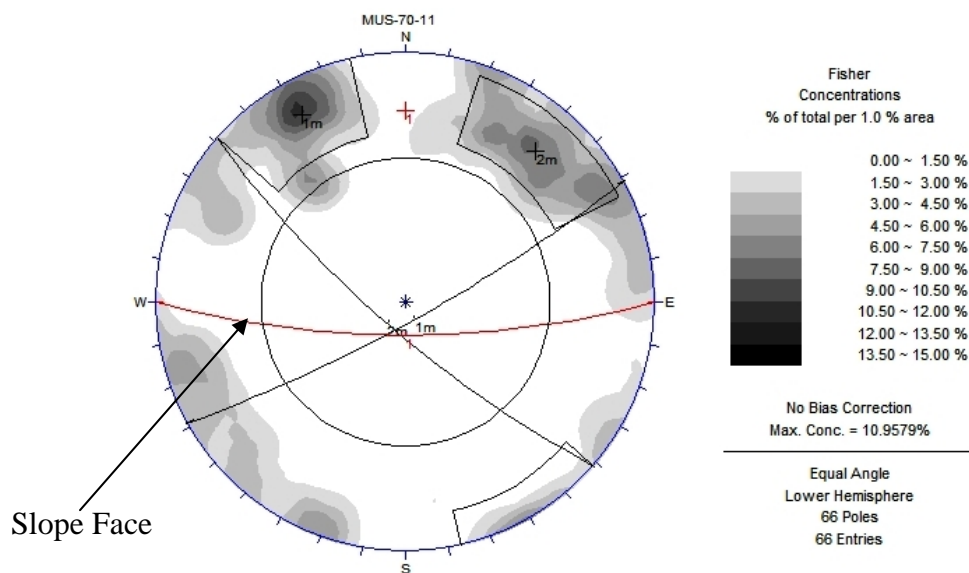
Figure 13B -10: Kinematic analysis for MUS-70-11 site.
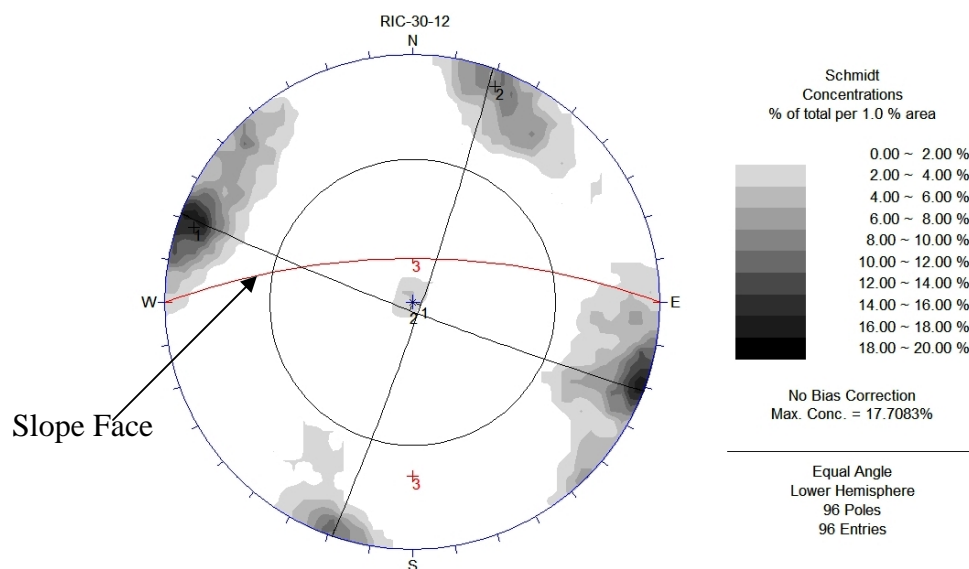
Figure 13B-11: Kinematic analysis for RIC-30-12 site.
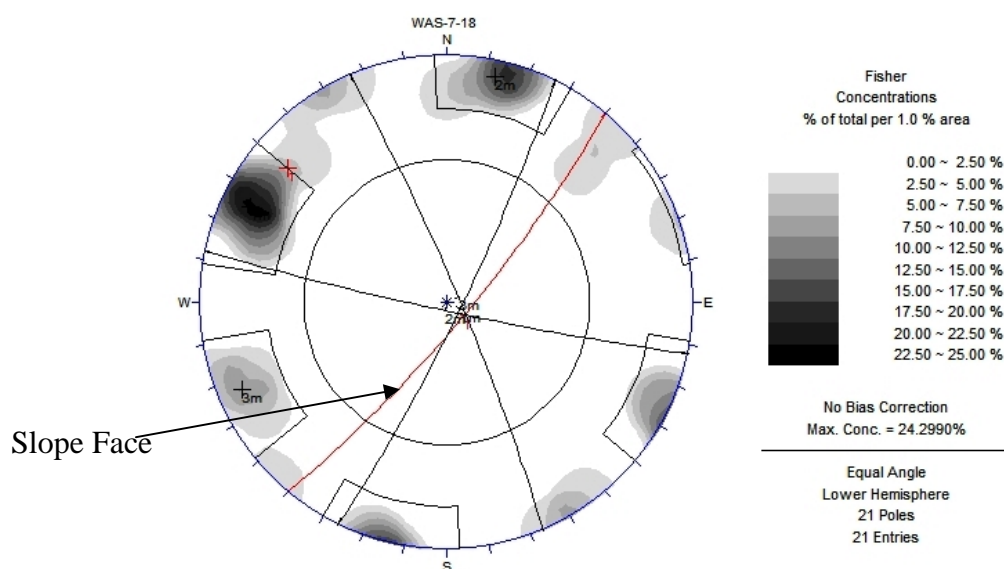
Figure 13B-12: Kinematic analysis for WAS-7-18 site.

APPENDIX 13-C

SENSITIVITY ANALYSIS USING QUANTITATIVE APPROACH
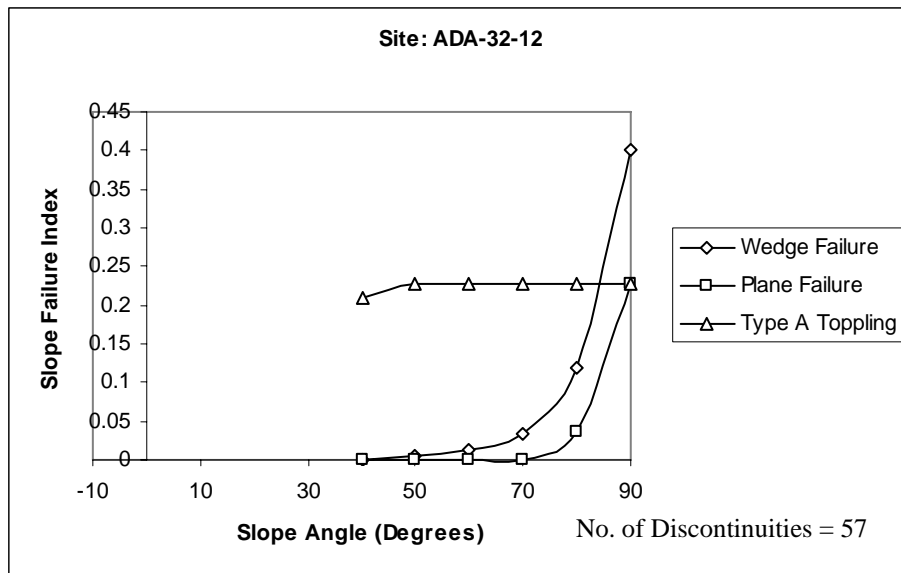
Figure 13C-1: Sensitivity analysis for ADA-32-12 site.
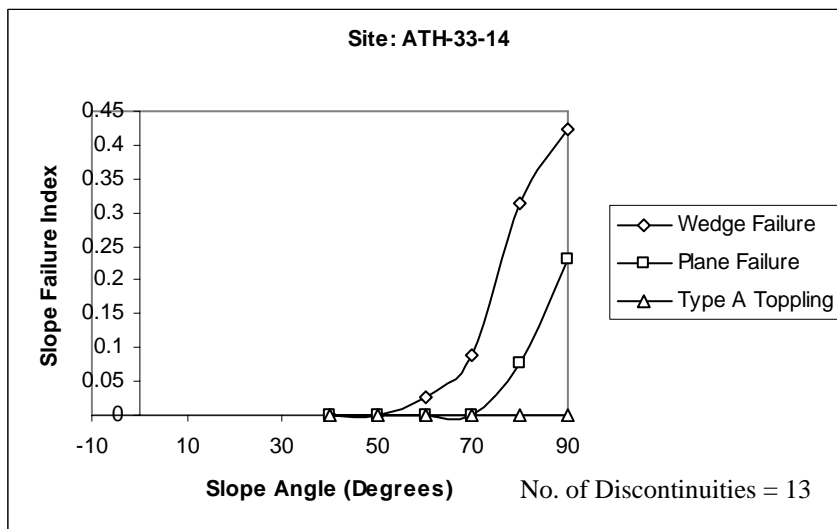
Figure 13C-2: Sensitivity analysis for ATH-33-14 site.
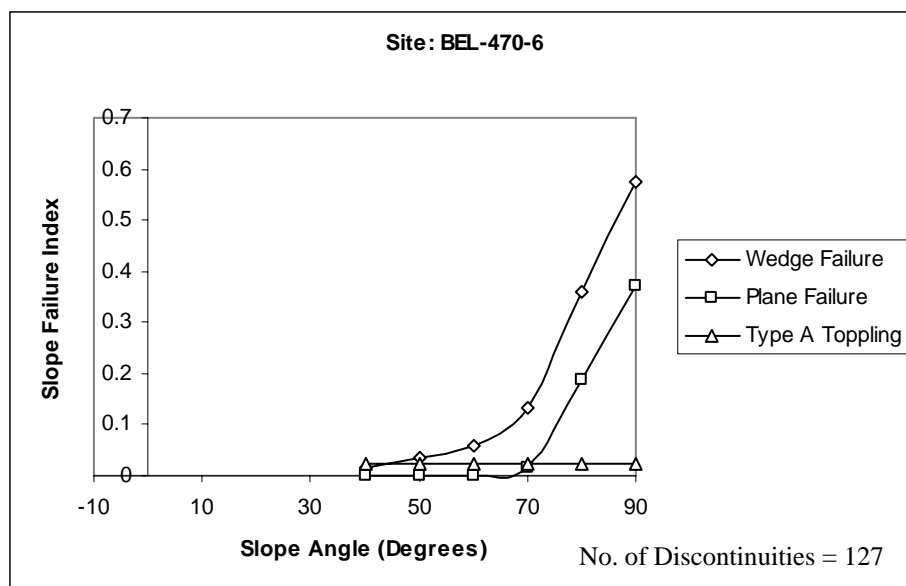
Site: BEL-470-6

Figure 13C-3: Sensitivity analysis for BEL-470-6 site.

Count = 127

Site: CLA-4-8
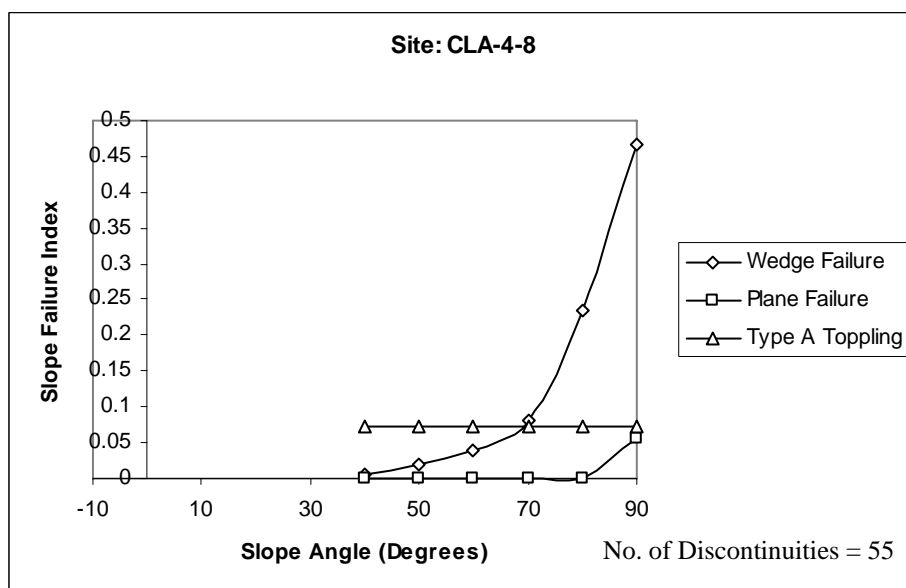
Figure 13C-4: Sensitivity analysis for CLA-4-8 site.
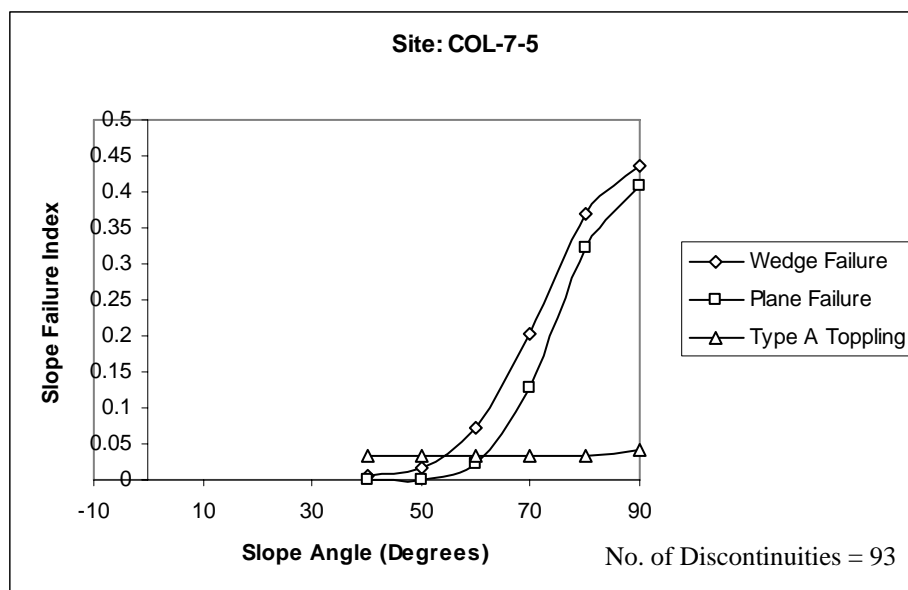
Figure 13C-5: Sensitivity analysis for COL-7-5 site.
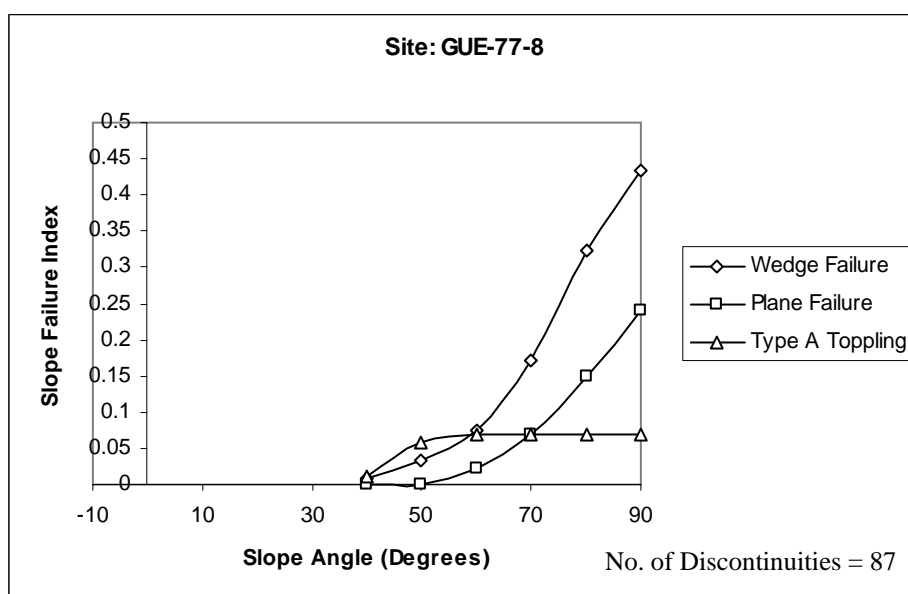
Figure 13C-6: Sensitivity analysis for GUE-77-8 site.
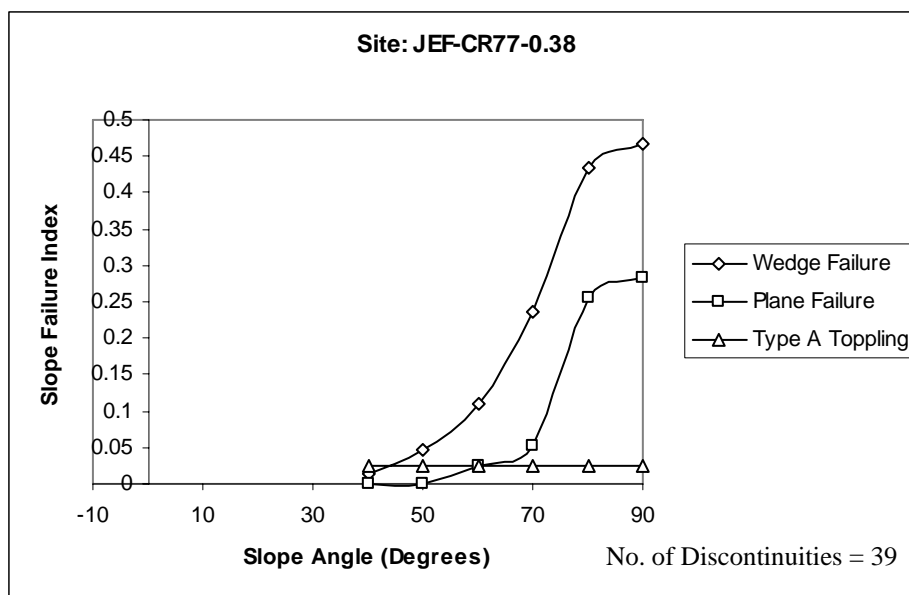
Figure 13C-7: Sensitivity analysis for JEF-CR77-0.38 site.
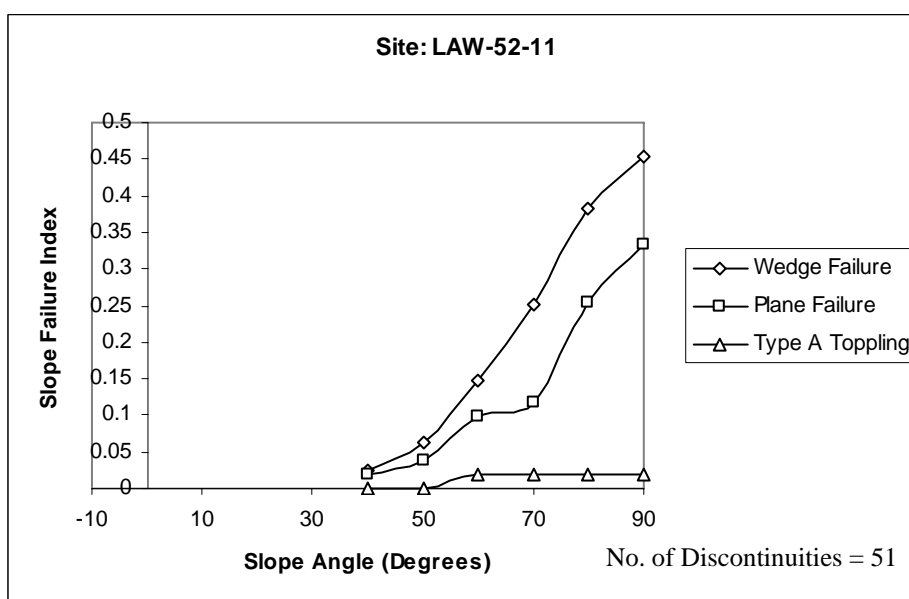
Figure 13C-8: Sensitivity analysis for LAW-52-11 site.
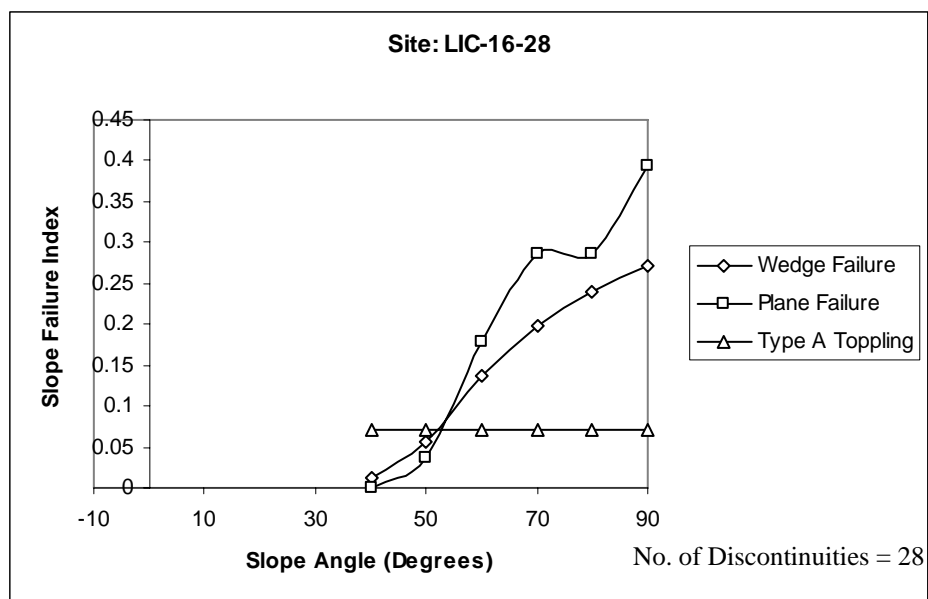
Figure 13C-9: Sensitivity analysis for LIC-16-28 site.
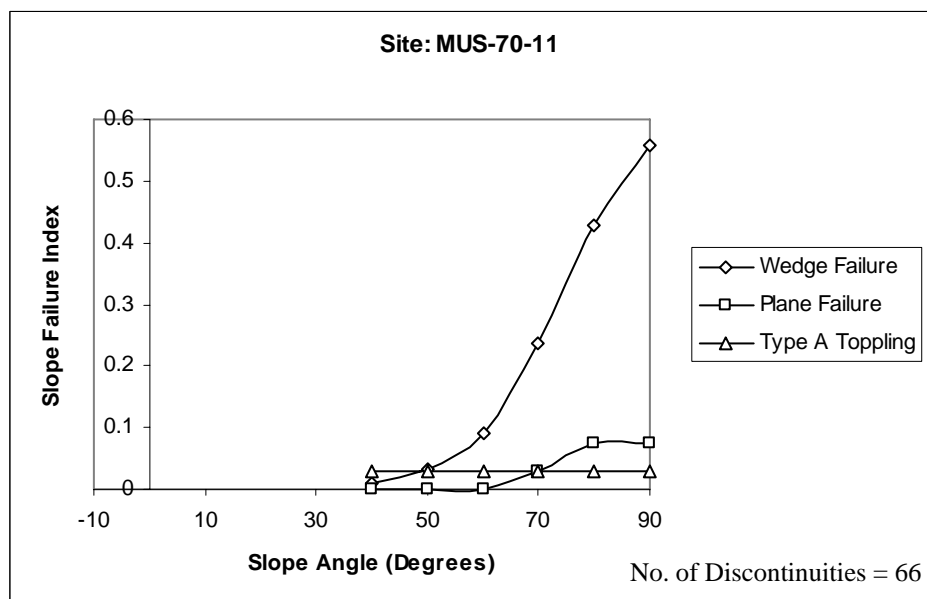
Figure 13C-10: Sensitivity analysis for MUS-70-11 site.
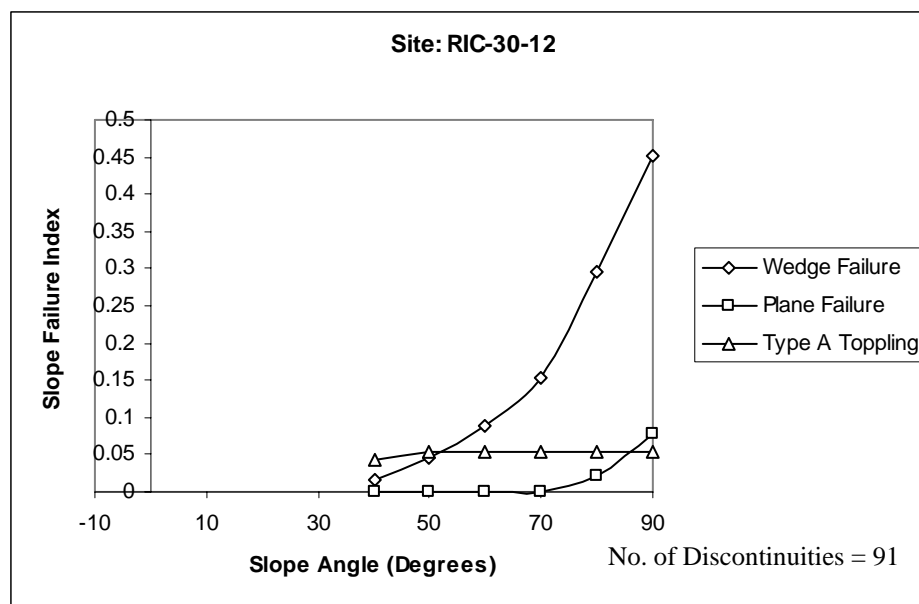
Figure 13C-11: Sensitivity analysis for RIC-30-12 site.
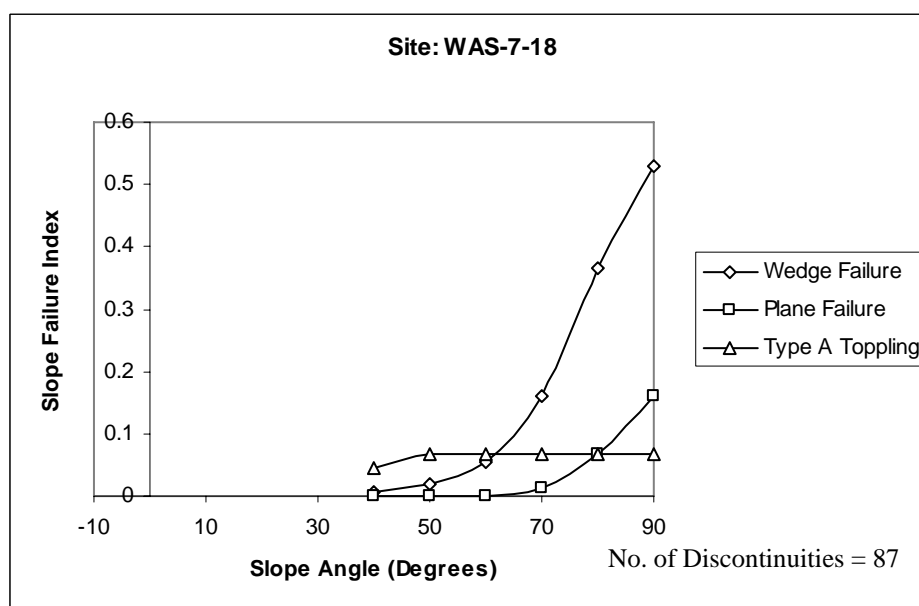
Figure 13C-12: Sensitivity analysis for WAS-7-18 site.

APPENDIX 13-D

RESULTS OF STABILITY ANALYSIS USING THE SLIDE SOFTWARE
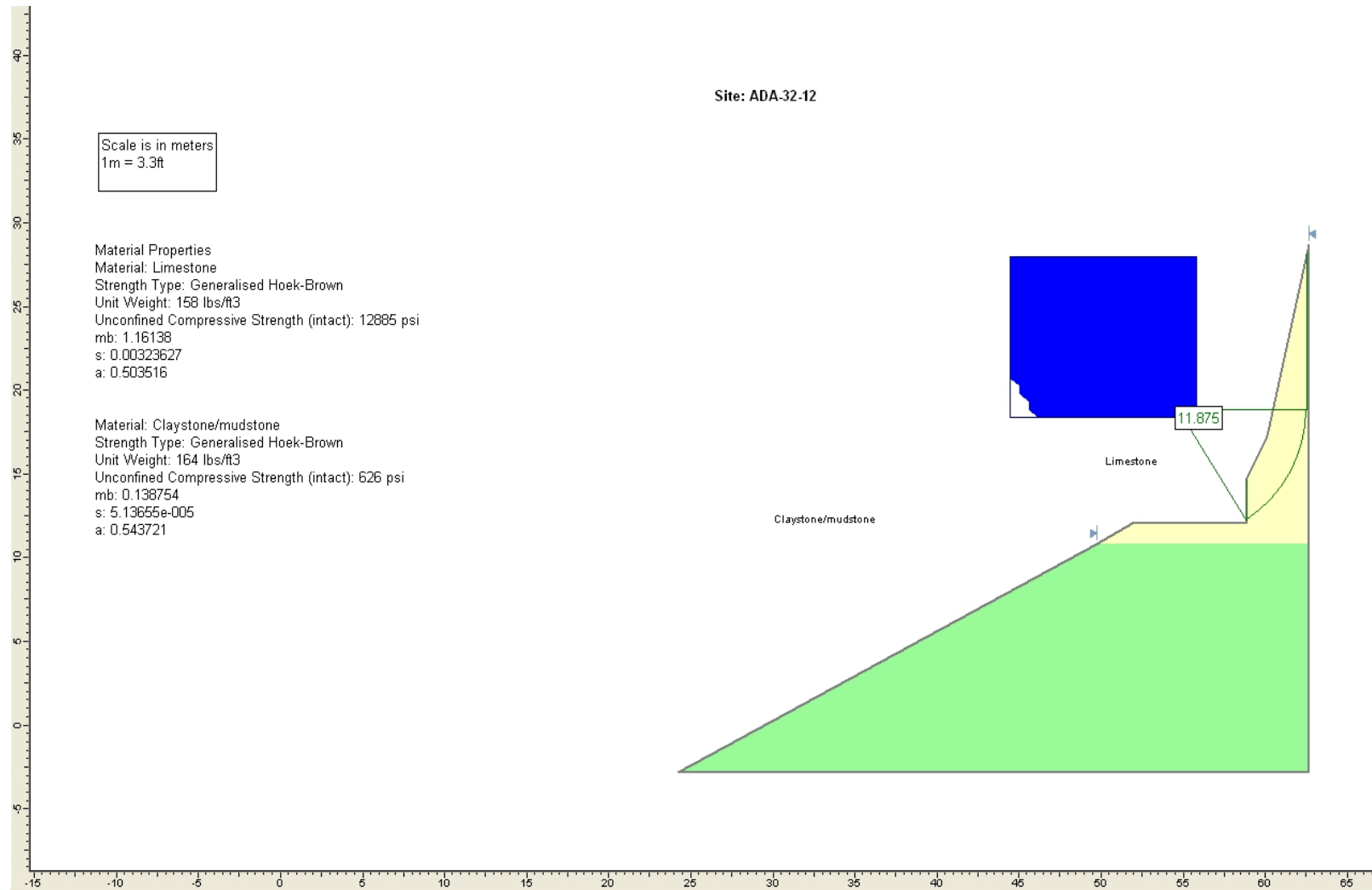
Figure 13D-1: Result of stability analysis for ADA-32-12 site. The number in the box represents the factor of safety value for the curved failure surface shown.
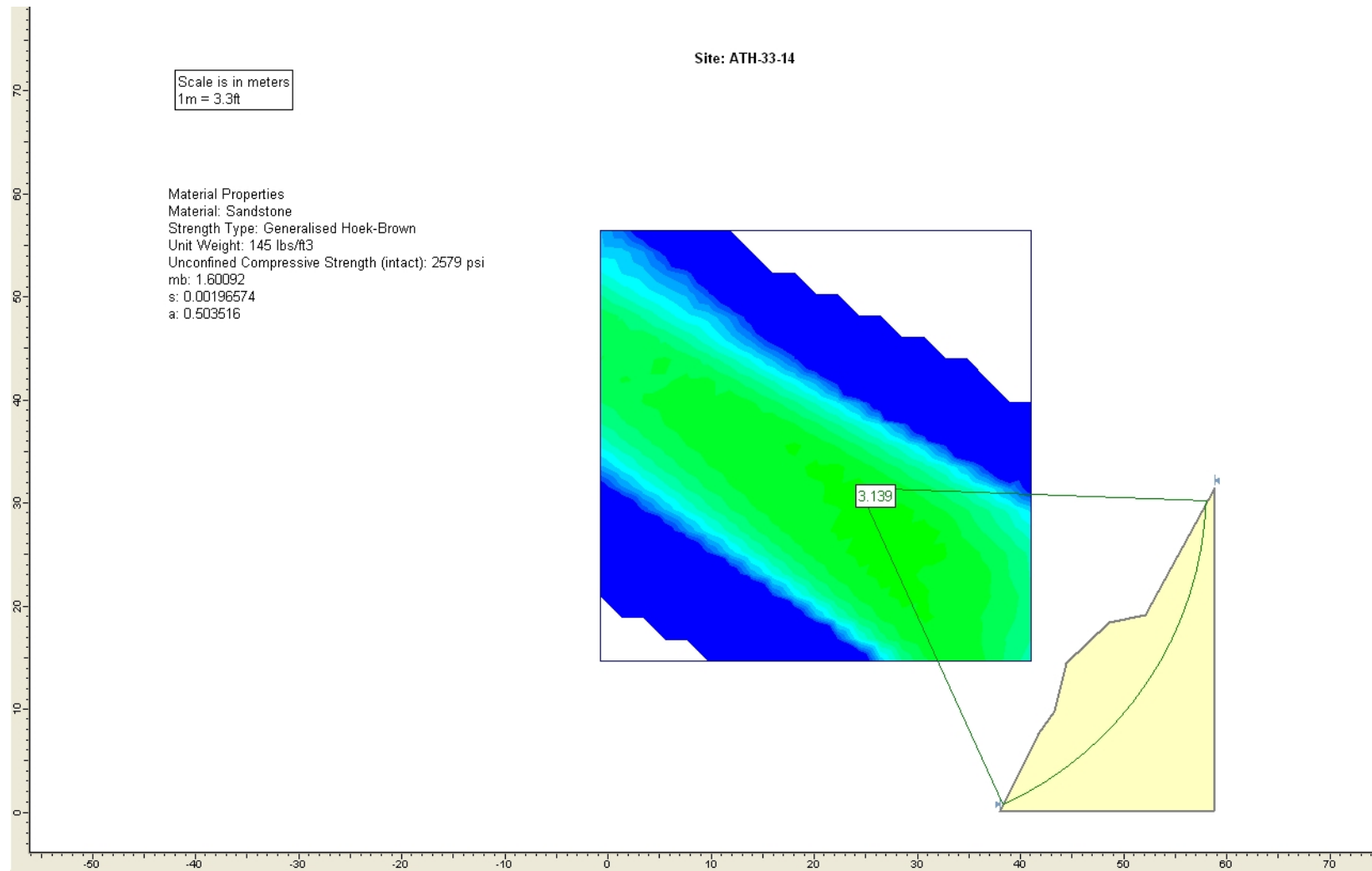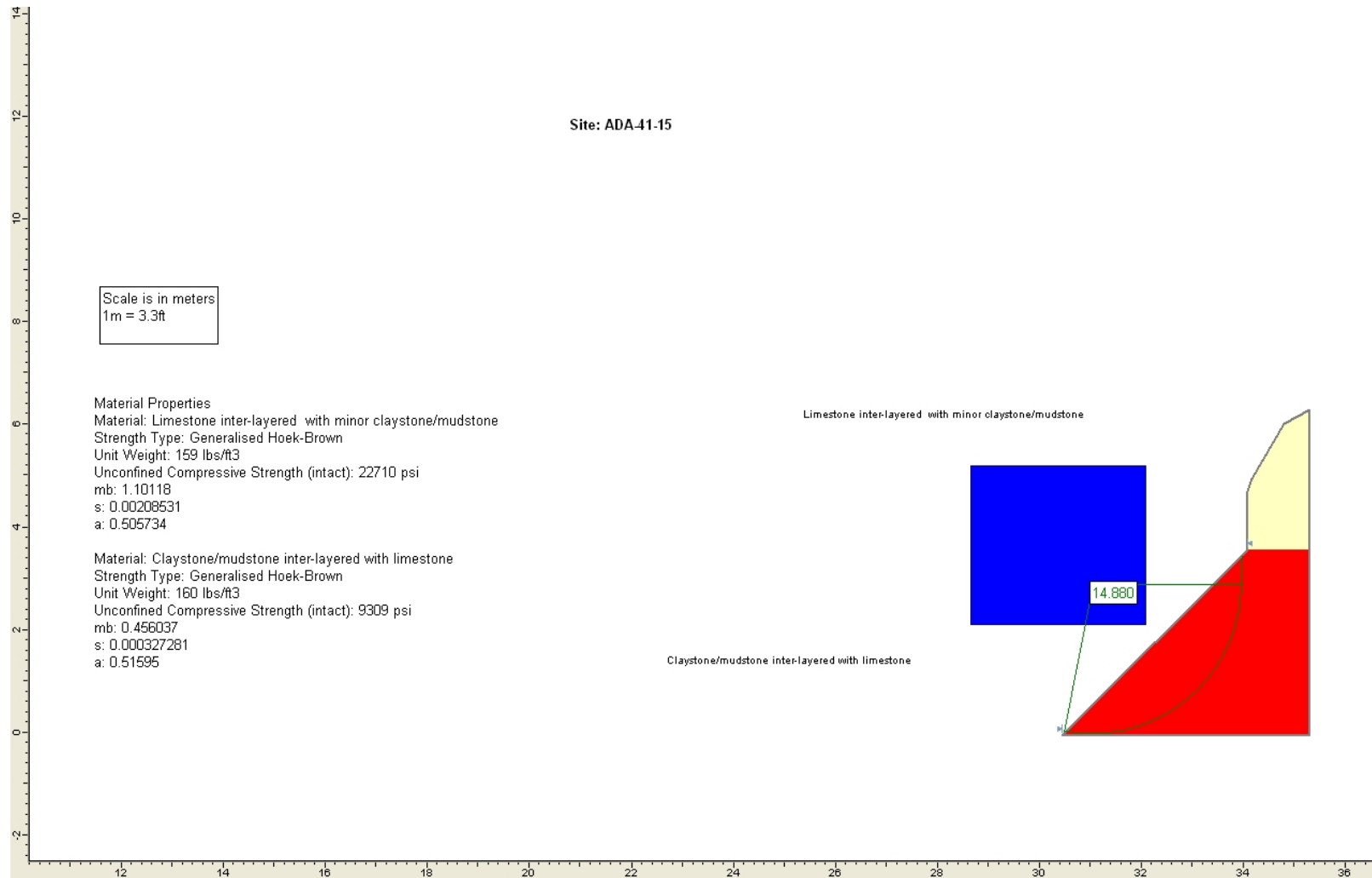
Figure 13D-2: Result of stability analysis for ATH-33-14 site. The number in the box represents the factor of safety value for the curved failure surface shown.
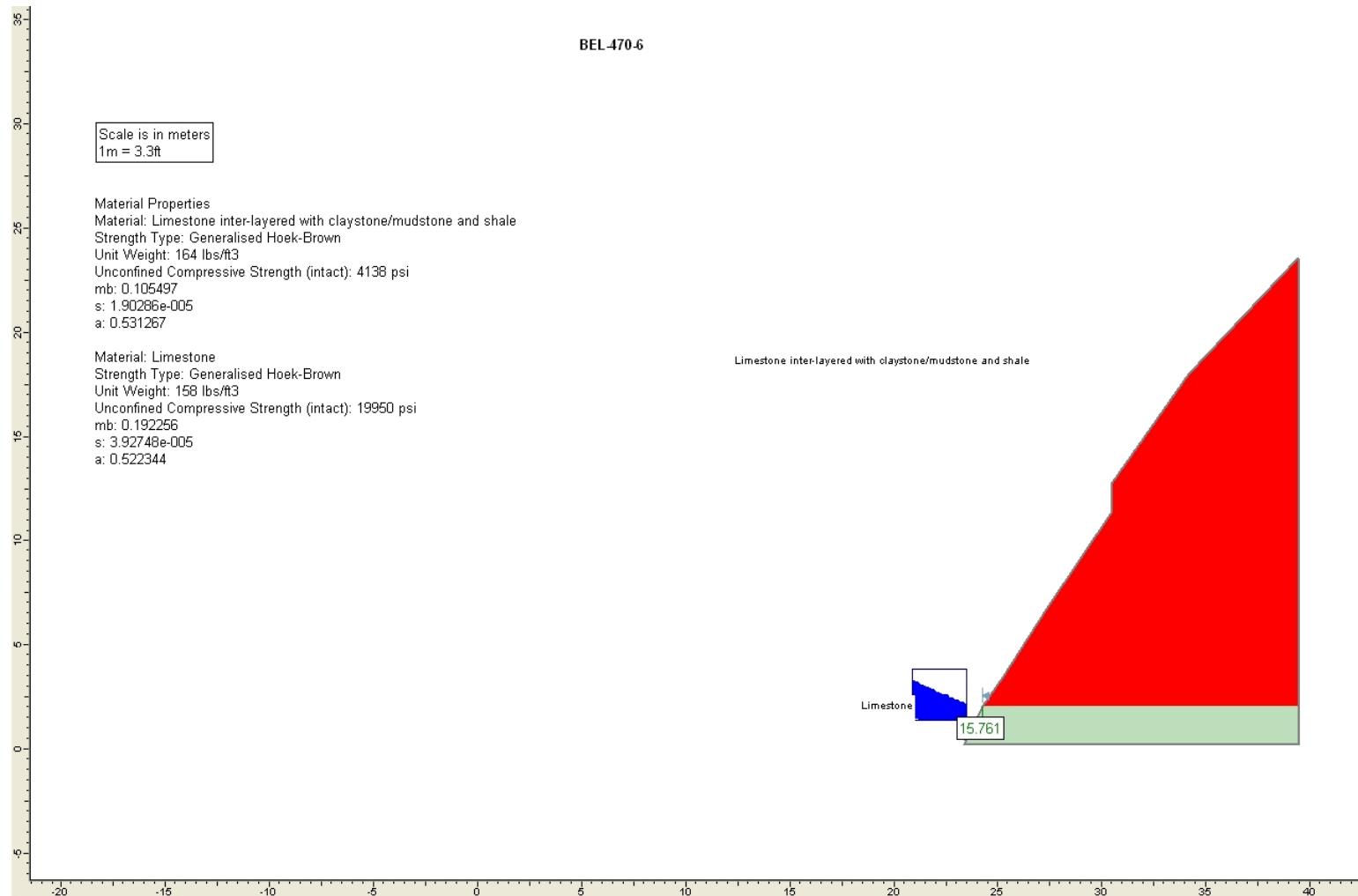
Figure 13D-3: Result of stability analysis for BEL-470-6 site. The number in the box represents the factor of safety value for the curved failure surface shown.
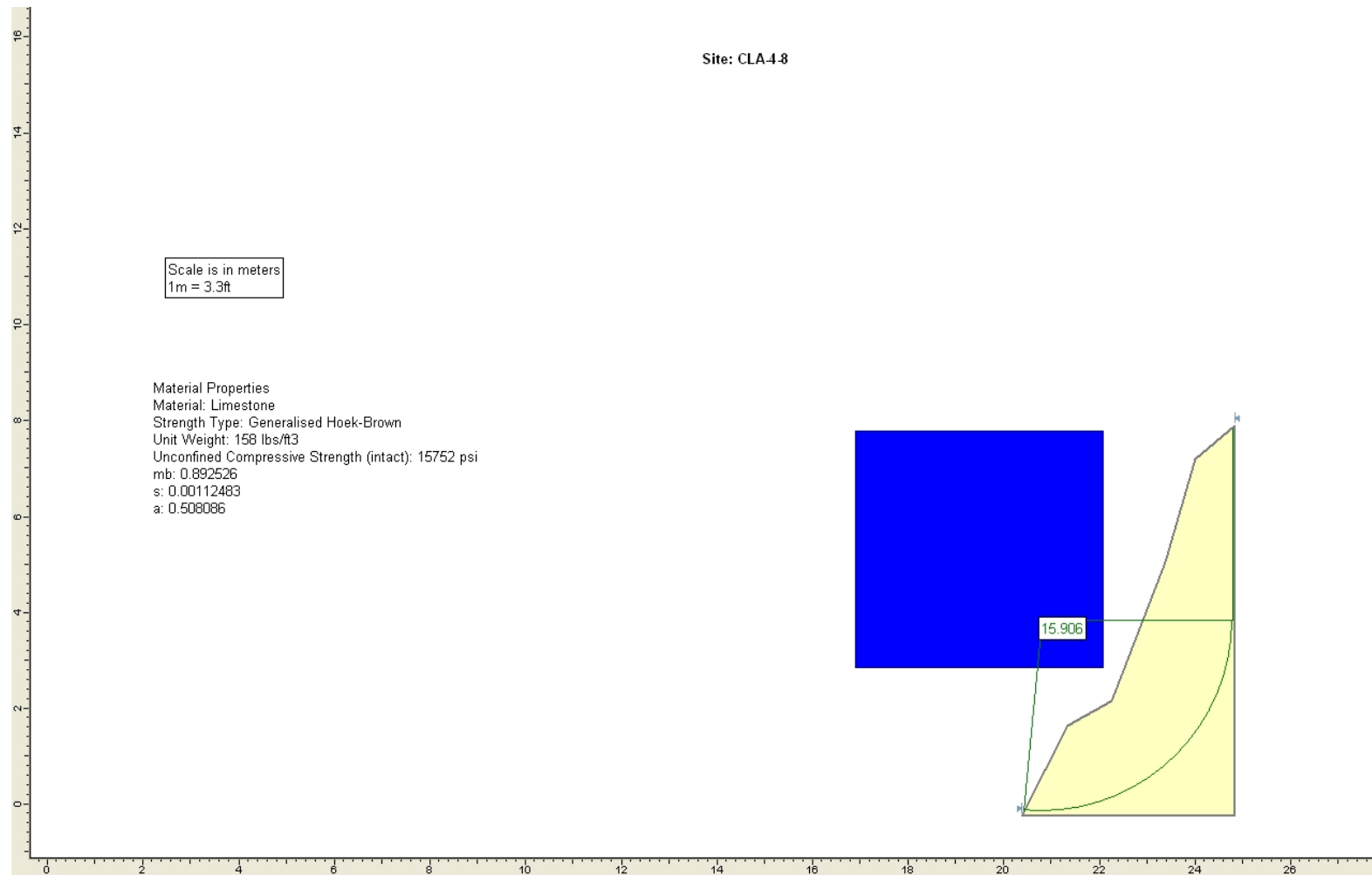
Figure 13D-4: Result of stability analysis for CLA-4-8 site. The number in the box represents the factor of safety value for the curved failure surface shown.
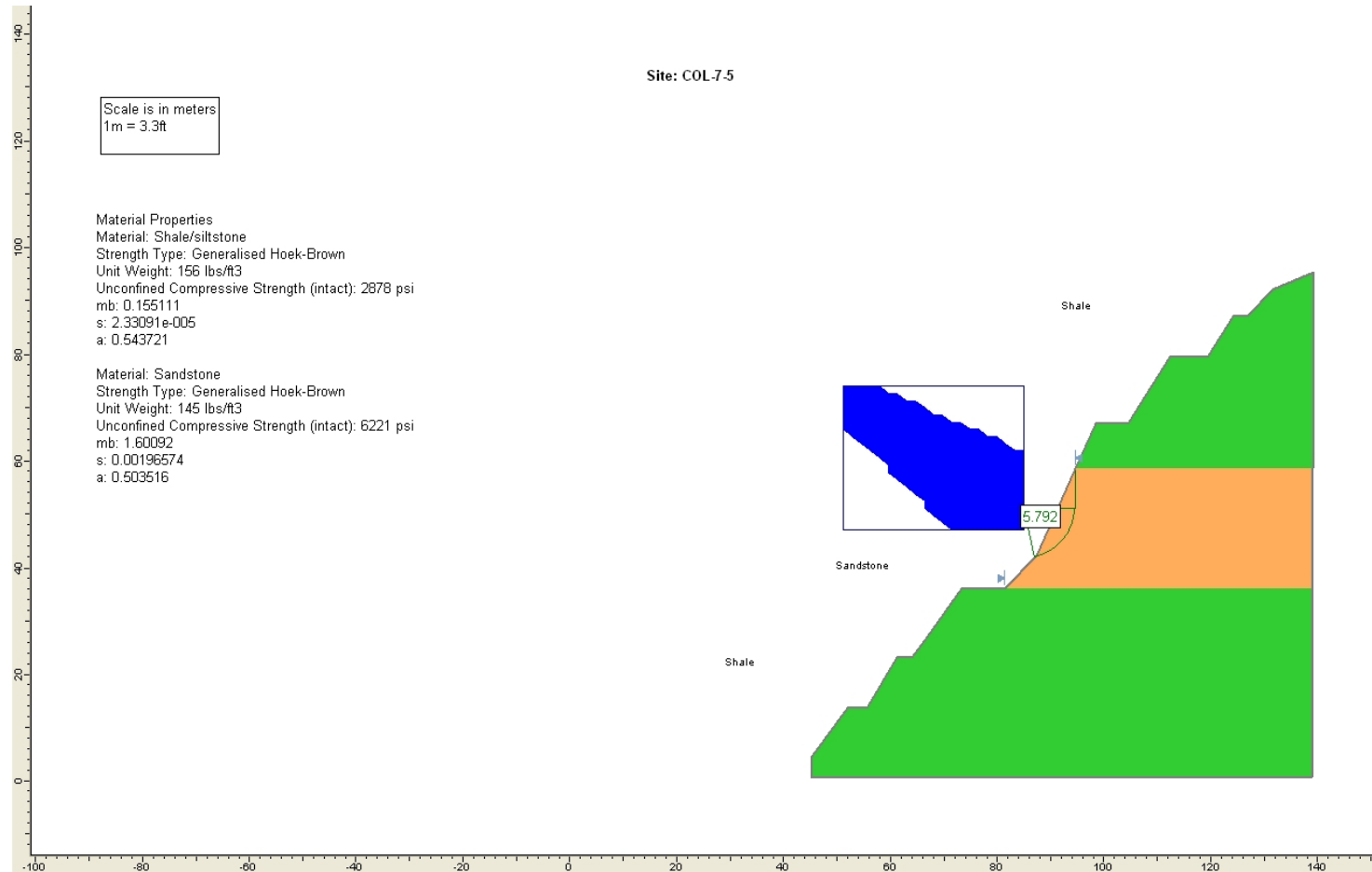
Figure 13D-5: Result of stability analysis for COL-7-5 site. The number in the box represents the factor of safety value for the curved failure surface shown.
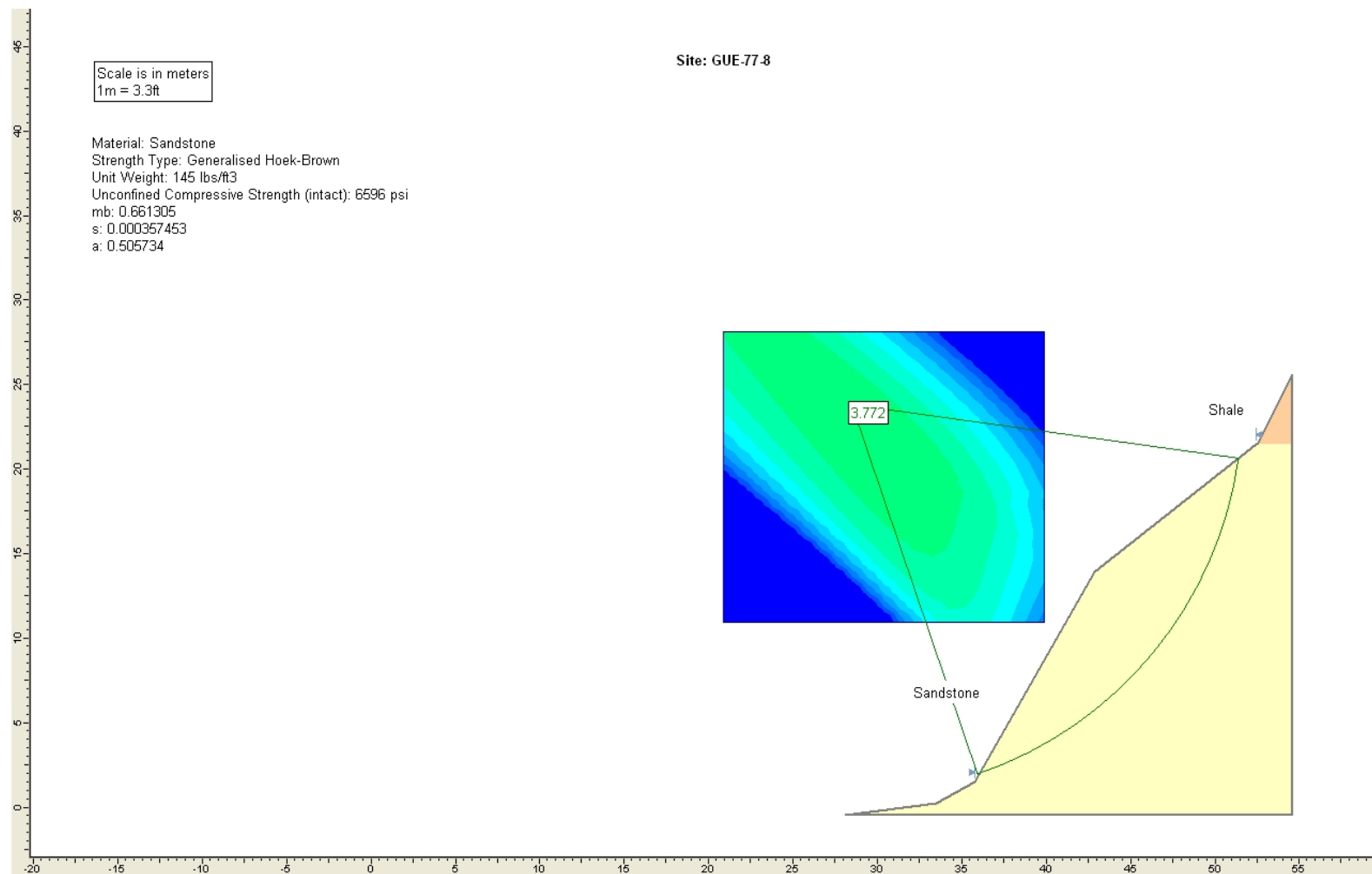
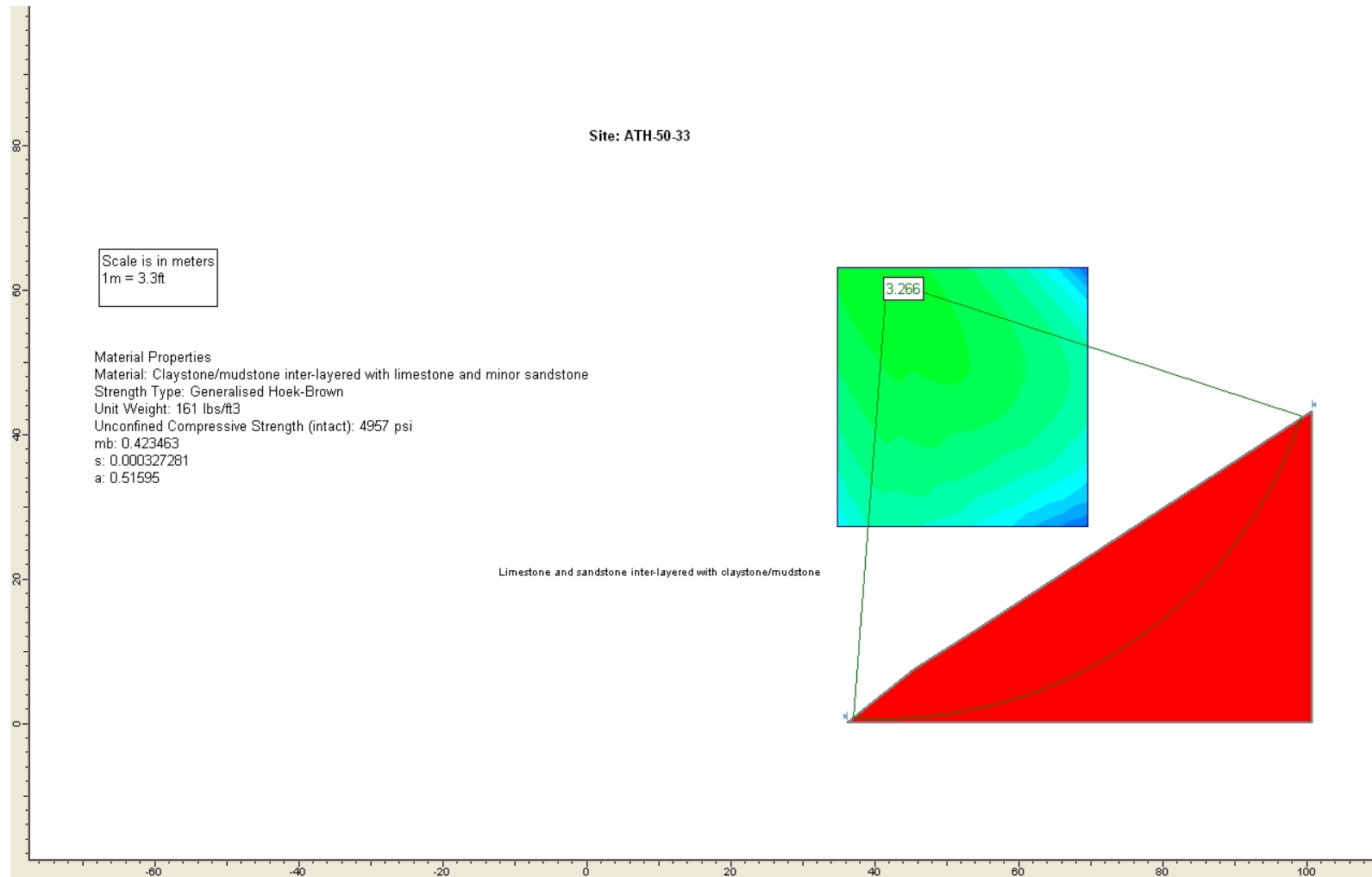Figure 13D-6: Result of stability analysis for GUE-77-8 site. The number in the box represents the factor of safety value for the curved failure surface shown.
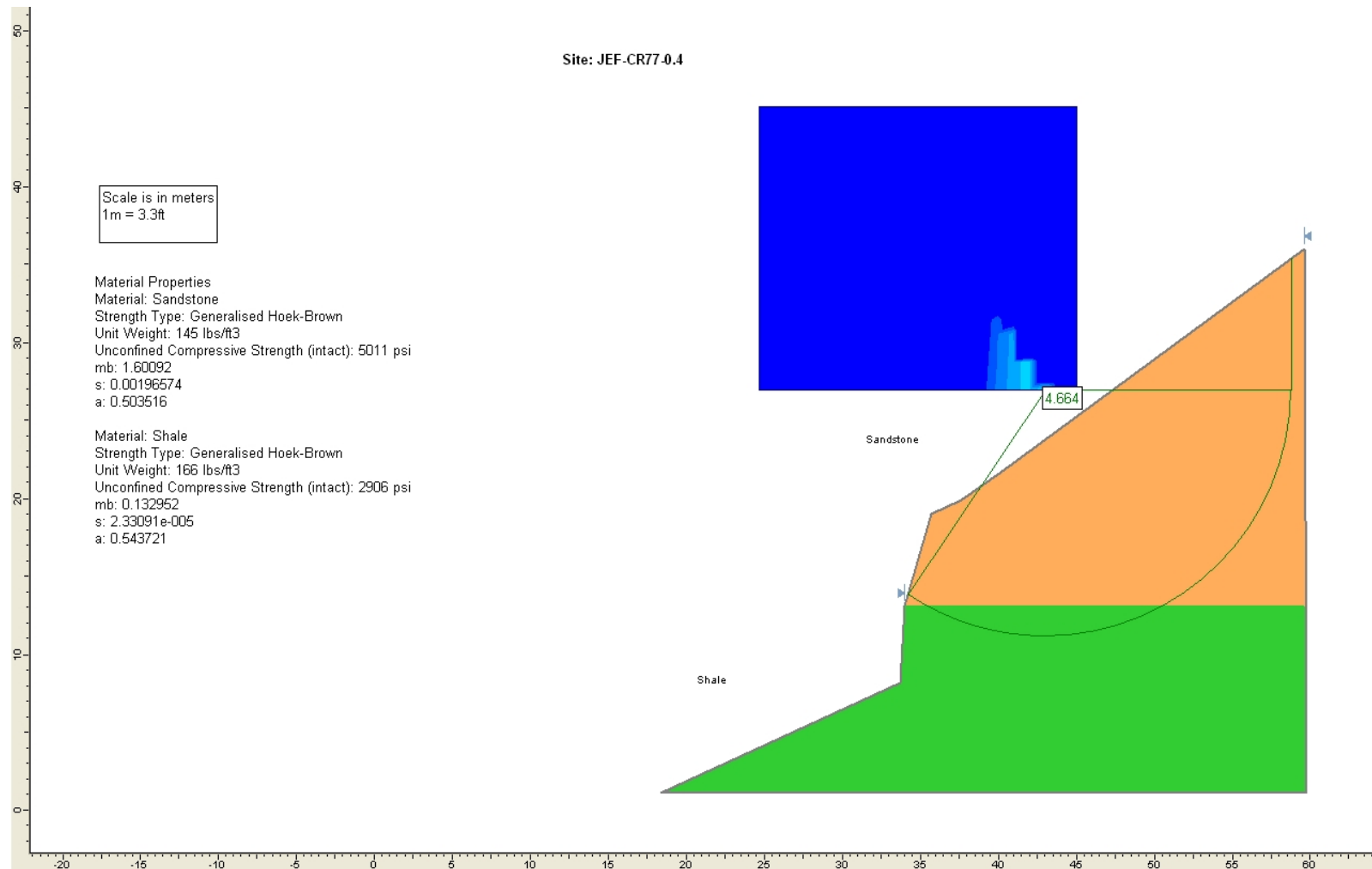
Figure 13D-7: Result of stability analysis for JEF-CR77-0.4 site. The number in the box represents the factor of safety value for the curved failure surface shown.
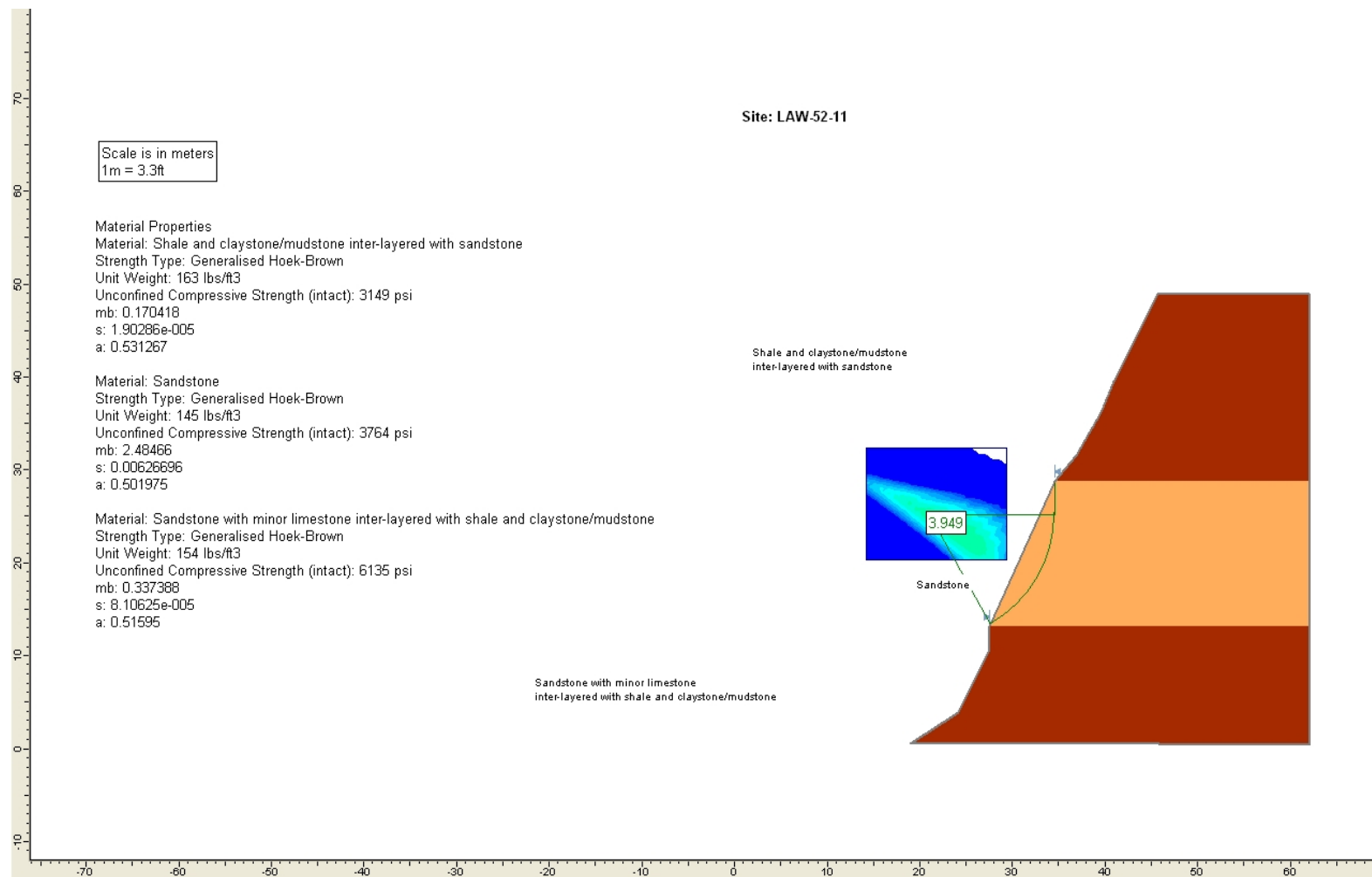
Figure 13D-8: Result of stability analysis for LAW-52-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.
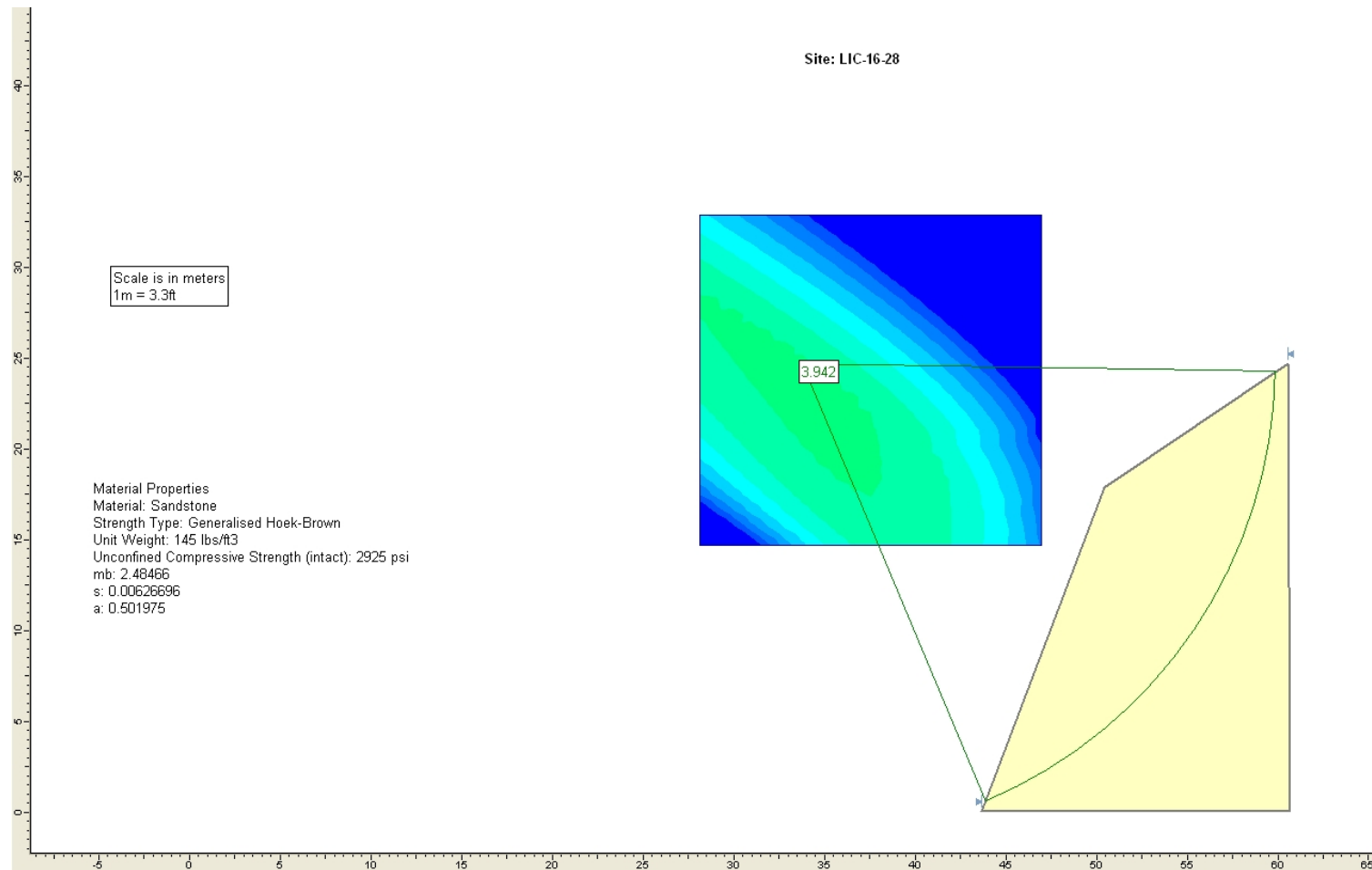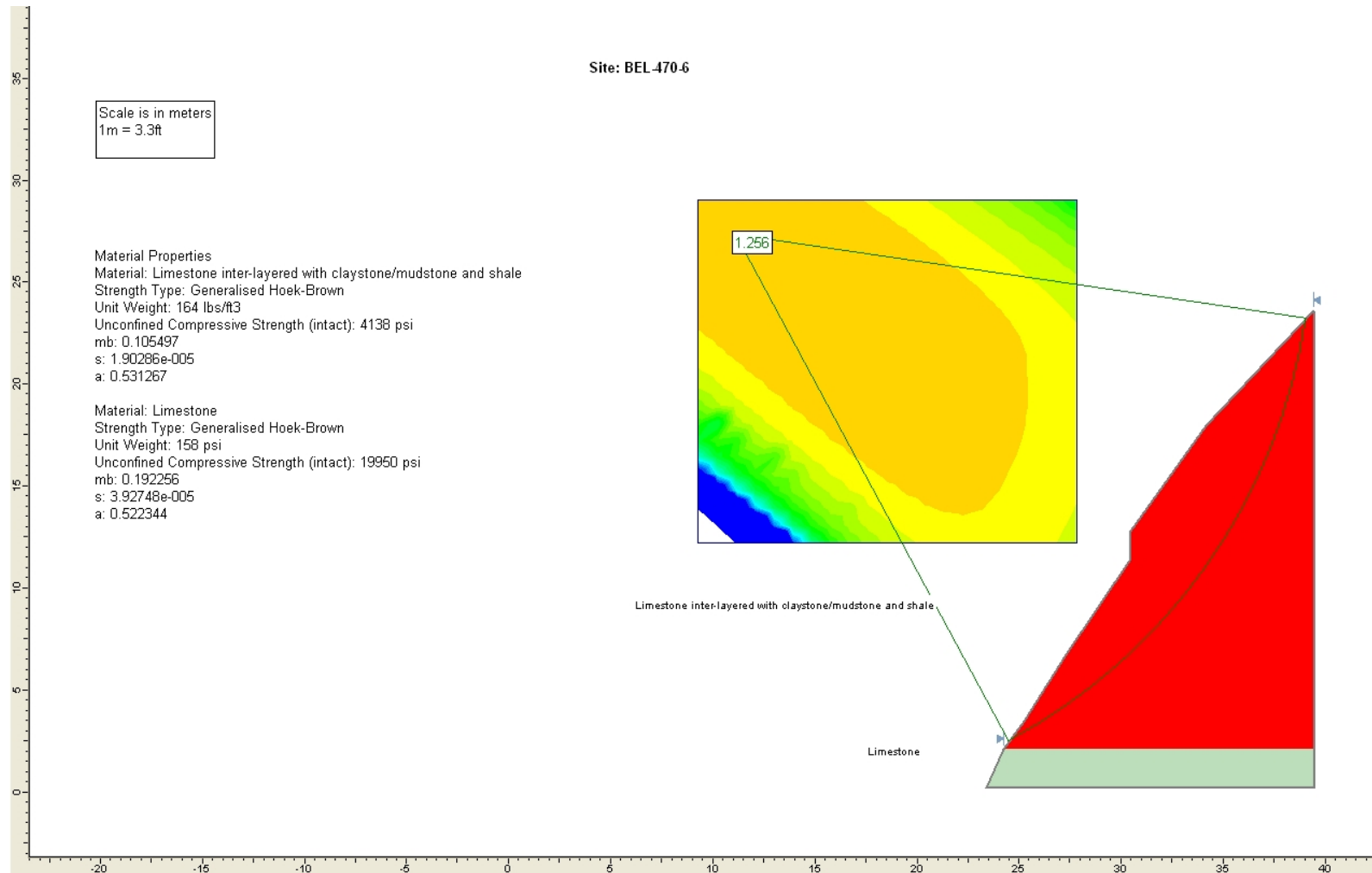
Figure 13D-9: Result of stability analysis for LIC-16-28 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Site: MUS-70-11

Scale is in meters
1m = 3.3ft

Material Properties
Material: Sandstone
Strength Type: Generalised Hoek-Brown
Unit Weight: 145 lbs/ft3
Unconfined Compressive Strength (intact): 4573 psi
mb: 1.60092
s: 0.00196574
a: 0.503516

Material: Shale
Strength Type: Generalised Hoek-Brown
Unit Weight: 166 lbs/ft3
Unconfined Compressive Strength (intact): 3125 psi
mb: 0.208132
s: 5.13655e-005
a: 0.543721
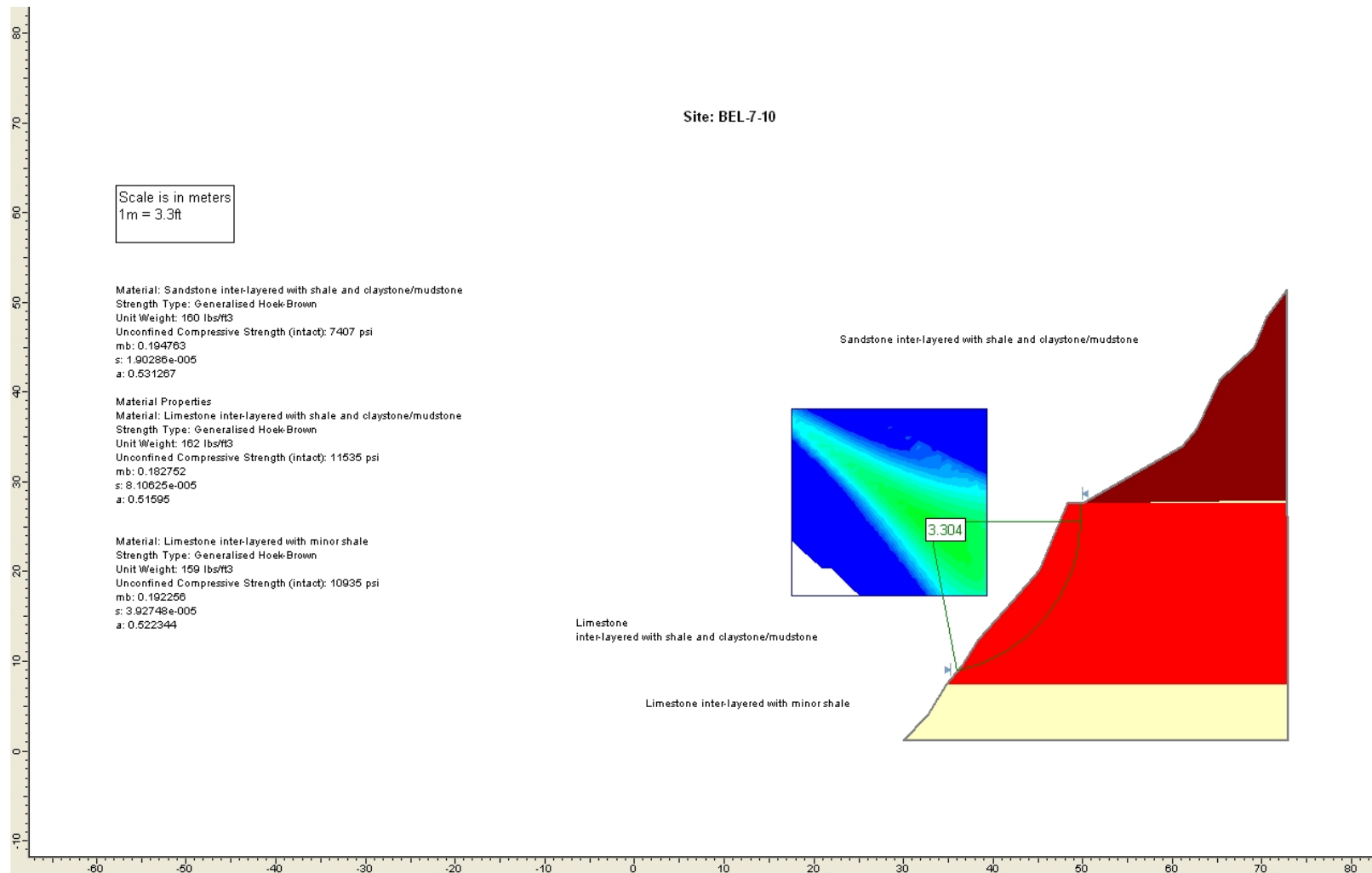
9.157

Sandstone

Shale
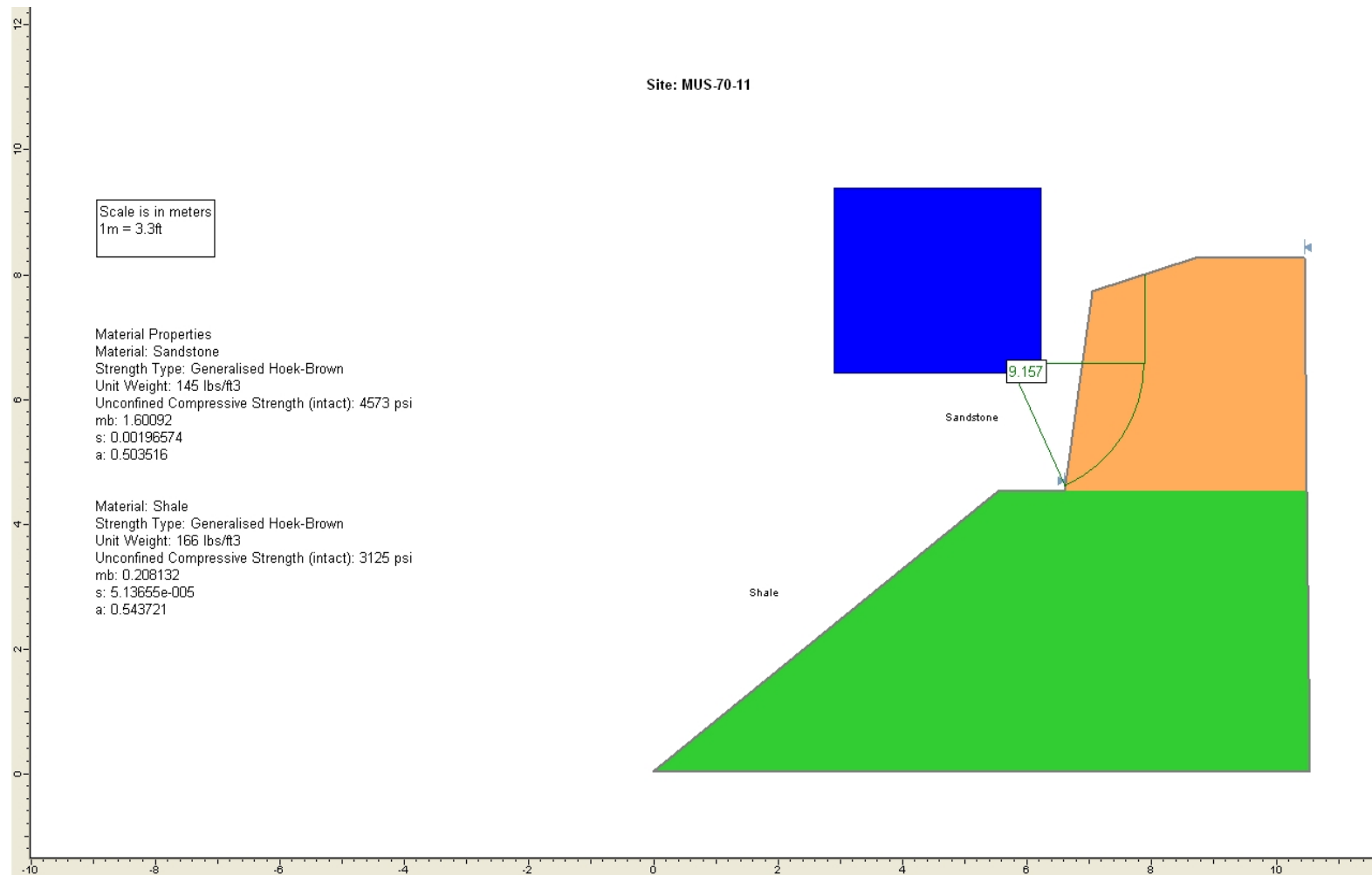
Figure 13D-10: Result of stability analysis for MUS-70-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.
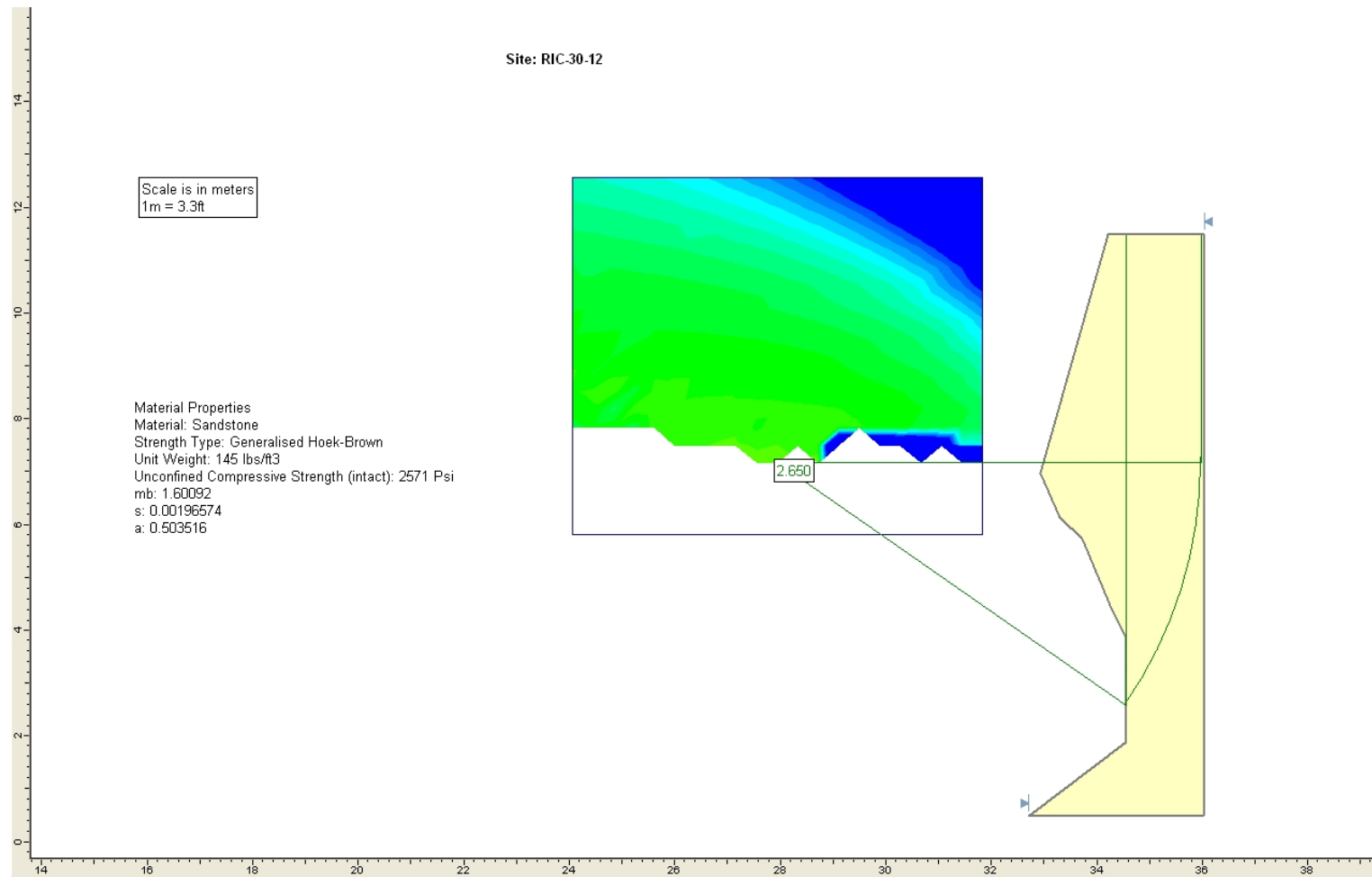
Figure 13D-11: Result of stability analysis for RIC-30-12 site. The number in the box represents the factor of safety value for the curved failure surface shown.
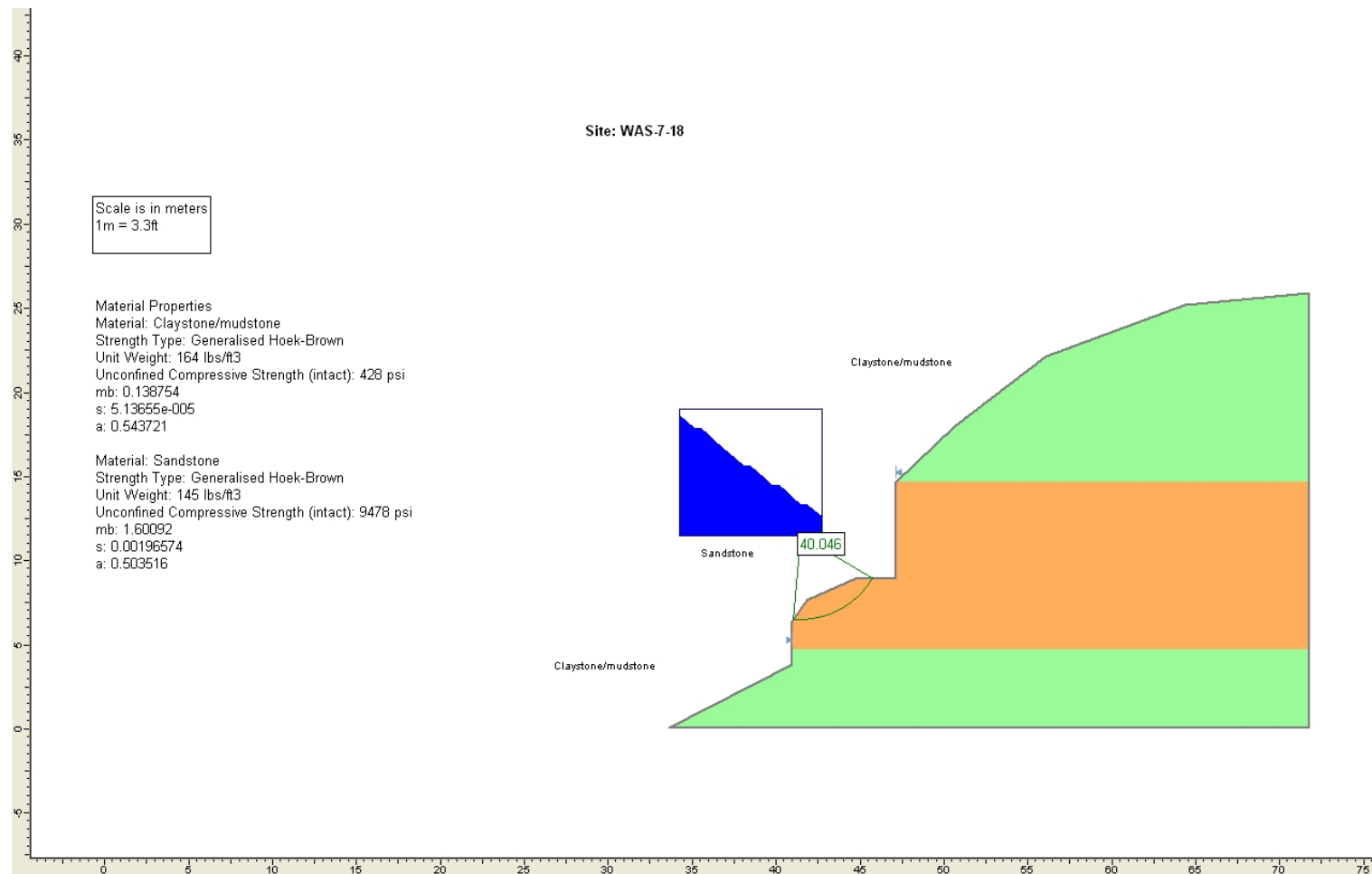
Figure 13D-12: Result of stability analysis for WAS-7-18 site. The number in the box represents the factor of safety value for the curved failure surface shown.

APPENDIX 14

STABILITY ANALYSIS FOR INCOMPETENT ROCK UNITS

APPENDIX 14-A

RESULTS OF STABILITY ANALYSIS USING THE SLIDE SOFTWARE
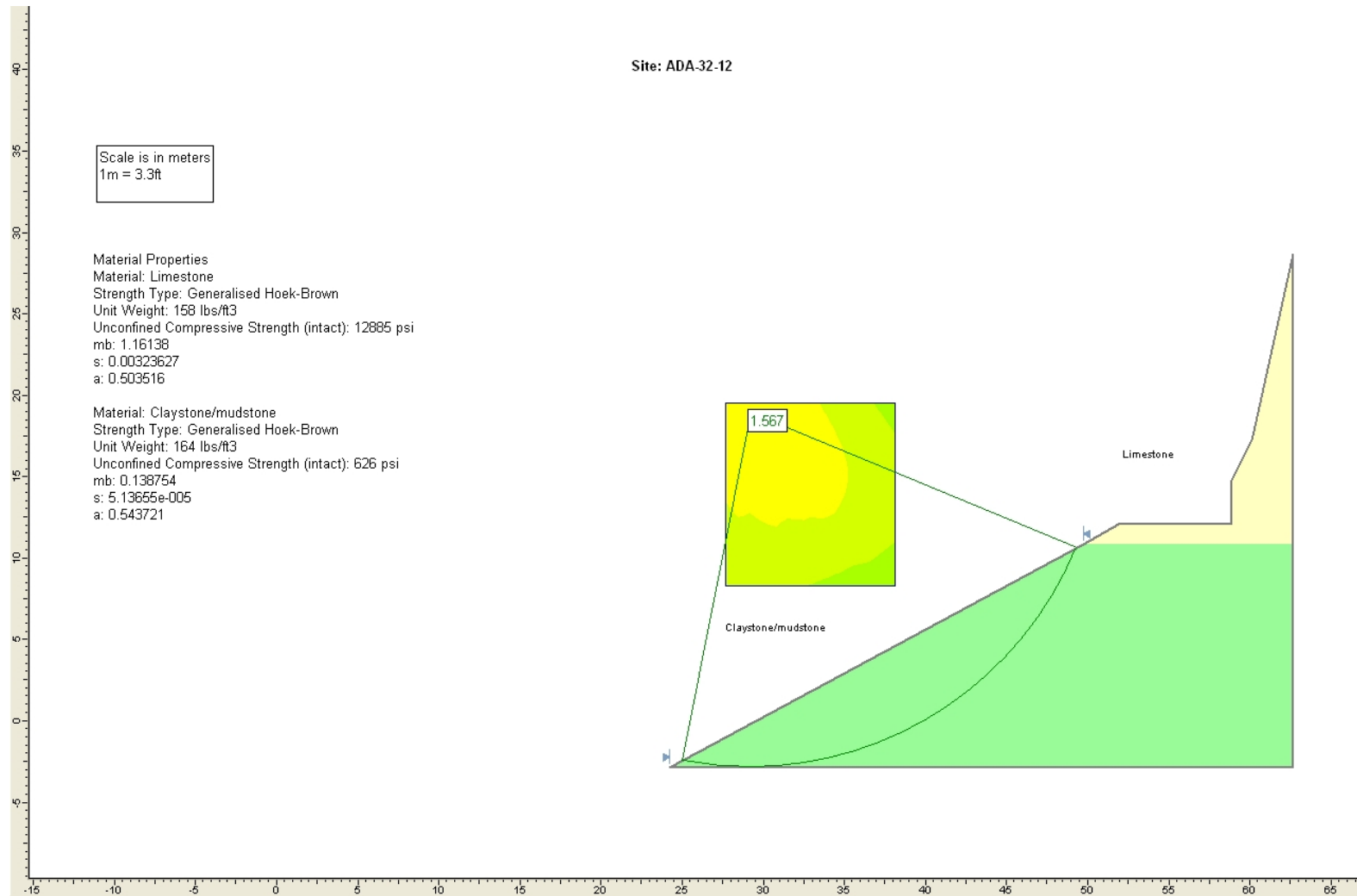
Figure 14A-1: Result of stability analysis for ADA-32-12 site. The number in the box represents the factor of safety value for the curved failure surface shown.
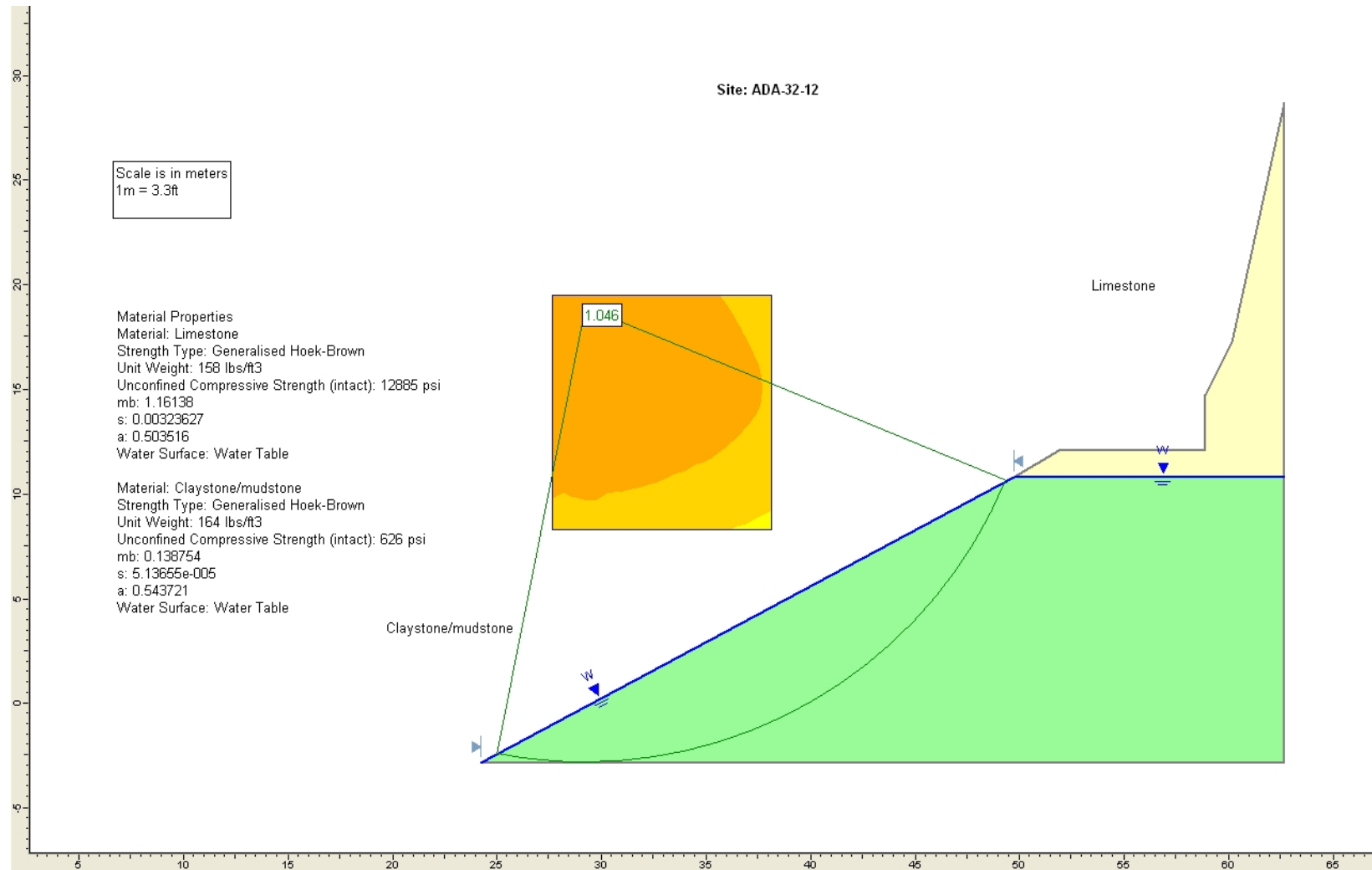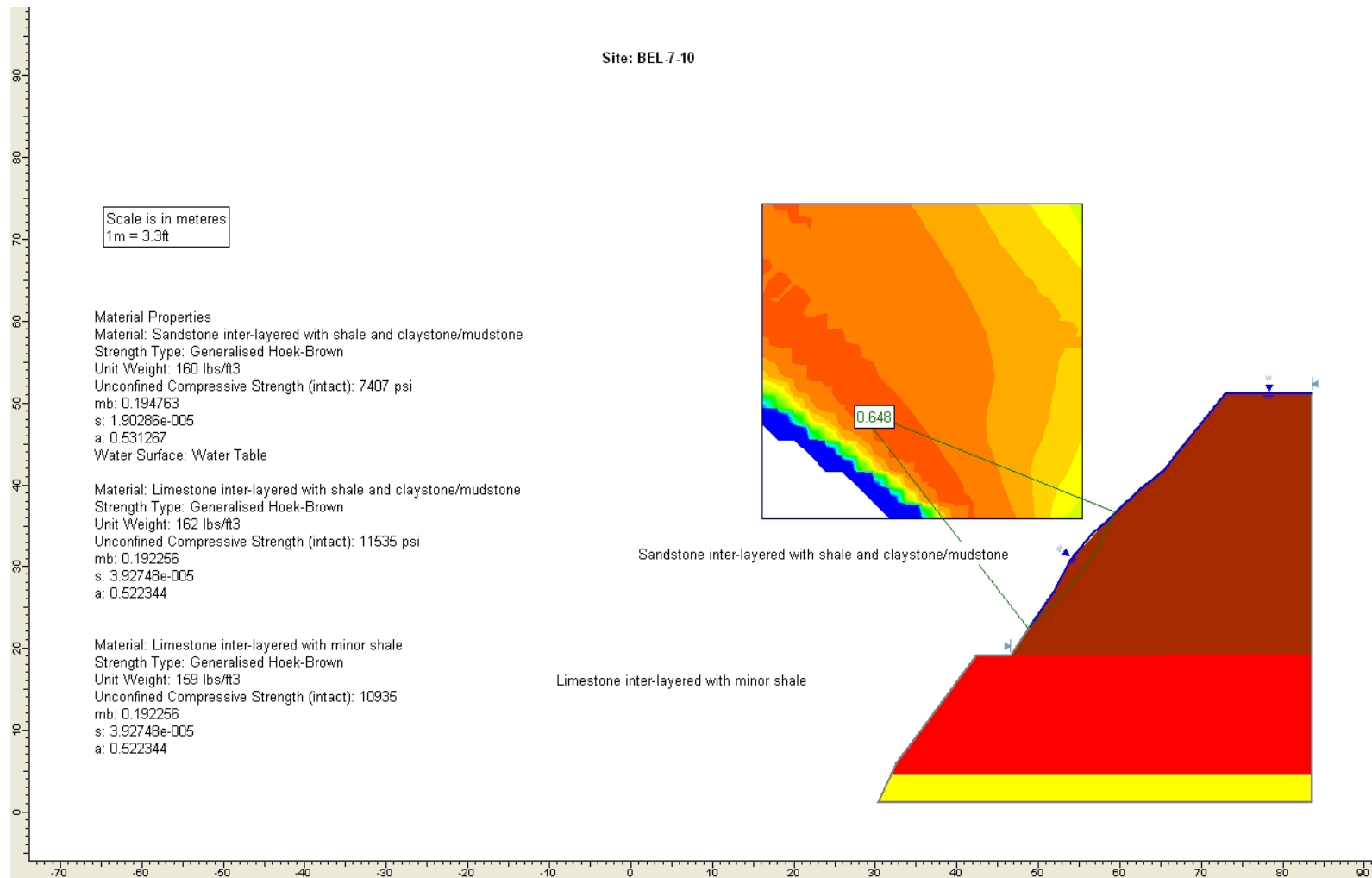
Figure 14A-2: Result of stability analysis for ADA-32-12 site (saturated conditions). The number in the box represents the factor of safety value for the curved failure surface shown.
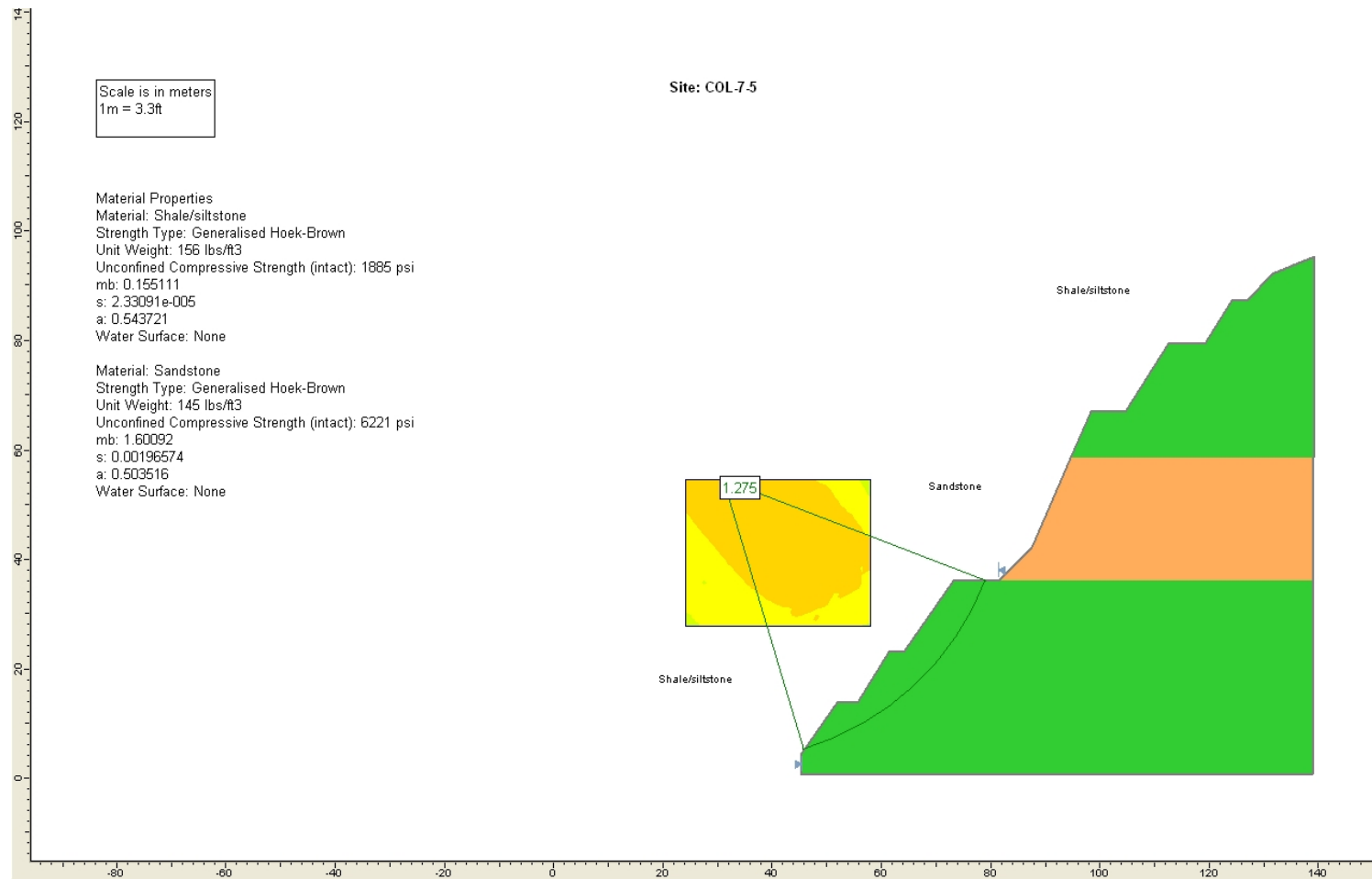
Figure 14A-3: Result of stability analysis for COL-7-5 site. The number in the box represents the factor of safety value for the curved failure surface shown.
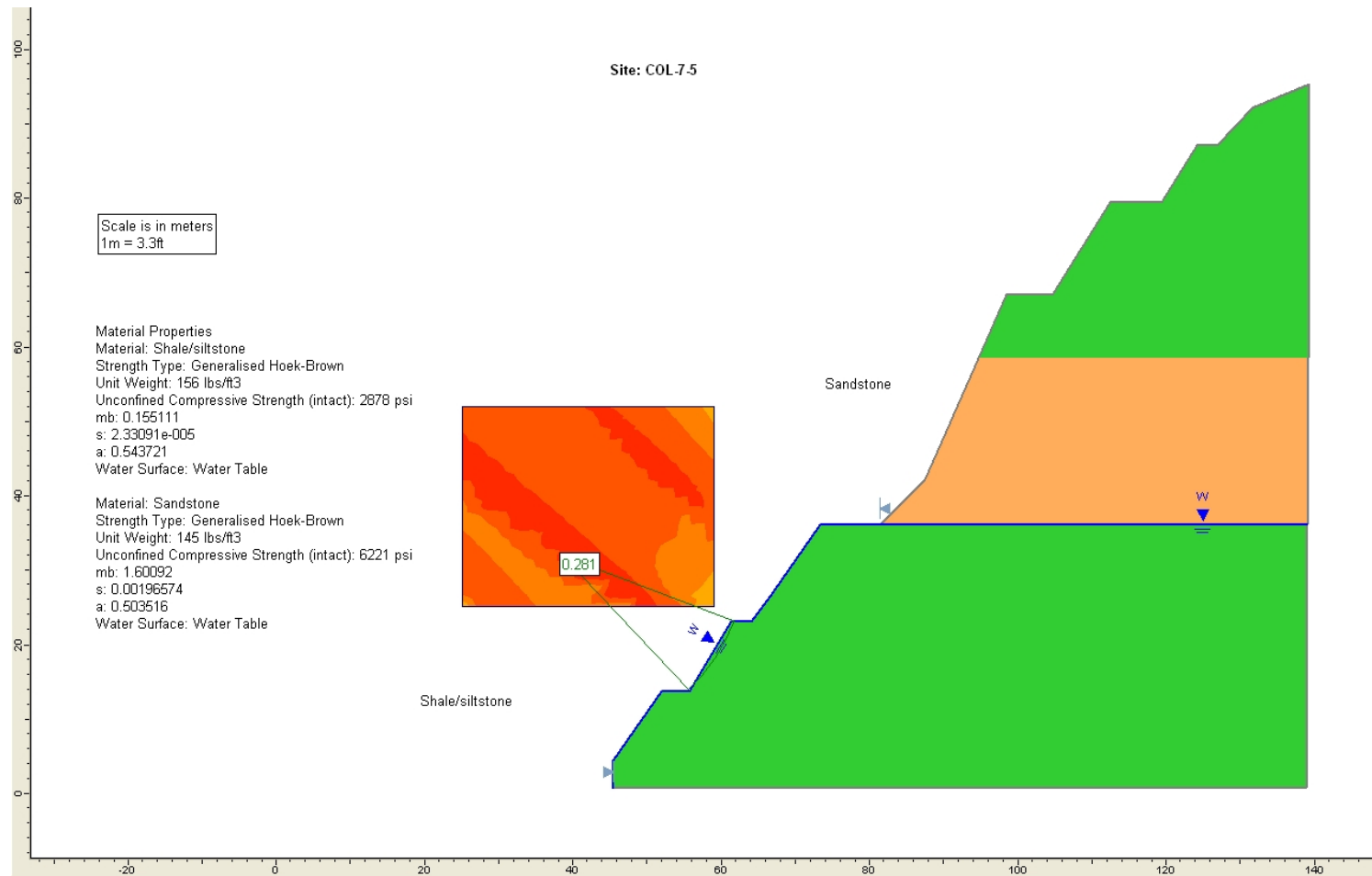
Figure 14A-4: Result of stability analysis for COL-7-5 site (saturated conditions). The number in the box represents the factor of safety value for the curved failure surface shown.
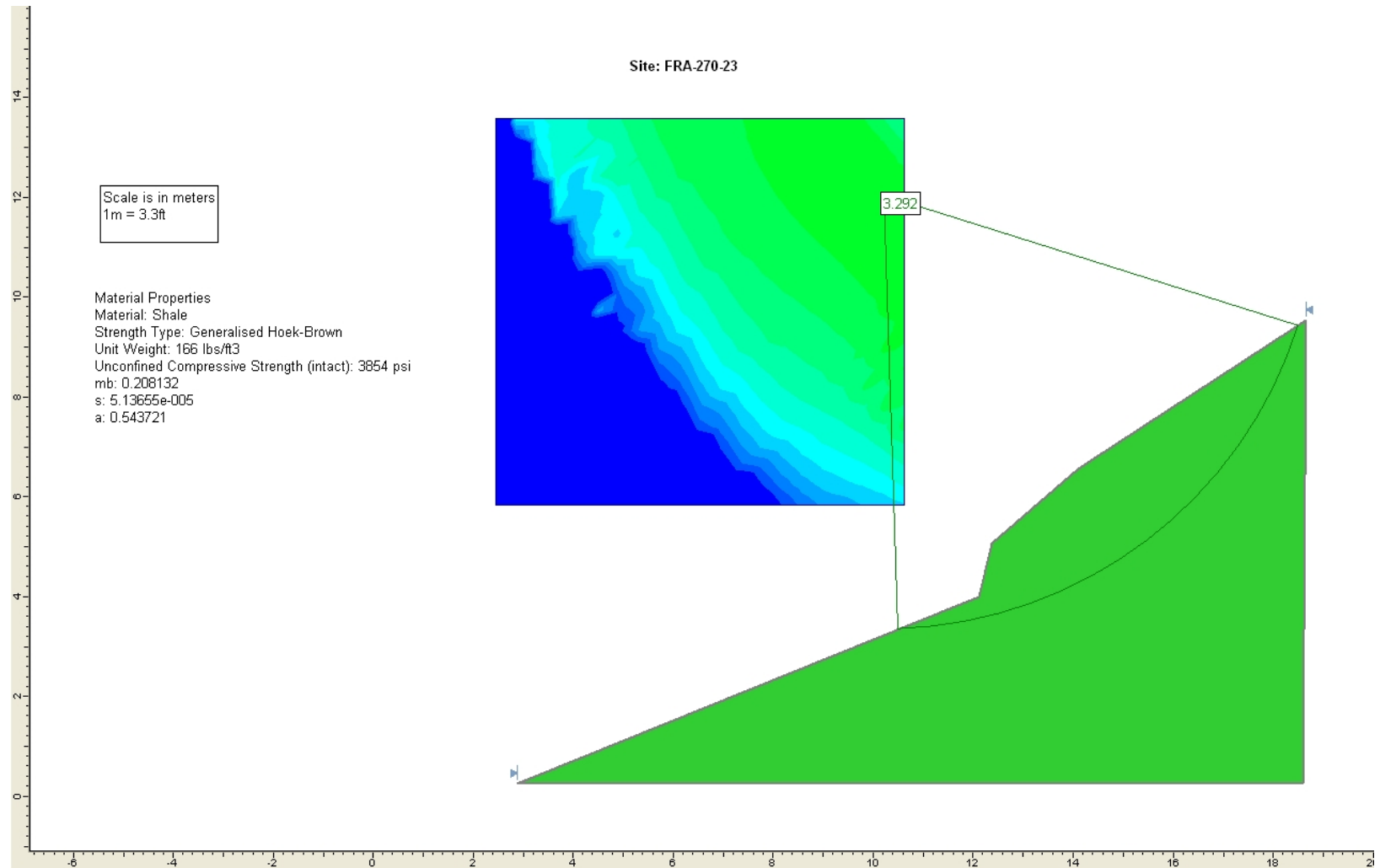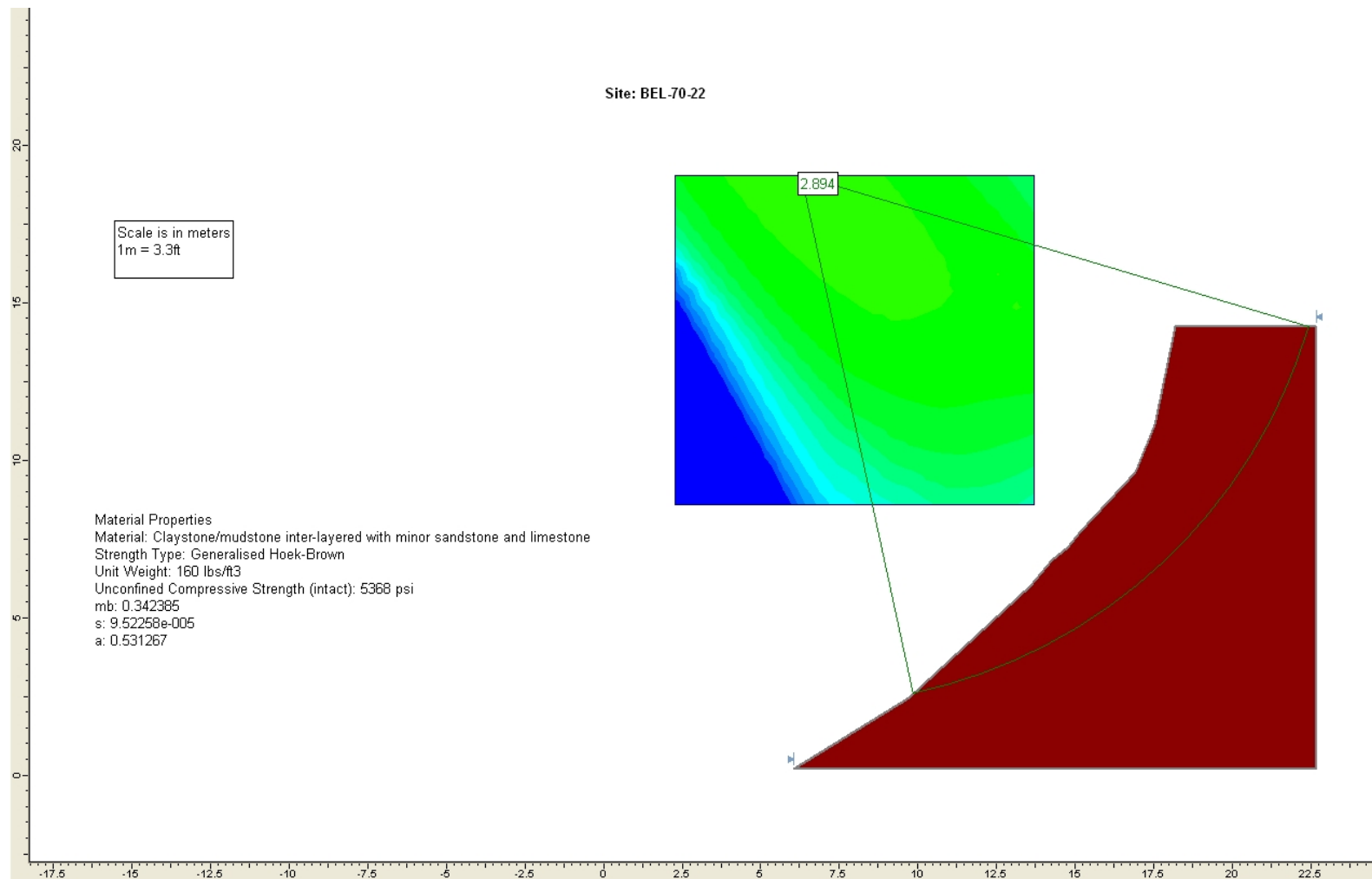
Figure 14A-5: Result of stability analysis for FRA-270-23. The number in the box represents the factor of safety value for the curved failure surface shown.
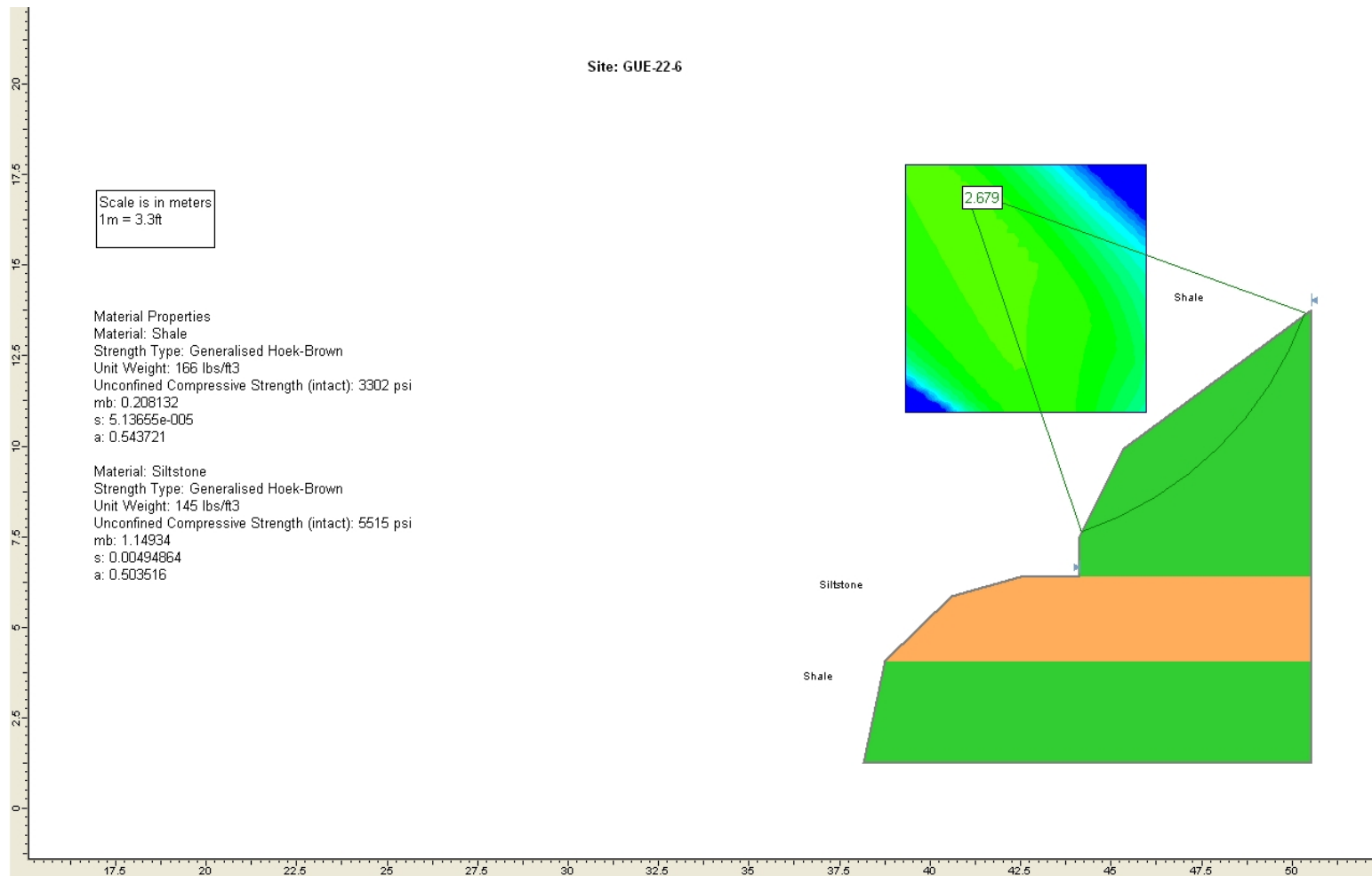
Figure 14A-6: Result of stability analysis for GUE-22-6 site. The number in the box represents the factor of safety value for the curved failure surface shown.
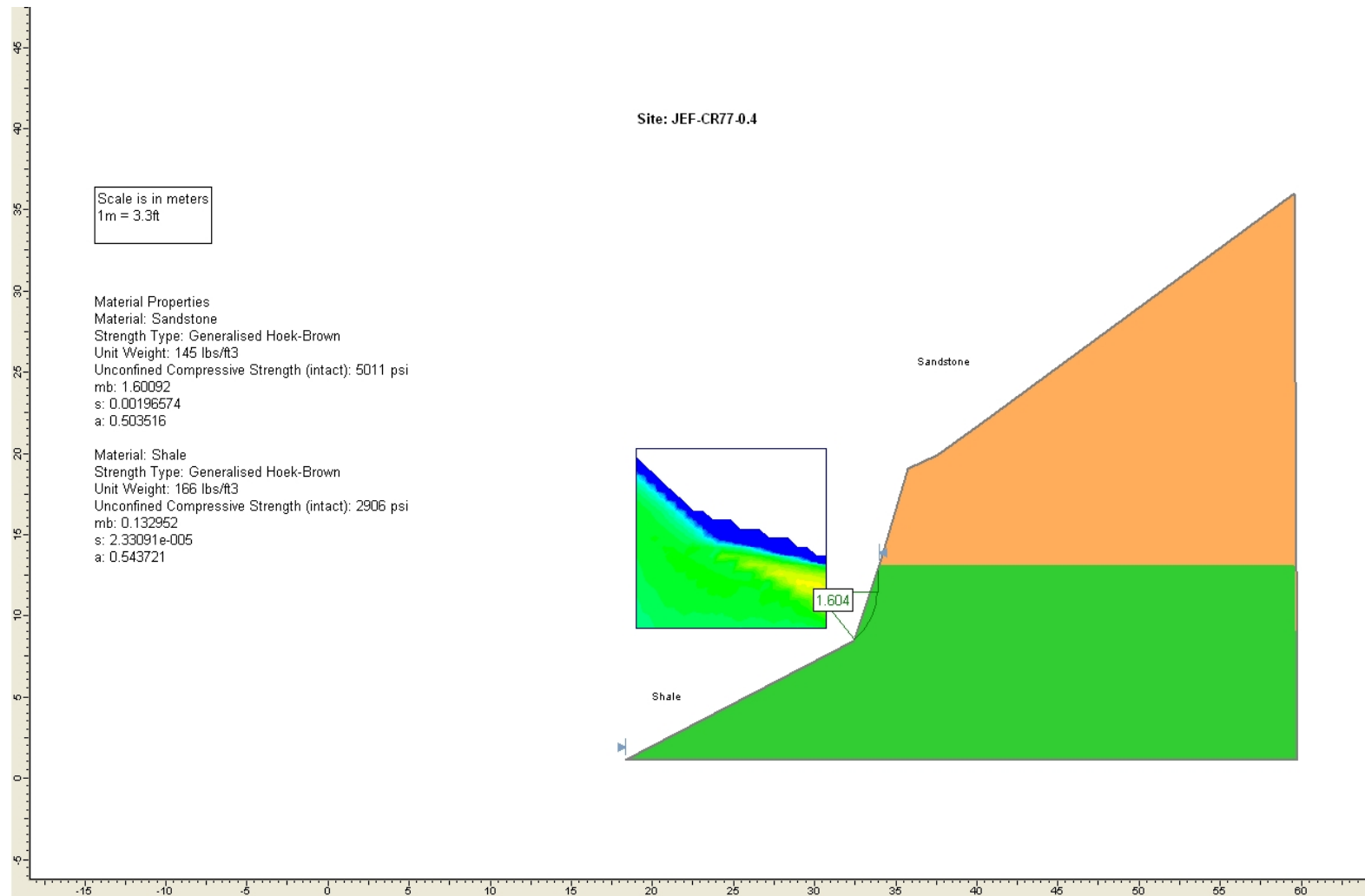
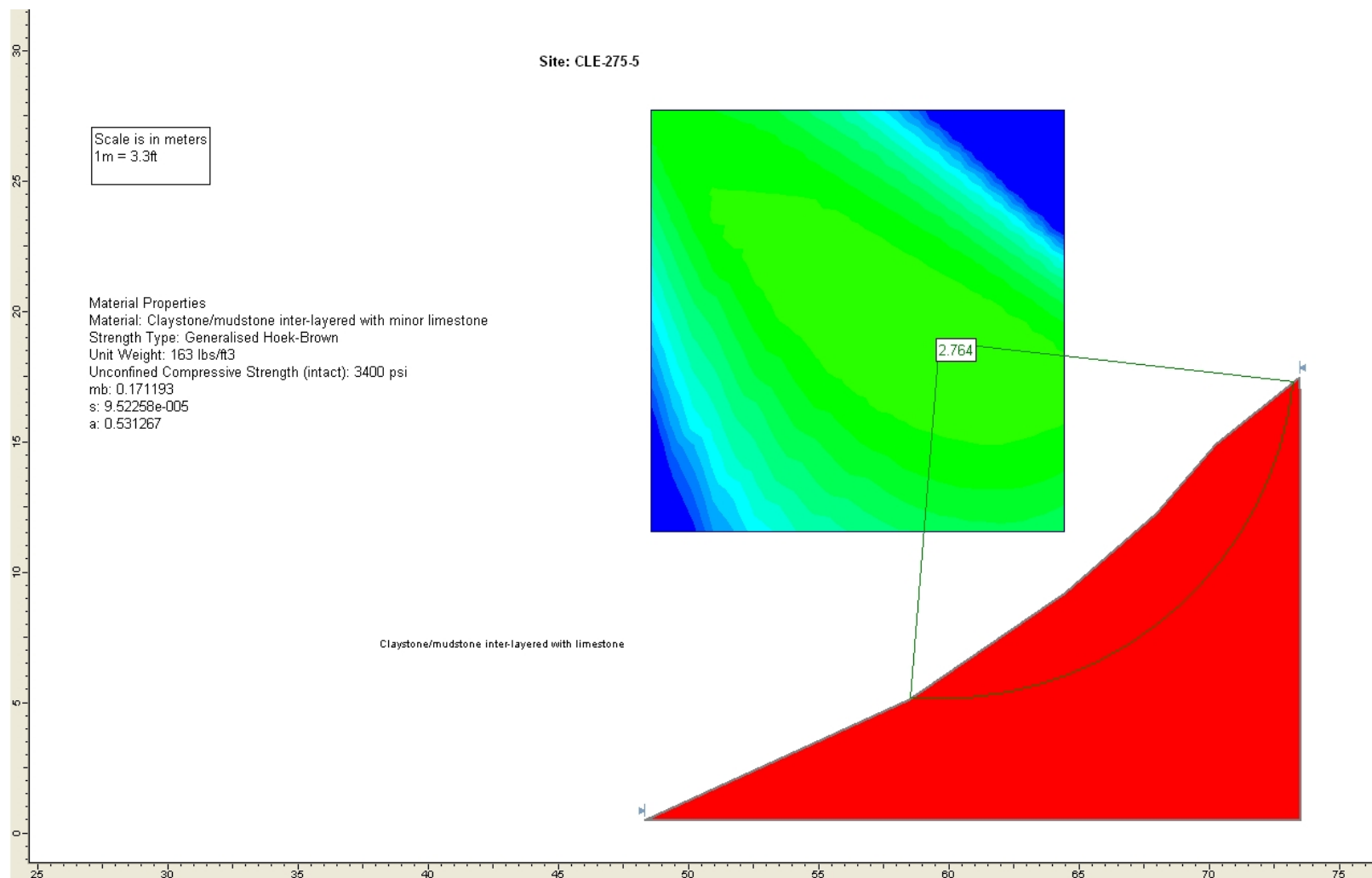Figure 14A-7: Result of stability analysis for JEF-CR77-0.4 site. The number in the box represents the factor of safety value for the curved failure surface shown.
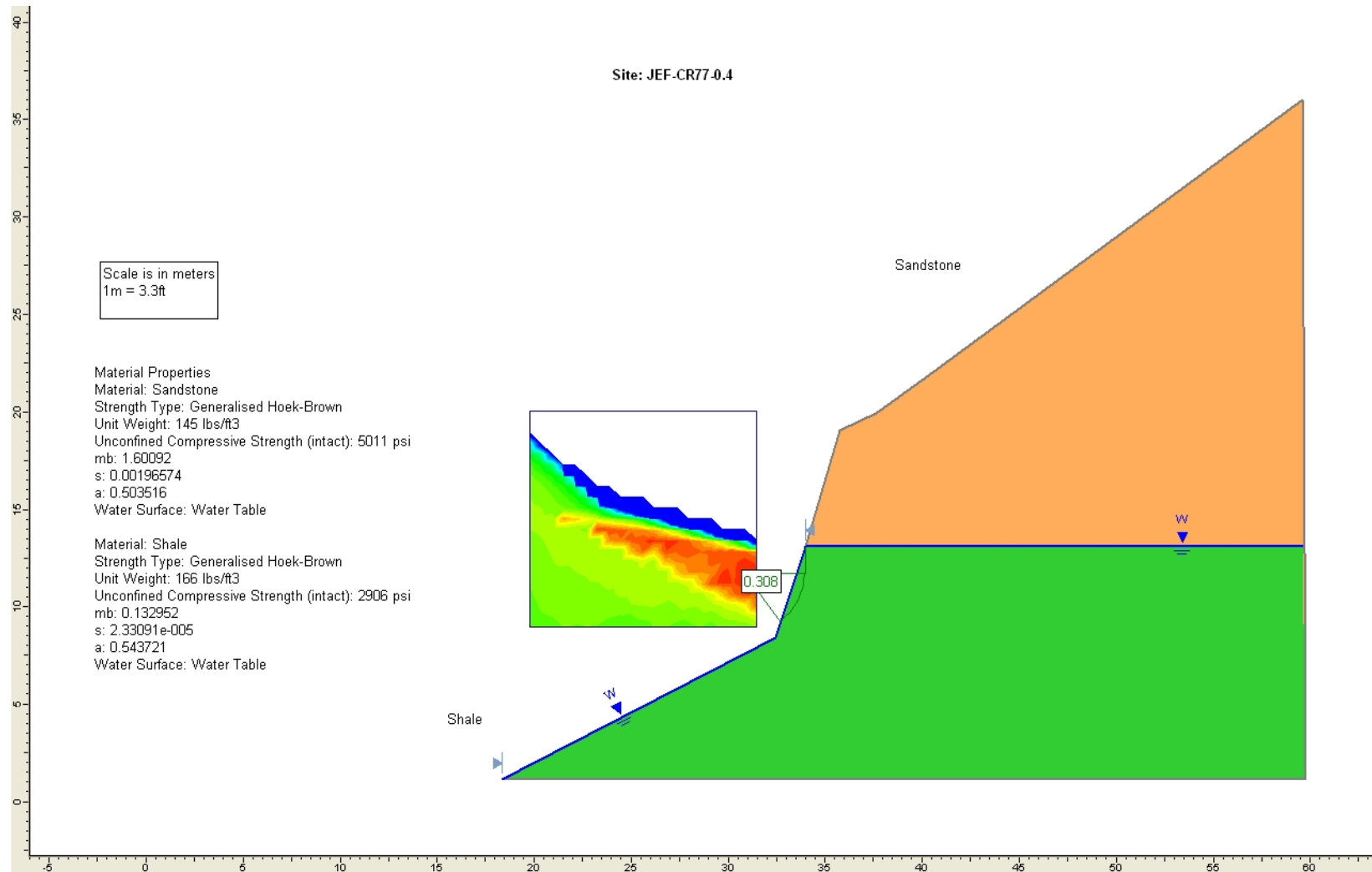
Figure 14A-8: Result of stability analysis for JEF-CR77-0.4 site (saturated conditions). The number in the box represents the factor of safety value for the curved failure surface shown.
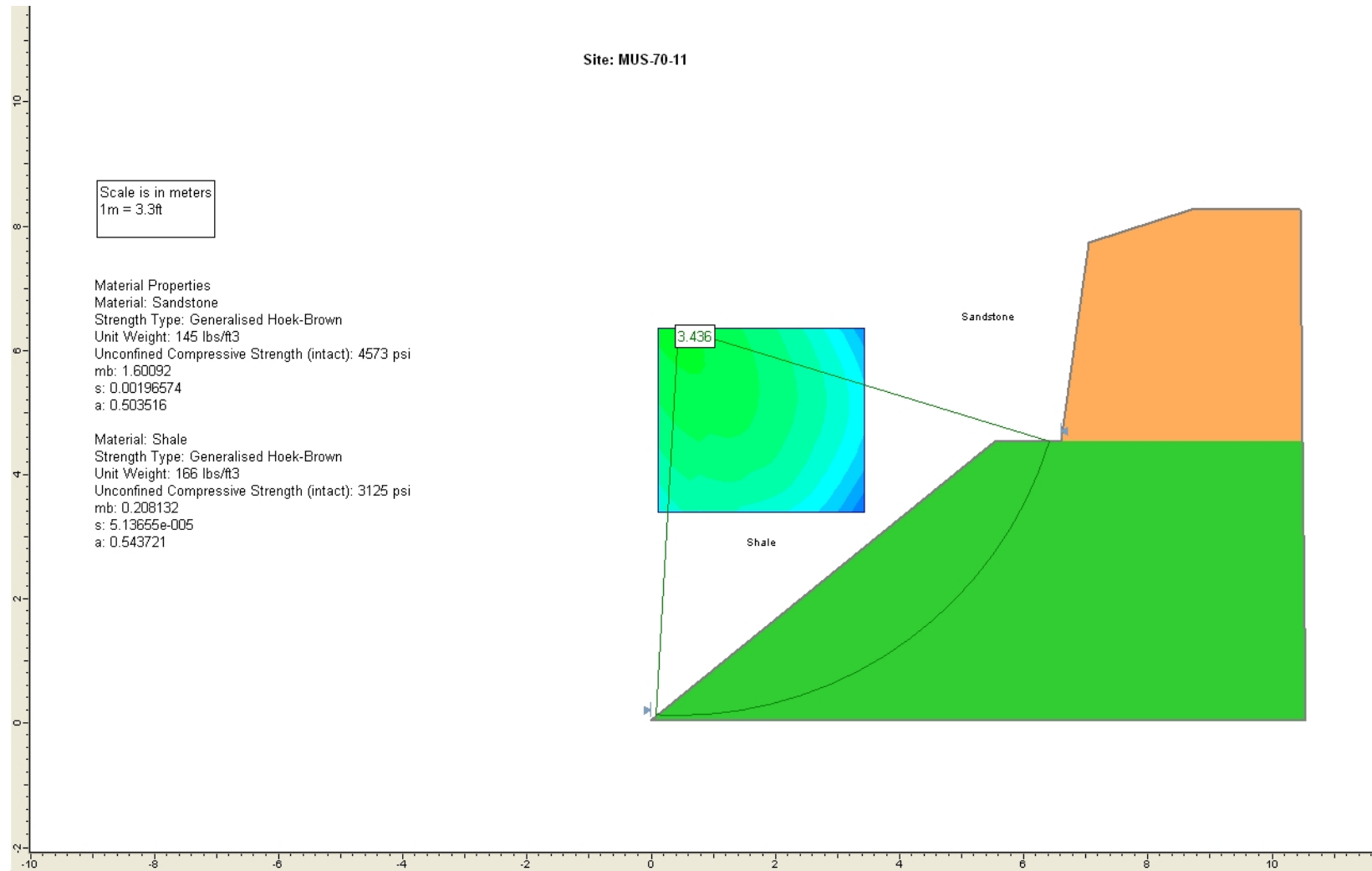
Figure 14A-9: Result of stability analysis for MUS-70-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.
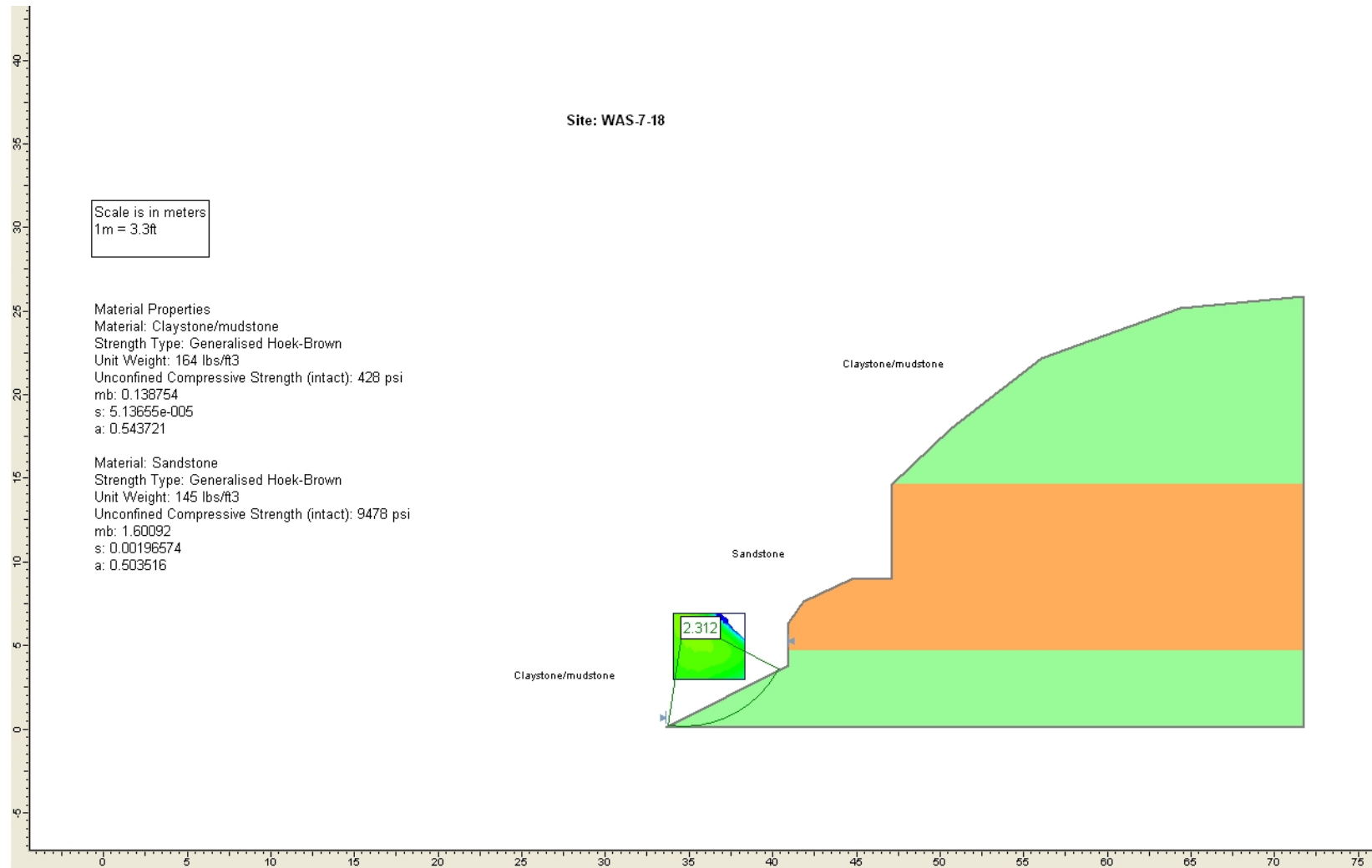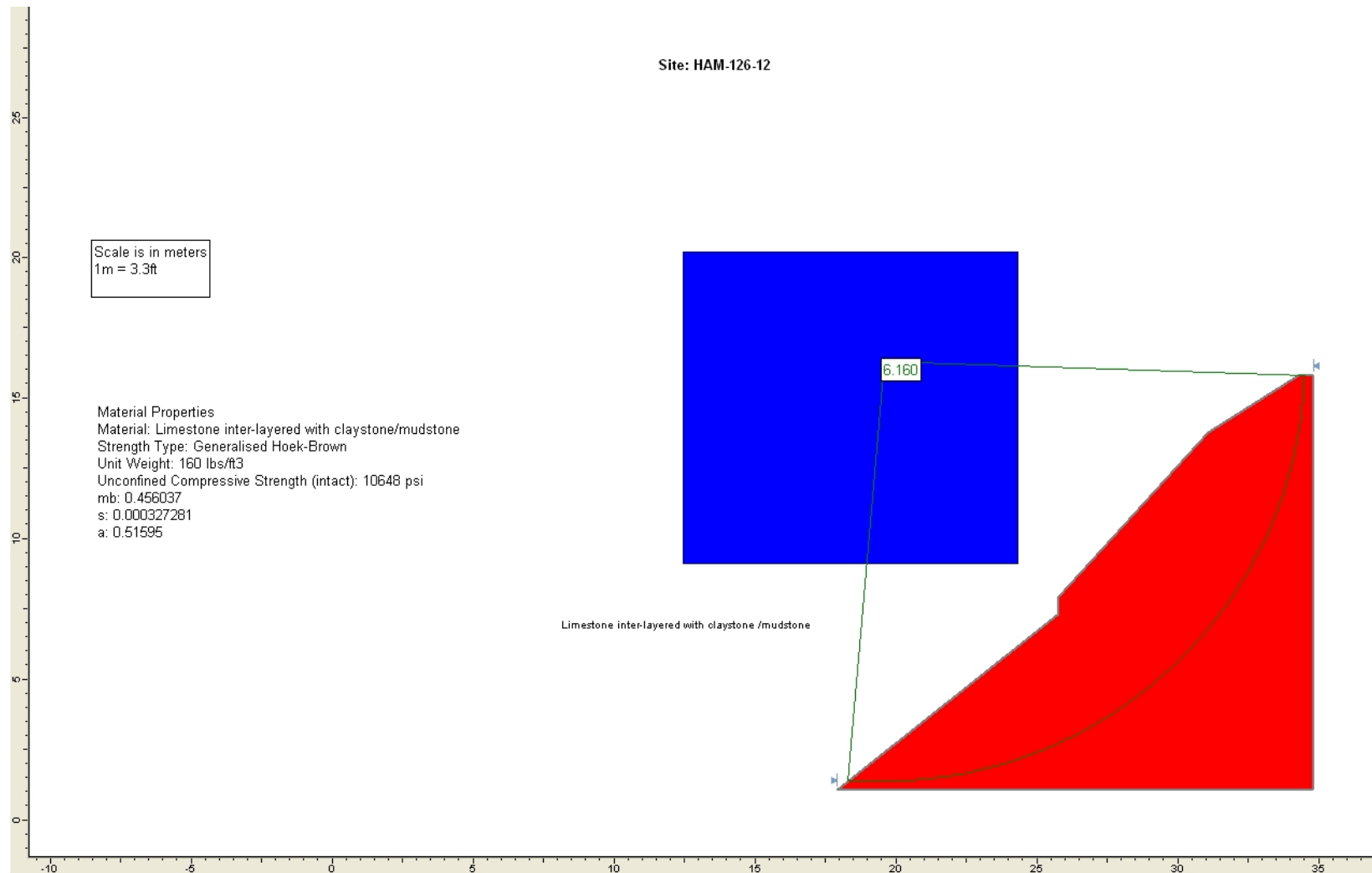
Figure 14A-10: Result of stability analysis for MUS-70-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.

APPENDIX 14-B

FREQUENCY HISTOGRAM AND CORRESPONDING DESCRIPTIVE
STATISTICS FOR NATURAL SLOPE ANGLES
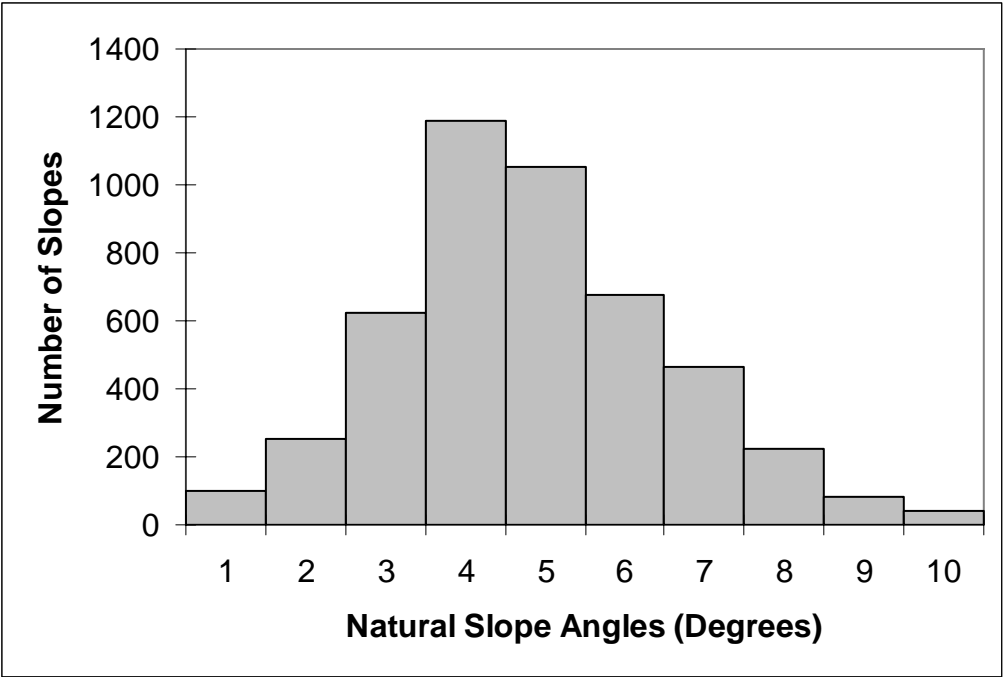
Mean	4
Standard Deviation	1.8
Minimum	0.02
Maximum	12
Count	4721

Figure 14B-1: Frequency histogram of natural slope angles and corresponding descriptive statistics for ATH-33-26 site.
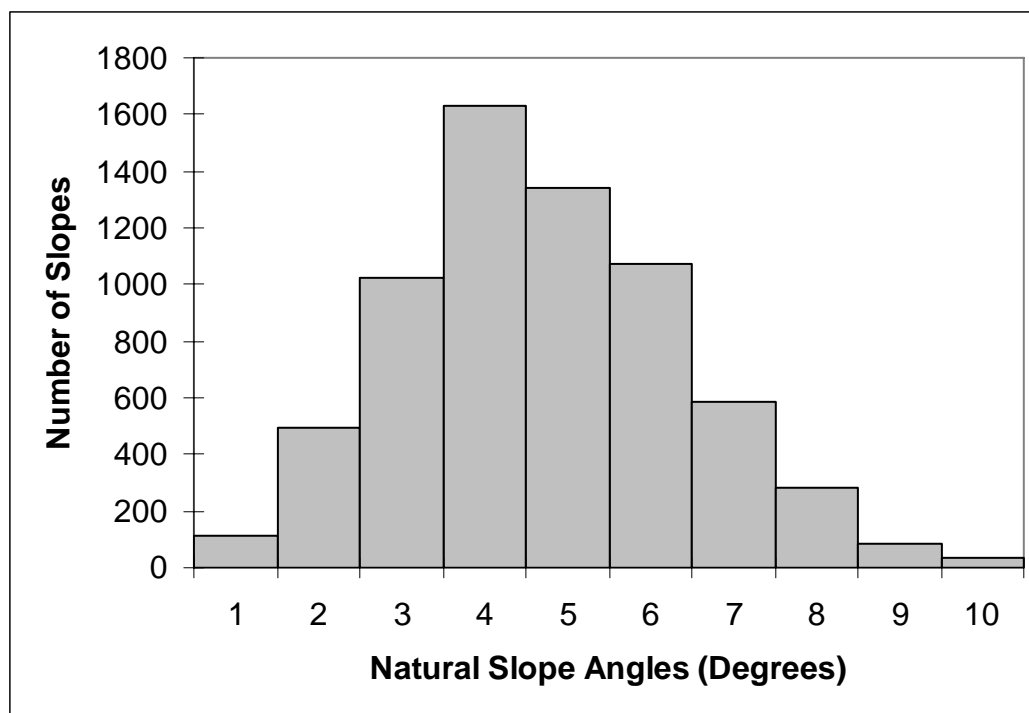
Mean	4
Standard Deviation	1.7
Minimum	0.08
Maximum	12
Count	6697

Figure 14B-2: Frequency histogram of natural slope angles and corresponding descriptive statistics for ATH-50-28 site.
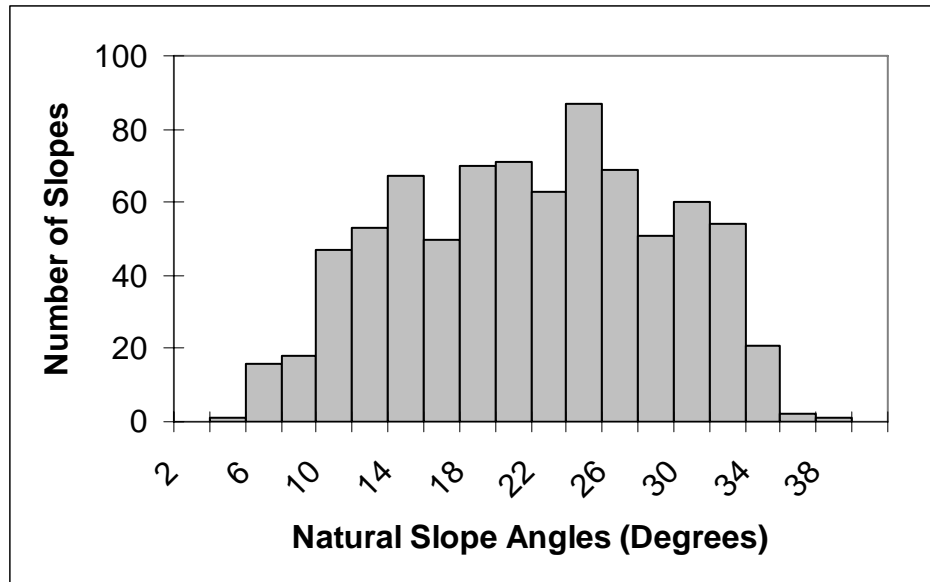
Mean	20
Standard Deviation	7.3
Minimum	2
Maximum	30
Count	801

Figure 14B-3: Frequency histogram of natural slope angles and corresponding descriptive statistics for COL-11-16 site.
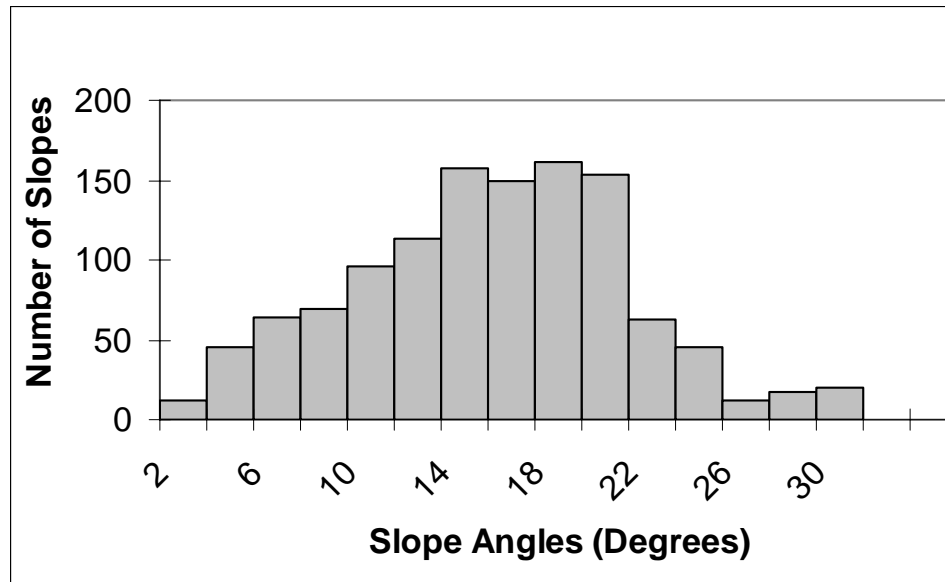
Mean	14
Standard Deviation	0.2
Minimum	1
Maximum	29
Count	1181

Figure 14B-4: Frequency histogram of natural slope angles and corresponding descriptive statistics for COL-30-30 site.
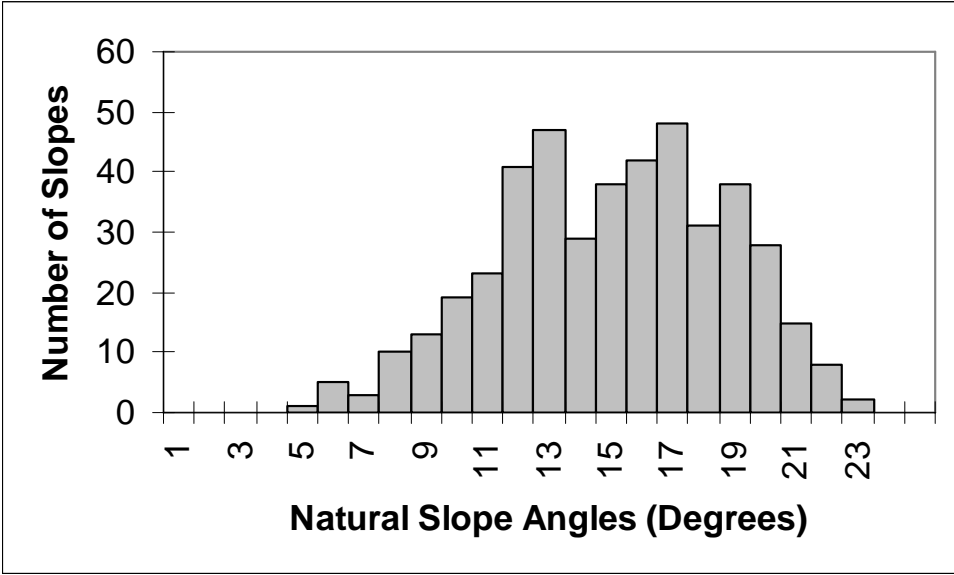
Mean	15
Standard Deviation	0.2
Minimum	5
Maximum	23
Count	441

Figure 14B-5: Frequency histogram of natural slope angles and corresponding descriptive statistics for FRA-270-23 site.
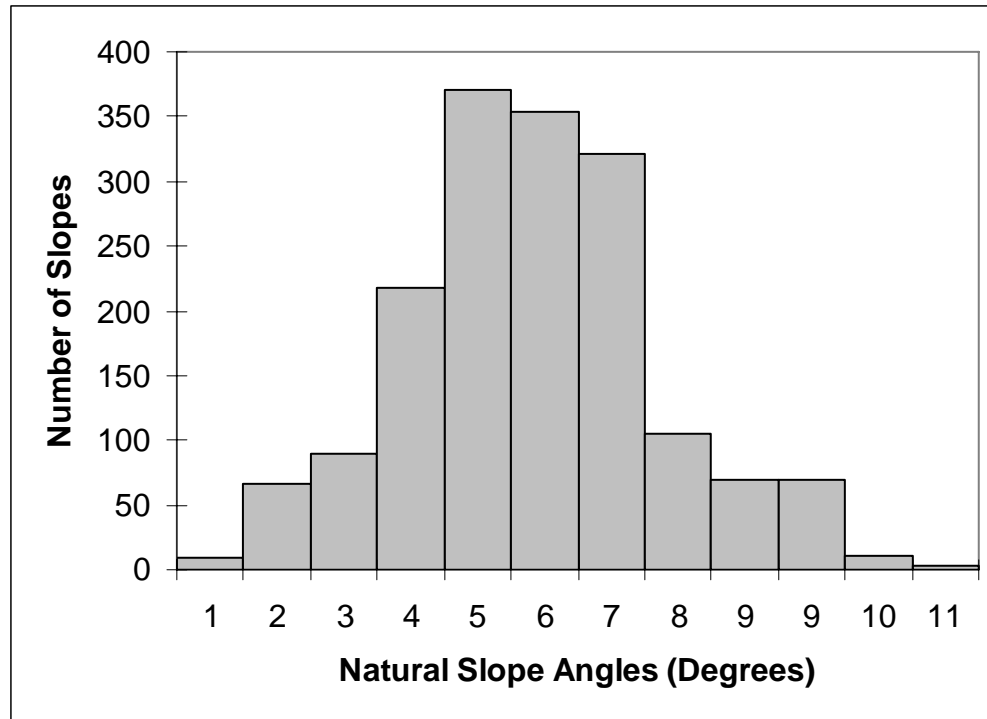
Mean	5
Standard Deviation	1.7
Minimum	0.3
Maximum	10
Count	1618

Figure 14B-6: Frequency histogram of natural slope angles and corresponding descriptive statistics for GUE-77-21 site.
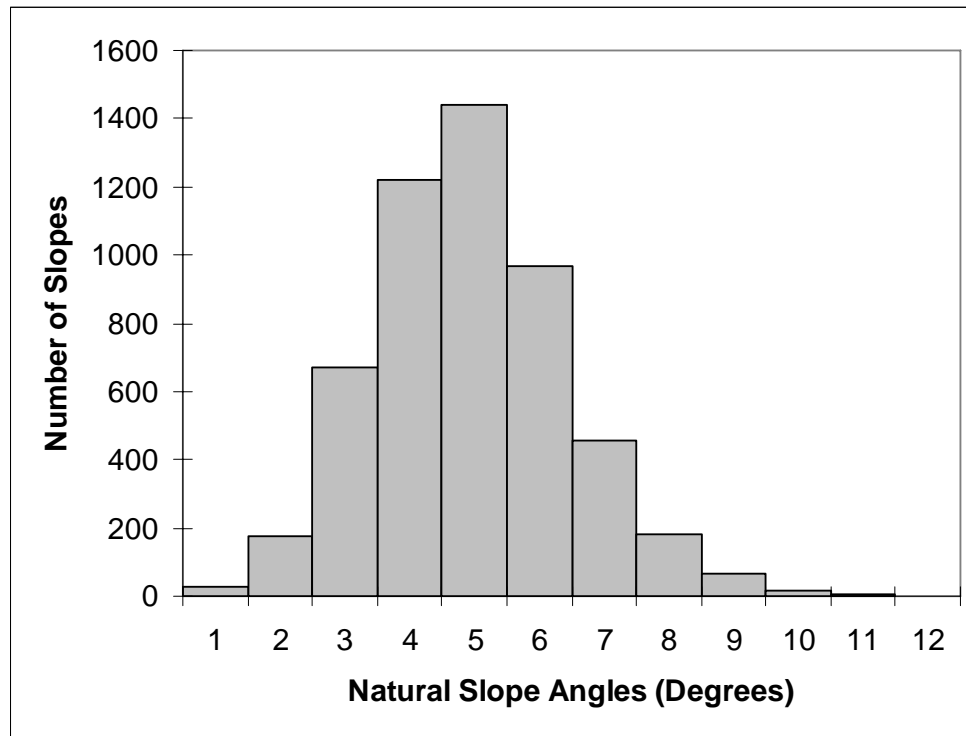
Mean	4
Standard Deviation	1.5
Minimum	0.3
Maximum	13
Count	5241

Figure 14B-7: Frequency histogram of natural slope angles and corresponding descriptive statistics for GUE-70-12.9 site.
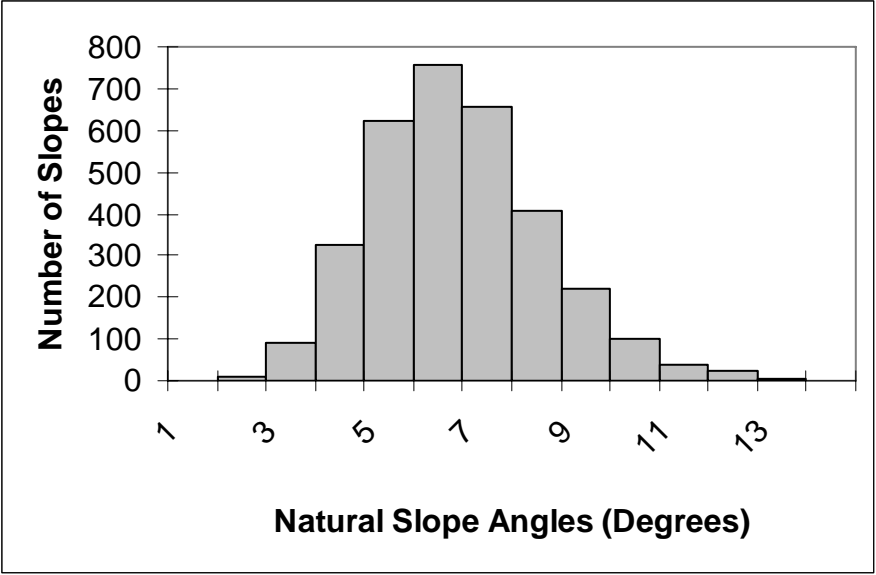
Mean	6
Standard Deviation	1.8
Minimum	1.5
Maximum	13
Count	3263

Figure 14B-8: Frequency histogram of natural slope angles and corresponding descriptive statistics for HAM-74-8.9 site.
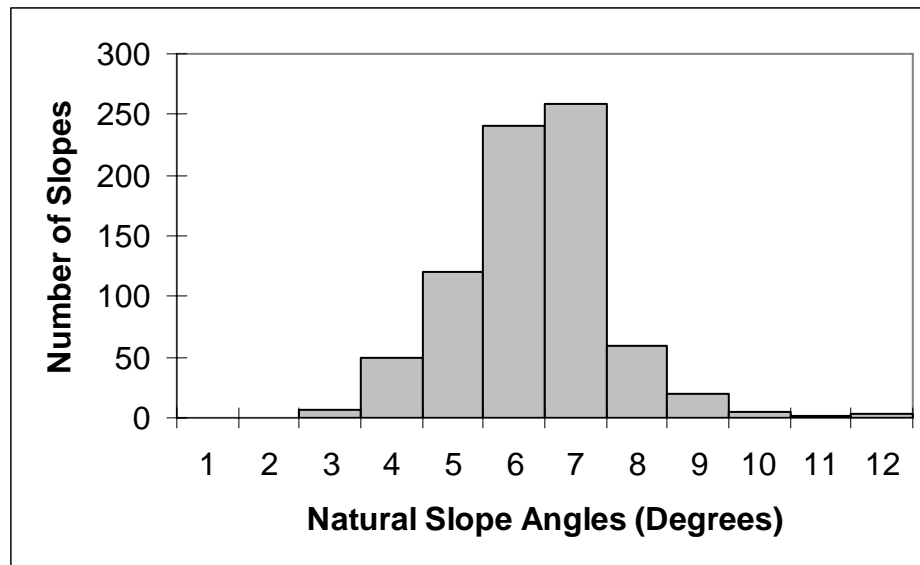
Mean	6
Standard Deviation	1.2
Minimum	2.5
Maximum	11
Count	764

Figure 14B-9: Frequency histogram of natural slope angles and corresponding descriptive statistics for HAM-74-12 site.
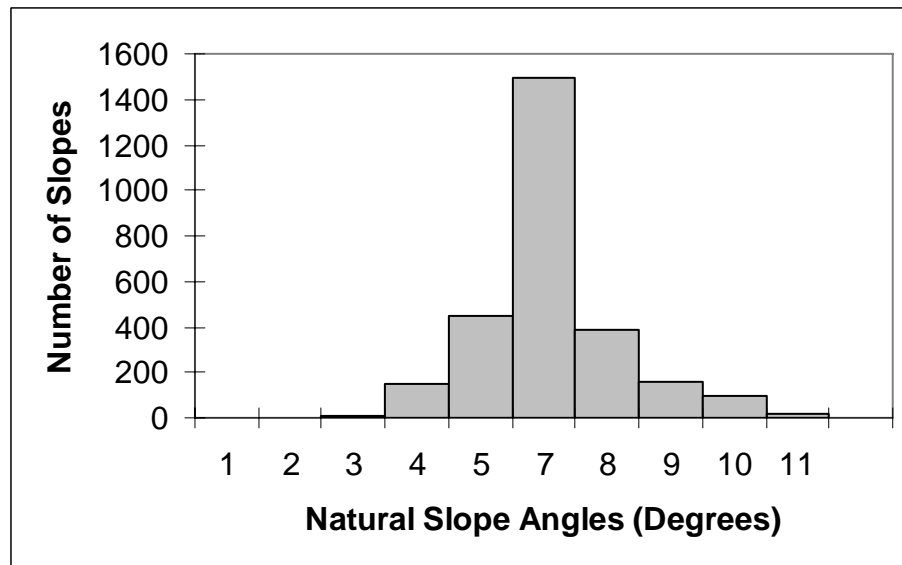
Mean	6
Standard Deviation	1.4
Minimum	0.6
Maximum	11
Count	2760

Figure 14B-10: Frequency histogram of natural slope angles and corresponding descriptive statistics for HAM-74-16.6 site.

APPENDIX 15

STABILITY ANALYSIS FOR INTER-LAYERED COMPETENT AND
INCOMPETENT ROCK UNITS

APPENDIX 15-A
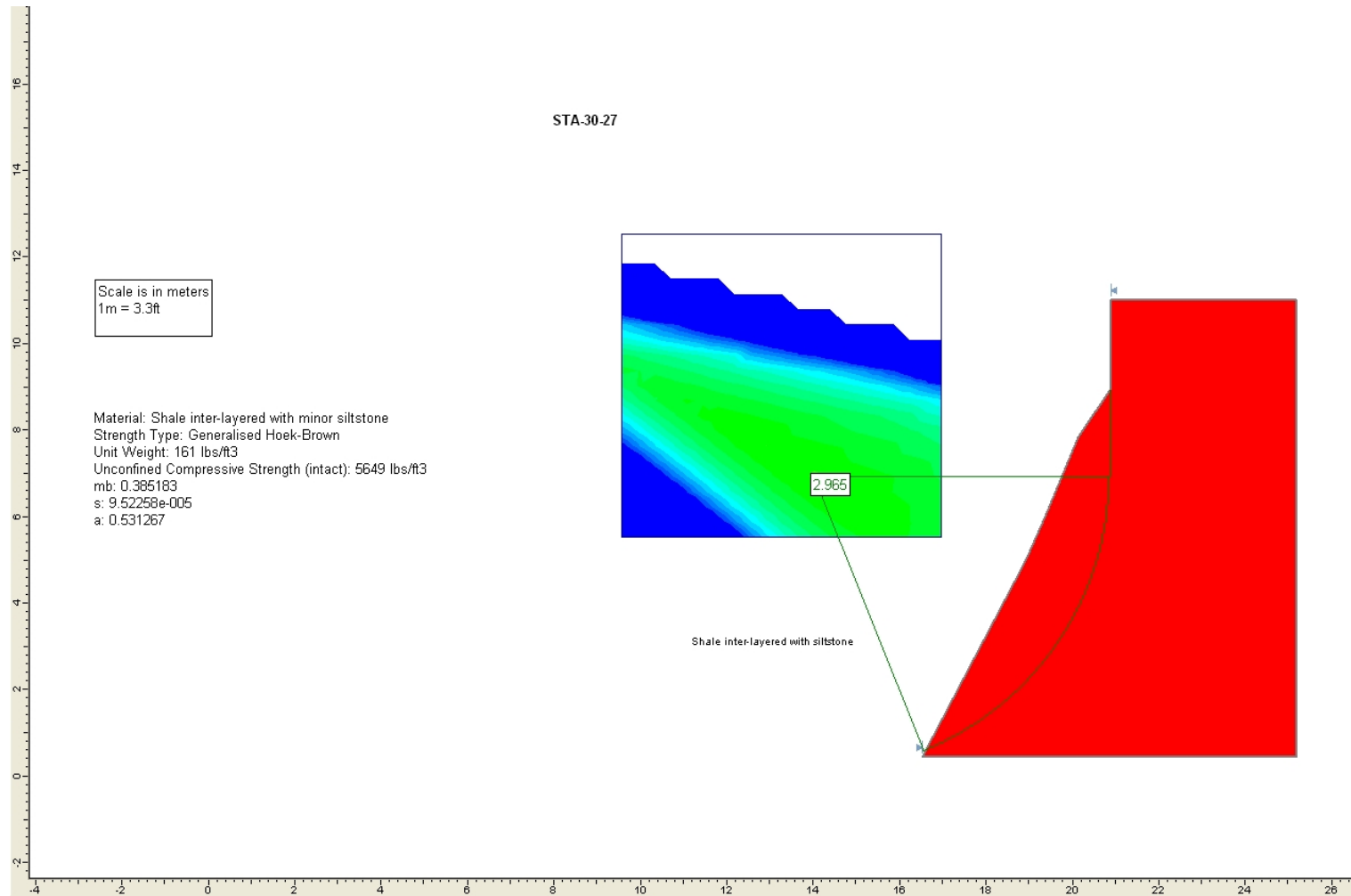
RESULTS OF STABILITY ANALYSIS USING THE SLIDE SOFTWARE

Figure 15A-1: Result of stability analysis for ADA-41-15 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-2: Result of stability analysis for ATH-50-33 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-3: Result of stability analysis for BEL-470-6 site. The number in the box represents the factor of safety value for the curved failure surface shown.
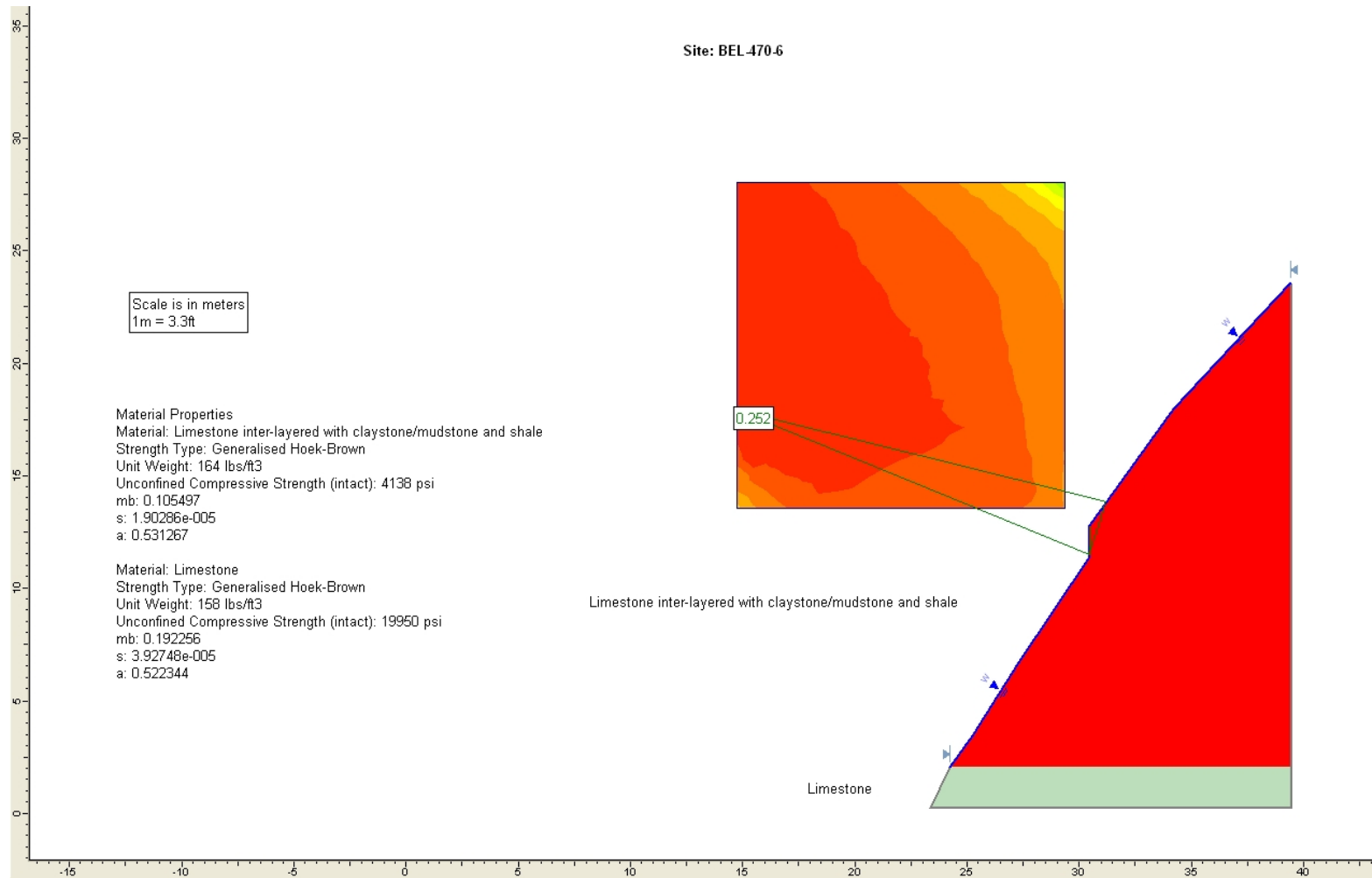
Figure 15A-4: Result of stability analysis for BEL-470-6 site (saturated conditions). The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-5: Result of stability analysis for BEL-7-10 site. The number in the box represents the factor of safety value for the curved failure surface shown.
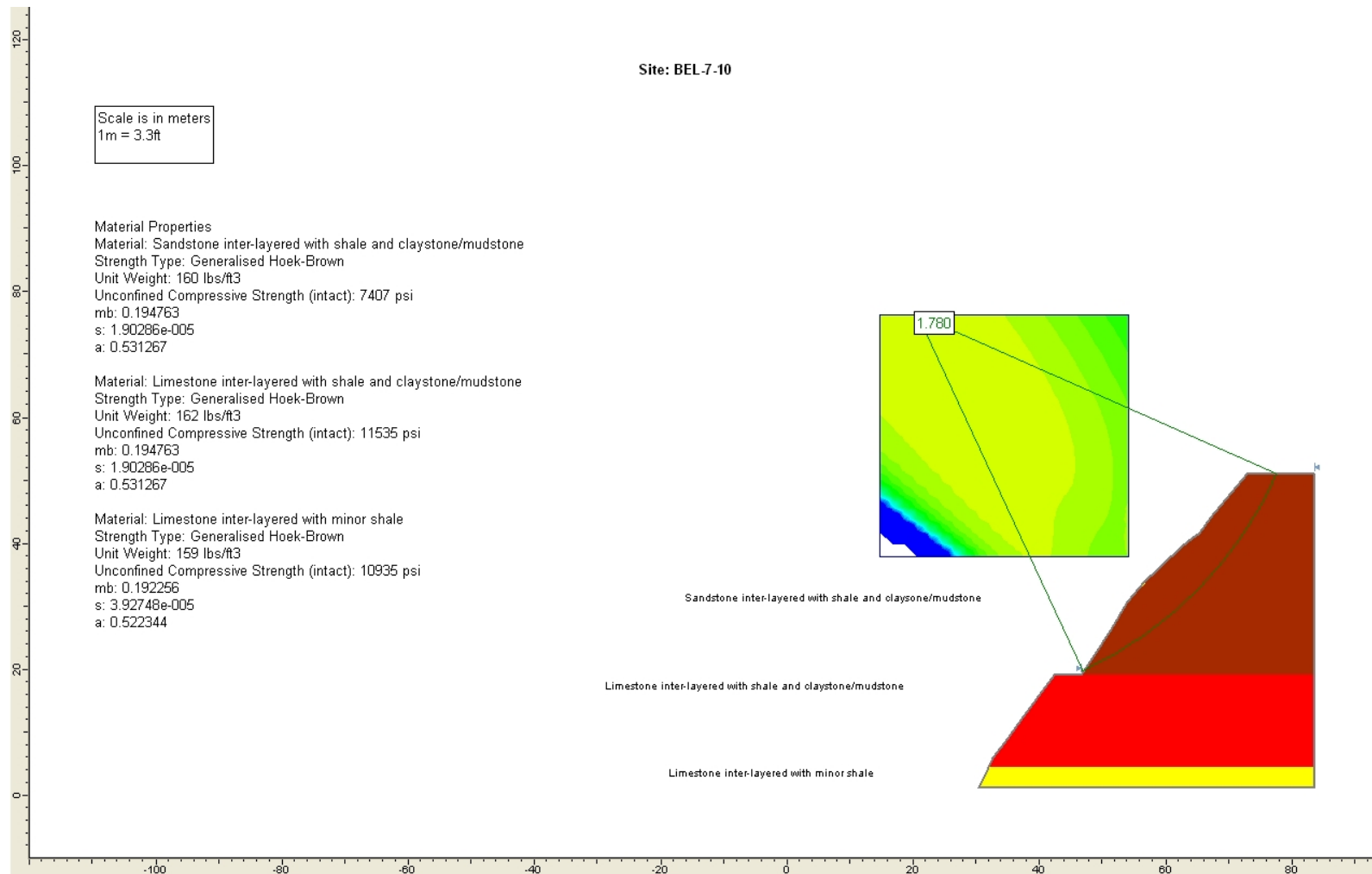
Figure 15A-6: Result of stability analysis for BEL-7-10 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-7: Result of stability analysis for BEL-7-10 site (saturated conditins). The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-8: Result of stability analysis for BEL-70-22 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-9: Result of stability analysis for CLE-275-5 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-10: Result of stability analysis for HAM-126-12 site. The number in the box represents the factor of safety value for the curved failure surface shown.
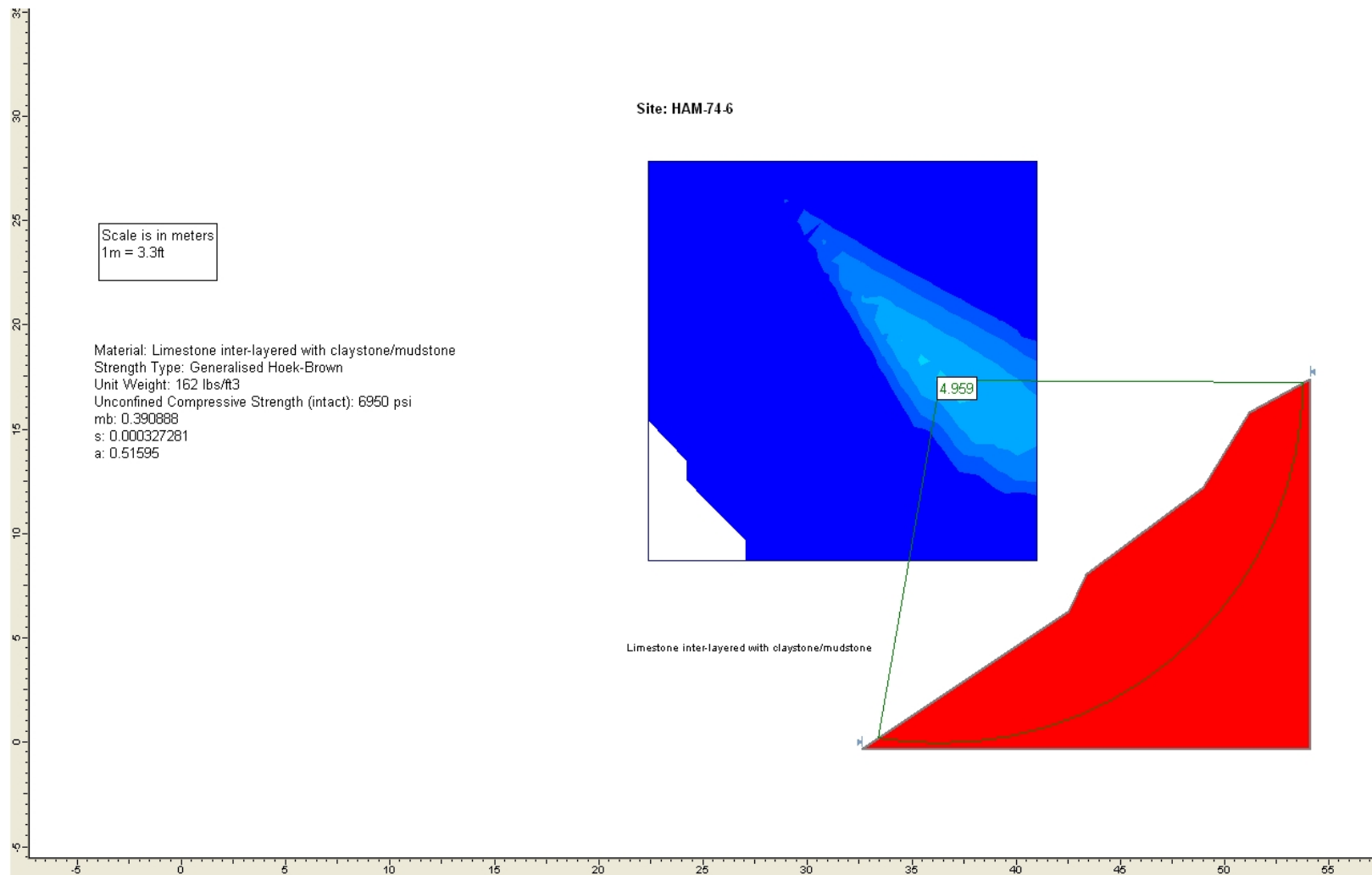
Figure 15A-11: Result of stability analysis for HAM-74-6 site. The number in the box represents the factor of safety value for the curved failure surface shown.
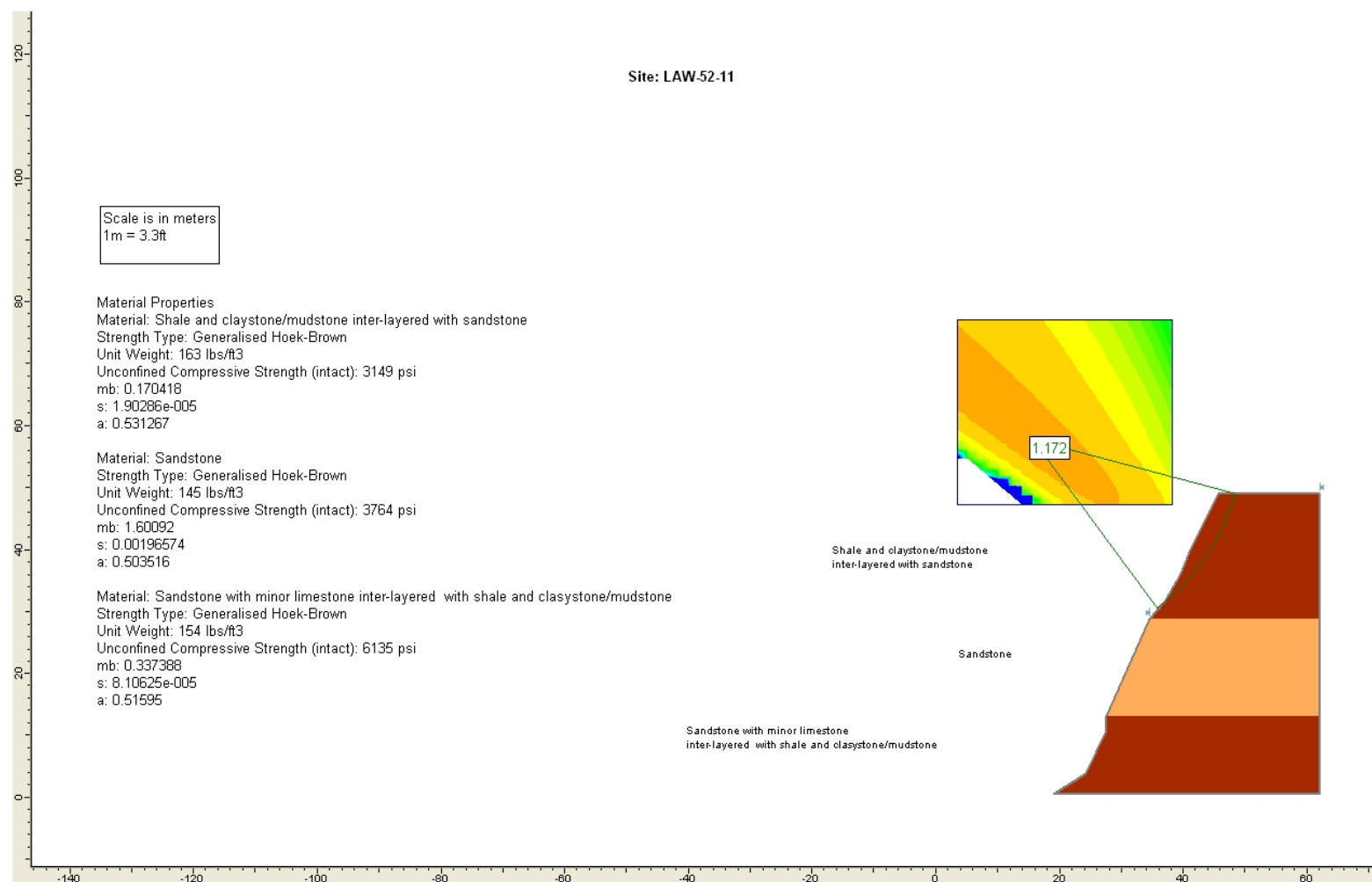
Figure 15A-12: Result of stability analysis for LAW-52-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.
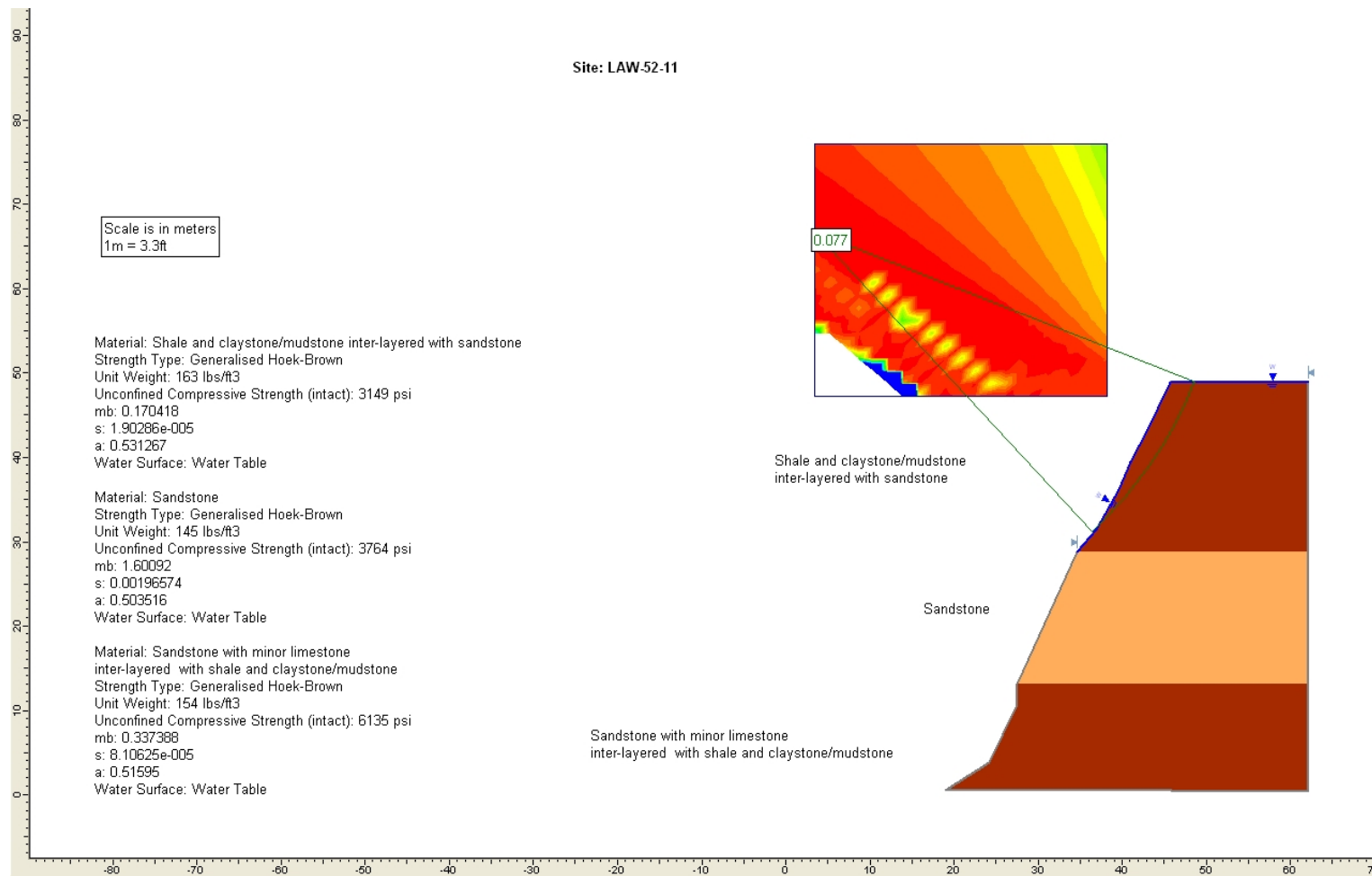
Figure 15A-13: Result of stability analysis for LAW-52-11 site (saturated conditions). The number in the box represents the factor of safety value for the curved failure surface shown.
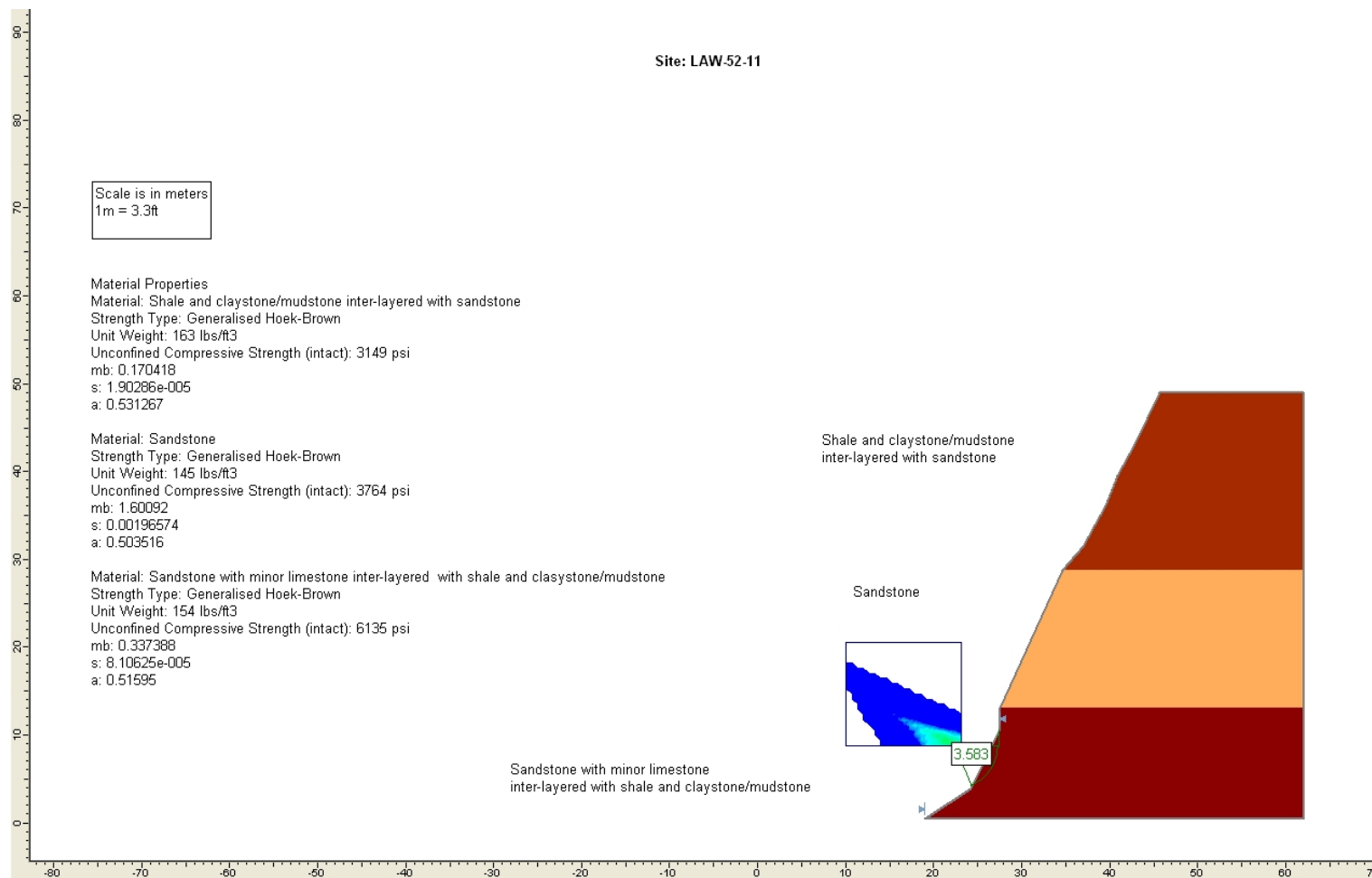
Figure 15A-14: Result of stability analysis for LAW-52-11 site. The number in the box represents the factor of safety value for the curved failure surface shown.
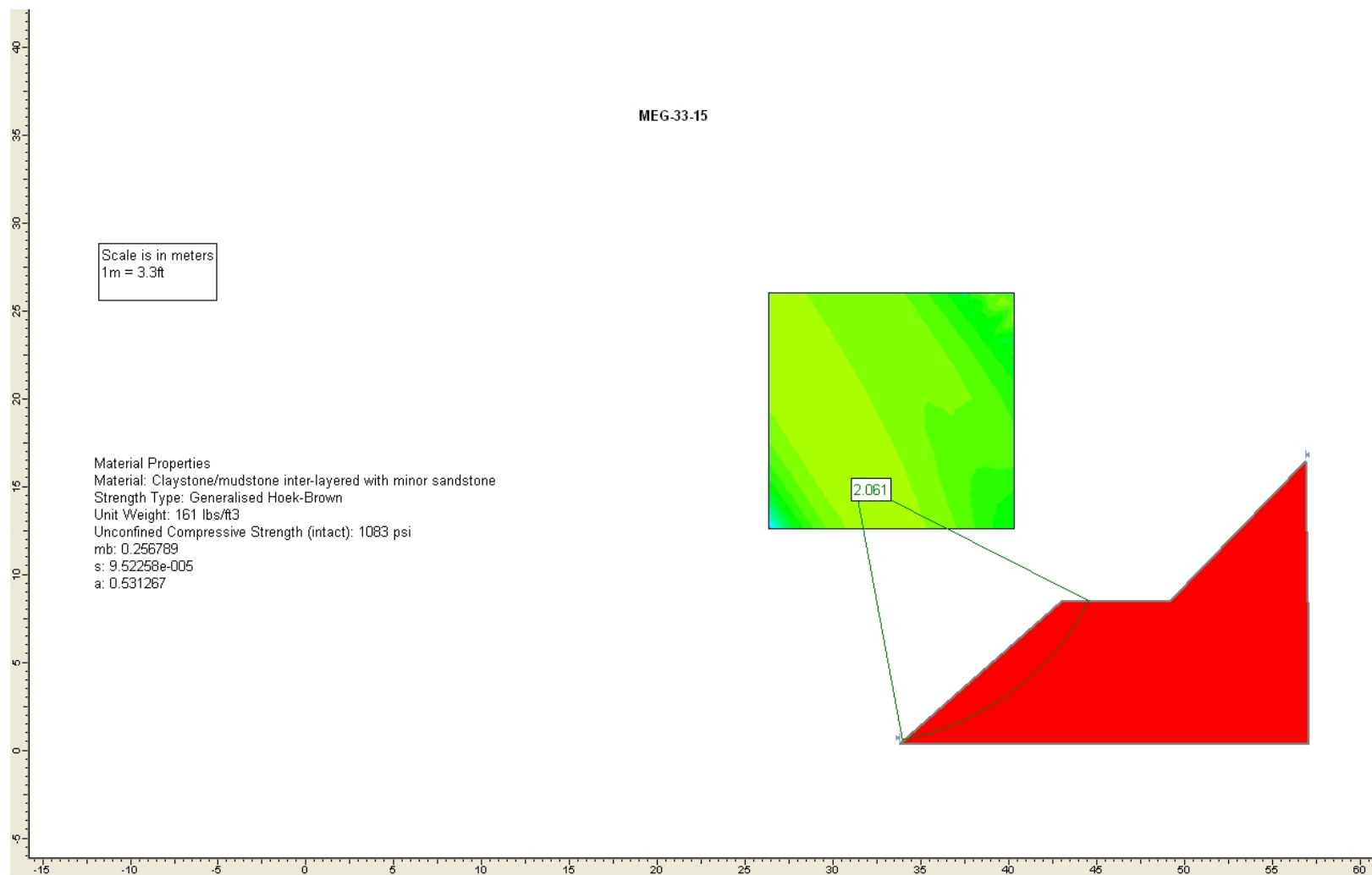
Figure 15A-15: Result of stability analysis for MEG-33-15 site. The number in the box represents the factor of safety value for the curved failure surface shown.
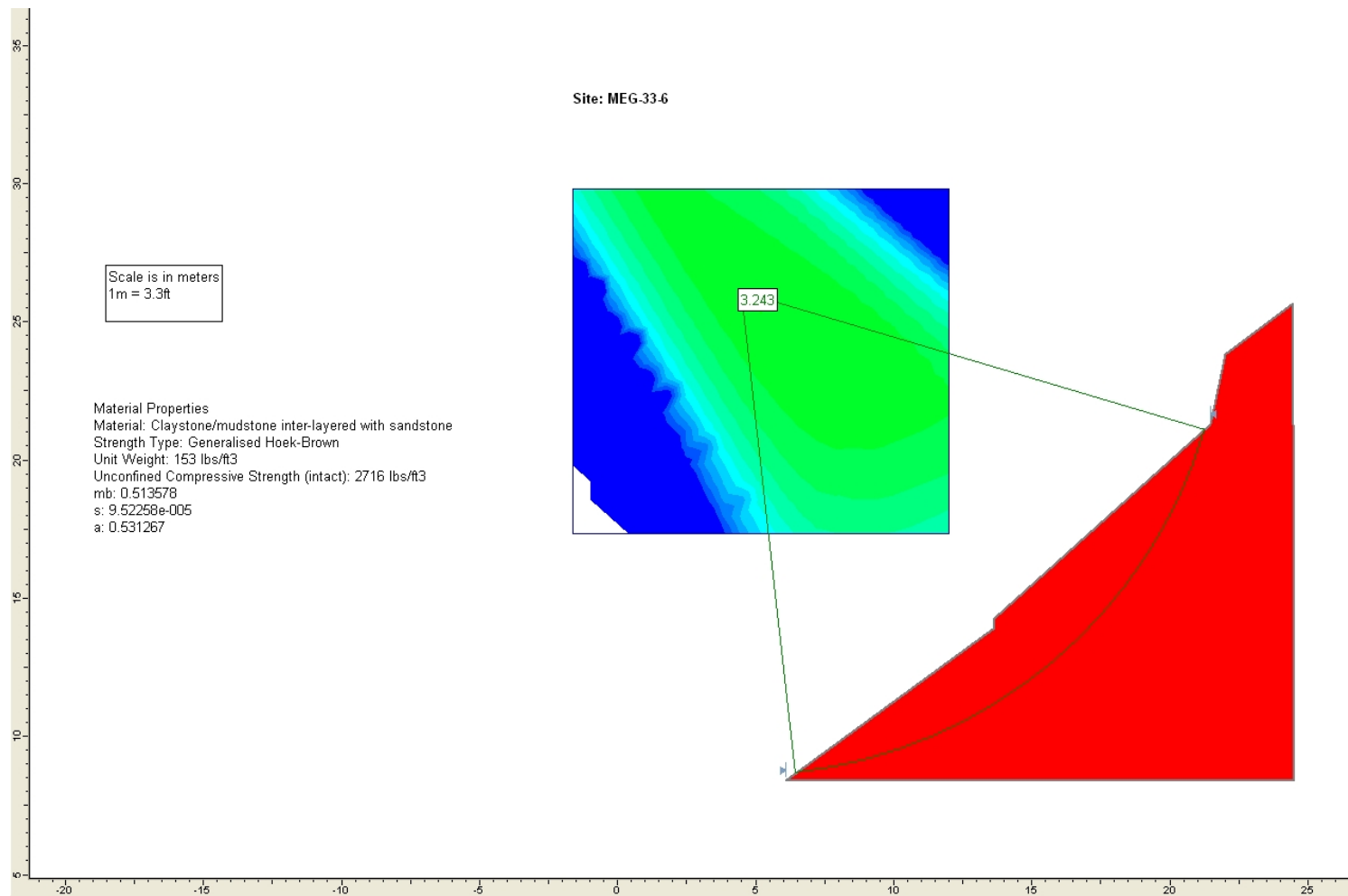
Figure 15A-16: Result of stability analysis for MEG-33-6 site. The number in the box represents the factor of safety value for the curved failure surface shown.

Figure 15A-17: Result of stability analysis for STA-30-27 site. The number in the box represents the factor of safety value for the curved failure surface shown.

APPENDIX 15-B

DATA USED FOR BI-VARIATE AND MULTIVARIATE STATISTICS
AND CORRESPONDING DESCRIPTIVE STATISTICS

DATA USED FOR DETERMINING AMOUNT OF RECESSION

DATA ON SLOPE ANGLES OF UNDERCUTTING UNITS

Table 15B-1: Non- transformed data used for multi-variate statistics.

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Original Slope Angle of Undercutting Unit	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Rate of Undercutting (in/yr)
BEL-470-6	LST*	37.2	1.4	0.4	50.2	27	62	30	20.8	82	2.7
BEL-470-6	LST	21.9	1.4	0.3	86.5	25.9	62	30	11.2	63	2.1
BEL-470-6	LST	22	1	0.3	50.2	27	62	30	0	76.8	2.6
BEL-470-6	LST	38.3	1.9	0.5	86.5	25.9	62	30	24.7	49.8	1.7
BEL-7-10	SST**	40	5	0.2	91.3	37.8	55	35	34.3	34.3	1
BEL-70-1.6	SST	24.4	12	0.4	2.2	38.6	63	44	0	144	3.3
BEL-70-22	LST	35.3	4	0.6	11.1	13.6	63	46	0	80.4	1.7
BEL-70-22	SST	52.8	7	0.9	93.3	33.2	63	46	27.8	43.3	0.9
BEL-70-22	SST	23.8	1	0.4	58	33.1	63	46	24	105.6	2.3
BEL-7-10	LST	164.3	0.9	0.7	71.4	27	55	35	9.4	73.8	2.1
BEL-7-10	LST	72.4	1.1	0.3	71.4	25.9	55	35	0	55.9	1.6
BEL-7-24	SST	30.3	53.9	0.4	86.3	37.9	41	.	48	48	1.4
COL-7-3	SST	24.3	24.2	0.4	48	18.8	45	37	1.8	80.2	2.2
COL-7-3	SST	60.4	60.4	0.6	48	44.4	45	37	39.8	39.8	1.1

Table 15B-1 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Original Slope Angle of Undercutting Unit	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Rate of Undercutting (in/yr)
COL-7-3	SST	54.7	54.7	0.6	48	44.4	45	37	25.3	30.7	0.8
COL-7-3	SST	60.4	60.4	0.6	48	44.4	45	37	0	39.8	1.1
COL-7-5	SST	175.8	1.6	0.9	90.1	30.3	50	19	10.5	20	1.1
COL-7-5	SST	165	15	0.8	99.3	300	50	19	0	0	0
JEF-22-8(N-facing)	SST	38.1	38.1	0.6	53.6	64.1	45	22	19.7	34.5	1.6
JEF-22-8(N-facing)	SST	25.8	25.8	0.4	53.6	64.1	45	22	79	74.3	3.4
JEF-22-8(N-facing)	SST	26.6	26.6	0.4	53.6	64.1	45	22	1.9	73.2	3.3
JEF-22-8(N-facing)	SST	19.3	19.3	0.3	53.6	64.1	45	22	27.6	72.3	3.3
JEF-22-8(S-facing)	SST	7.6	7.6	0.2	8.7	74.6	45	22	62.4	62.4	2.8
JEF-22-8(S-facing)	SST	16.2	16.2	0.5	8.7	74.6	45	22	23.9	23.9	1.1
JEF-7-23	SST	130.5	10.7	0.8	88.4	188	58	40	39.7	39.7	1
JEF-7-23	LST	189.7	26.3	0.9	88.4	15.1	58	40	26.3	38.4	1
JEF-7-23	LST	205.6	2.1	0.9	88.4	15.1	58	40	6.2	36.4	0.9
JEF-7-23	SST	197.9	7.2	0.9	88.4	188	58	40	21.6	21.6	0.5

Table 15B-1 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Original Slope Angle of Undercutting Unit	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Rate of Undercutting (in/yr)
JEF-7-23	LST	169.3	31.2	0.9	88.4	15.1	58	40	1.2	17.5	0.4
JEF-7-23	SST	160.4	2.5	0.9	88.4	188	58	40	11.8	11.8	0.3
JEF-7-23	LST	140.2	2.4	0.9	88.4	15.1	58	40	6.8	48	1.2
JEF-7-23	SST	183.8	8.1	0.9	88.4	188	58	40	7.8	7.8	0.2
JEF-7-6	SST	100.2	12.8	0.8	92.1	196.6	70	54	11.8	11.8	0.2
JEF-CR77-0.6	SST	46.2	5.9	0.5	5.2	164.8	75	19	10.6	143.9	7.6
JEF-CR77-0.6	SST	38.3	7.9	0.5	5.2	164.8	75	19	18	72.9	3.8
JEF-CR77-0.6	SST	65.9	14.7	0.7	5.2	164.8	75	19	73.3	73.7	3.9
JEF-CR77-0.6 CR77	SST	25.1	21.4	0.5	5.2	164.8	75	19	40	43.2	2.3
LAW-52-12	LST	139	3.8	0.9	19.7	360	70	10	18	18	1.8
LAW-52-12	LST	139.1	3.8	1	19.7	360	70	10	1.9	18	1.8
LAW-52-12	LST	163.1	2.7	1	19.7	360	70	10	1.9	18	1.8
LAW-52-12	SST	122.5	10.4	0.8	70	840	70	10	0	0	0
LAW-52-12	SST	135.2	6.2	0.9	35.4	840	70	10	16.2	26.6	2.7

Table 15B-1 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Original Slope Angle of Undercutting Unit	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Rate of Undercutting (in/yr)
LAW-52-12	SST	135.2	7.2	0.9	35.4	840	70	10	8.8	26.6	2.7
LAW-52-12	SST	154.2	5.2	0.9	35.4	840	70	10	8.8	26.6	2.7
LAW-52-13	SST	118.2	45.6	0.9	87.2	360	70	43	36.6	36.6	0.9
LAW-52-13	SST	126	54.4	1	87.2	360	70	43	36.6	36.6	0.9
LAW-52-13	SST	120.8	45.8	0.9	87.2	360	70	43	36.6	36.6	0.9
LAW-52-13	SST	118.2	45.6	0.9	48.8	360	70	43	31.4	31.4	0.7
LAW-52-13	SST	126	54.4	1	48.8	360	70	43	31.4	31.4	0.7
LAW-52-13	SST	120.8	45.8	0.9	48.8	360	70	43	31.4	31.4	0.7
MUS-70-25	SST	30.3	21	0.3	86.7	70.3	75	42	0	76.6	1.8
WAS-77-15 (799***)	LST	103.5	2.6	0.9	27.3	8.7	45	42	12	85.3	2
WAS-77-15 (799)	LST	74	4.2	0.6	72.9	9.4	45	42	21	118	2.8
WAS-77-15 (799)	LST	113.6	1.1	1	33.7	4.8	45	42	12.8	56	1.3
WAS-77-15(801)	LST	71.8	3.1	0.7	27.3	8.7	45	42	12	82.8	2
WAS-77-15(801*)	LST	81.9	0.5	0.8	33.7	4.8	45	42	12.8	53.5	1.3

Table 15B-1 (contd.).

Site	Undercut Rock Type *	Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Original Slope Angle of Undercutting Unit	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Rate of Undercutting (in/yr)
WAS-77-15(801)	LST	39.2	2	0.4	72.9	9.4	45	42	21	100.4	2.4
WAS-77-15(810*\)	LST	37.3	2.1	0.4	27.3	8.7	45	42	26.4	131.9	3.1
WAS-77-15(810)	LST	48	2.9	0.5	33.7	4.8	45	42	10.4	154.4	3.7

* LST = Limestone, **SST = Sandstone *** feet marker used when sites fall within the same mile marker

Table 15B-2: Descriptive statistics for non-transformed data used for multi-variate statistics.

Descriptive Statistic		Distance of Undercut Rock Unit From Slope Crest (ft)	Total Thickness of Undercut Rock Unit (ft)	Relative Position of Undercut Rock Unit From Slope Crest (Distance of Undercut Rock Unit From Slope Crest /Total Slope Height)	Slake Durability Index of Undercutting Rock Unit (%)	Spacing of Orthogonal Joints Within Undercut Rock Unit (in)	Age of Road Cut (yr)	Amount of Undercutting (in)	Total Amount of Undercutting (in)	Original Slope Angle of Undercutting Unit
Mean		89.3	15.7	0.7	54.6	165.5	32.4	19.1	53.9	58.2
95% Confidence Interval for Mean	Lower Bound	74.1	11	0.6	46.6	106.9	29.2	14.5	44.3	55.3
	Upper Bound	104.5	20.4	0.7	62.5	224.1	35.6	23.7	63.5	61.1
Median		73.2	7.2	0.7	51.9	64.1	37.0	14.5	41.5	58
Variance		3345.2	323.6	0.1	905.7	49630.5	148.9	305.9	1332.8	122.6
Std. Deviation		57.8	18	0.3	30.1	222.8	12.2	17.5	36.5	11.1
Minimum		7.6	0.5	0.2	2.2	4.8	10.0	0.0	0.0	41
Maximum		205.6	60.4	1	99.3	840.0	54.0	79.0	154.4	75
Range		198	59.9	0.8	97.1	835.2	44.0	79.0	154.4	34
Skewness		0.3	1.3	-0.4	-0.2	2.0	-0.6	1.4	1.0	-0.01
Kurtosis		-1.3	0.4	-1.4	-1.3	3.6	-0.9	2.6	0.6	-1.5

Table 15B-3: Transformed data used for multi-variate statistics.

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Total Thickness of Undercut Rock Unit (Log)	Relative Position of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Slake Durability Index of Undercutting Rock Unit (Reflectd Adjusted SQRT)	Spacing of Orthogonal Joints Within Undercut Rock Unit (Log)	Age of Road Cut (Adjusted SQRT)	Original Slope Angle of Undercutting Unit (Squared)	Total Amount of Undercutting (Log-Transformed)
BEL-470-6	LST*	5.5	0.1	1.1	3.8	1.4	4.6	3844	1.9
BEL-470-6	LST	3.9	0.1	1	7.2	1.4	4.6	3844	1.8
BEL-470-6	LST	3.9	0	1	3.8	1.4	4.6	3844	1.9
BEL-470-6	LST	5.6	0.3	1.1	7.2	1.4	4.6	3844	1.7
BEL-7-10	LST	12.6	0	1.2	5.5	1.4	5.1	3025	1.9
BEL-7-10	LST	8.1	0	1	5.5	1.4	5.1	3025	1.7
BEL-70-1.6	SST	4.2	1.1	1.1	1	1.6	5.9	3969	2.2
BEL-70-22	LST	5.4	0.6	1.2	1.5	1.1	6.1	3969	1.9
BEL-70-22	SST**	6.8	0.8	1.3	8.3	1.5	6.1	3969	1.6
BEL-70-22	SST	4.1	0	1.1	4.4	1.5	6.1	3969	2
BEL-7-10	SST	5.8	0.7	1	7.9	1.6	5.1	3025	1.5
BEL-7-24	SST	4.9	1.7	1.1	7.2	1.6		1681	1.7
COL-7-3	SST	4.2	1.4	1.1	3.7	1.3	5.3	2025	1.9
COL-7-3	SST	7.3	1.8	1.2	3.7	1.6	5.3	2025	1.6
COL-7-3	SST	6.9	1.7	1.2	3.7	1.6	5.3	2025	1.5
COL-7-3	SST	7.3	1.8	1.2	3.7	1.6	5.3	2025	1.6
COL-7-5	SST	13	0.2	1.3	7.7	1.5	3.2	2500	1.3
COL-7-5	SST	12.6	1.2	1.3	9.9	2.5	3.2	2500	

Table 15B-3 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Total Thickness of Undercut Rock Unit (Log)	Relative Position of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Slake Durability Index of Undercutting Rock Unit (Reflectd Adjusted SQRT)	Spacing of Orthogonal Joints Within Undercut Rock Unit (Log)	Age of Road Cut (Adjusted SQRT)	Original Slope Angle of Undercutting Unit (Squared)	Total Amount of Undercutting (Log-Transformed)
JEF-22-8 (N-facing)	SST	5.6	1.6	1.2	4.1	1.8	3.6	2025	1.5
JEF-22-8 (N-facing)	SST	4.4	1.4	1.1	4.1	1.8	3.6	2025	1.9
JEF-22-8 (N-facing)	SST	4.5	1.4	1.1	4.1	1.8	3.6	2025	1.9
JEF-22-8 (N-facing)	SST	3.6	1.3	1	4.1	1.8	3.6	2025	1.9
JEF-22-8 (S-facing)	SST	1	0.9	1	1.3	1.9	3.6	2025	1.8
JEF-22-8 (S-facing)	SST	3.1	1.2	1.1	1.3	1.9	3.6	2025	1.4
JEF-7-23	LST	11.6	0.4	1.3	7.5	1.2	5.6	3364	1.7
JEF-7-23	LST	13.5	1.4	1.3	7.5	1.2	5.6	3364	1.6
JEF-7-23	LST	14.1	0.3	1.3	7.5	1.2	5.6	3364	1.6
JEF-7-23	LST	12.8	1.5	1.3	7.5	1.2	5.6	3364	1.2
JEF-7-23	SST	11.1	1	1.3	7.5	2.3	5.6	3364	1.6
JEF-7-23	SST	13.3	0.9	1.3	7.5	2.3	5.6	3364	0.9
JEF-7-23	SST	13.8	0.9	1.3	7.5	2.3	5.6	3364	1.3
JEF-7-23	SST	12.4	0.4	1.3	7.5	2.3	5.6	3364	1.1
JEF-7-6	SST	9.7	1.1	1.3	8	2.3	6.7	4900	1.1
JEF-CR77 -0.4	SST	6.3	0.8	1.1	1.2	2.2	3.2	5625	2.2
JEF-CR77 -0.5	SST	5.6	0.9	1.1	1.2	2.2	3.2	5625	1.9
JEF-CR77 -0.6	SST	7.7	1.2	1.2	1.2	2.2	3.2	5625	1.9

Table 15B-3 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Total Thickness of Undercut Rock Unit (Log)	Relative Position of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Slake Durability Index of Undercutting Rock Unit (Reflectd Adjusted SQRT)	Spacing of Orthogonal Joints Within Undercut Rock Unit (Log)	Age of Road Cut (Adjusted SQRT)	Original Slope Angle of Undercutting Unit (Squared)	Total Amount of Undercutting (Log-Transformed)
JEF-CR77 -0.7	SST	4.3	1.3	1.1	1.2	2.2	3.2	5625	1.6
LAW-52-12	LST	11.5	0.6	1.3	1.9	2.6	1	4900	1.3
LAW-52-12	LST	11.5	0.6	1.3	1.9	2.6	1	4900	1.3
LAW-52-12	LST	12.5	0.4	1.3	1.9	2.6	1	4900	1.3
LAW-52-12	SST	10.8	1	1.3	5.4	2.9	1	4900	
LAW-52-12	SST	11.3	0.8	1.3	2.8	2.9	1	4900	1.4
LAW-52-12	SST	11.3	0.9	1.3	2.8	2.9	1	4900	1.4
LAW-52-12	SST	12.1	0.7	1.3	2.8	2.9	1	4900	1.4
LAW-52-13	SST	10.6	1.7	1.3	7.3	2.6	5.8	4900	1.6
LAW-52-13	SST	10.9	1.7	1.3	7.3	2.6	5.8	4900	1.6
LAW-52-13	SST	10.7	1.7	1.3	7.3	2.6	5.8	4900	1.6
LAW-52-13	SST	10.6	1.7	1.3	3.7	2.6	5.8	4900	1.5
LAW-52-13	SST	10.9	1.7	1.3	3.7	2.6	5.8	4900	1.5
LAW-52-13	SST	10.7	1.7	1.3	3.7	2.6	5.8	4900	1.5
MUS-70-25	SST	4.9	1.3	1	7.2	1.8	5.7	5625	1.9
WAS-77-15 (799***)	LST	9.8	0.4	1.3	2.4	0.9	5.7	2025	1.9
WAS-77-15 (801*)	LST	8.7	-0.3	1.3	2.7	0.7	5.7	2025	1.7

Table 15B-3 (contd.).

Site	Undercut Rock Type	Distance of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Total Thickness of Undercut Rock Unit (Log)	Relative Position of Undercut Rock Unit From Slope Crest (Adjusted SQRT)	Slake Durability Index of Undercutting Rock Unit (Reflectd Adjusted SQRT)	Spacing of Orthogonal Joints Within Undercut Rock Unit (Log)	Age of Road Cut (Adjusted SQRT)	Original Slope Angle of Undercutting Unit (Squared)	Total Amount of Undercutting (Log-Transformed)
WAS-77-15 (801E)	LST	8.1	0.5	1.2	2.4	0.9	5.7	2025	1.9
WAS-77-15(799*)	LST	8.2	0.6	1.2	5.7	1	5.7	2025	2.1
WAS-77-15(799*)	LST	10.3	0	1.3	2.7	0.7	5.7	2025	1.7
WAS-77-15(801*)	LST	5.7	0.3	1.1	5.7	1	5.7	2025	2
WAS-77-15(810*)	LST	5.5	0.3	1.1	2.4	0.9	5.7	2025	2.1
WAS-77-15(810*)	LST	6.4	0.5	1.1	2.7	0.7	5.7	2025	2.2

* LST = Limestone, **SST = Sandstone *** feet marker used when sites fall within the same mile marker

Table 15B-4: Total amount of undercutting and present amount of undercutting data.

Site	Undercut Rock Type	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Difference Between Total Amount of Undercutting and Present Amount of Undercutting (in)	Proportion of Undercut Rock Unit Thickness That Produced Rockfalls (/1)	Adjusted Difference Between Total Amount of Undercutting and Present Amount of Undercutting (in)
BEL-470-6	LST*	20.8	82.0	61.2	1.0	61.2
BEL-470-6	LST	11.2	63.0	51.8	1.0	51.8
BEL-470-6	LST	0.0	76.8	76.8	1.0	76.8
BEL-470-6	LST	24.7	49.8	25.1	1.0	25.1
BEL-7-10	LST	9.4	73.8	64.4	1.0	64.4
BEL-7-10	LST	0.0	55.9	55.9	1.0	55.9
BEL-7-10	LST	0.5	0.5	0.0	0.0	0.0
BEL-7-10	SST**	34.3	34.3	0.0	0.0	0.0
COL-7-3	SST	1.8	80.2	78.4	1.0	78.4
JEF-22-8N	SST	19.7	34.5	14.8	0.0	0.0
JEF-22-8N	SST	79.0	74.3	-4.7	0.0	0.0
JEF-22-8N	SST	1.9	73.2	71.3	0.4	29.2
JEF-22-8N	SST	27.6	72.3	44.7	0.5	20.1
JEF-22-8S	SST	62.4	62.4	0.0	0.4	0.0
JEF-22-8S	SST	23.9	23.9	0.0	0.0	0.0
JEF-7-23	LST	6.2	36.4	30.1	1.0	30.1
JEF-7-23	LST	1.2	17.5	16.3	1.0	16.3
JEF-7-23	LST	26.3	38.4	12.1	1.0	12.1
JEF-7-23	LST	6.8	48.0	41.1	1.0	41.1
JEF-7-23	SST	39.7	39.7	0.0	0.0	0.0
JEF-7-23	SST	21.6	21.6	0.0	0.0	0.0
JEF-7-23	SST	11.8	11.8	0.0	0.0	0.0
JEF-7-23	SST	7.8	7.8	0.0	0.0	0.0
JEF-7-6	SST	14.6	19.4	4.8	0.0	0.0
JEF-7-6	SST	14.6	17.8	3.1	0.0	0.0
JEF-7-6	SST	11.8	11.8	0.0	0.0	0.0
JEF-CR77-0.4	SST	10.6	143.9	133.3	0.9	120.0
JEF-CR77-0.4	SST	18.0	72.9	54.9	0.5	28.0
JEF-CR77-0.4	SST	73.3	73.7	0.4	0.1	0.0

Table 15B-4 (contd.).

Site	Undercut Rock Unit Lithology	Present Amount of Undercutting (in)	Total Amount of Undercutting (in)	Difference Between Total Amount of Undercutting and Present Amount of Undercutting (in)	Proportion of Undercut Rock Unit Thickness That Produced Rockfalls (/1)	Adjusted Difference Between Total Amount of Undercutting and Present Amount of Undercutting (in)
JEF-CR77-0.4	SST	40.0	43.2	3.2	0.1	0.3
LAW-52-12	LST	18.0	18.0	0.0	0.0	0.0
LAW-52-12	LST	1.9	18.0	16.1	0.0	0.0
LAW-52-12	LST	1.9	18.0	16.1	0.0	0.0
LAW-52-12	SST	0.0	0.0	0.0	0.0	0.0
LAW-52-12	SST	16.2	26.6	10.4	0.0	0.0
LAW-52-12	SST	0.0	0.0	0.0	0.0	0.0
LAW-52-12	SST	8.8	26.6	17.8	0.0	0.0
LAW-52-12	SST	0.0	0.0	0.0	0.0	0.0
LAW-52-12	SST	8.8	26.6	17.8	0.0	0.0
LAW-52-13	SST	36.6	36.6	0.0	0.0	0.0
LAW-52-13	SST	36.6	36.6	0.0	0.0	0.0
LAW-52-13	SST	36.6	36.6	0.0	0.0	0.0
LAW-52-13	SST	31.4	31.4	0.0	0.0	0.0
LAW-52-13	SST	31.4	31.4	0.0	0.0	0.0
LAW-52-13	SST	31.4	31.4	0.0	0.0	0.0
MUS-70-25	LST	0.0	80.4	80.4	1.0	80.4
WAS-77-15	LST	12.8	56.0	43.2	1.0	43.2
WAS-77-15	LST	12.0	85.3	73.3	1.0	73.3
WAS-77-15	LST	21.0	118.0	97.0	1.0	97.0
WAS-77-15	LST	12.0	94.6	82.6	1.0	82.6
WAS-77-15	LST	12.8	53.5	40.7	1.0	40.7
WAS-77-15	LST	12.0	82.8	70.8	1.0	70.8
WAS-77-15	LST	21.0	100.4	79.4	1.0	79.4
WAS-77-15	LST	26.4	131.9	105.5	1.0	105.5
WAS-77-15	LST	10.4	154.4	144.0	1.0	144.0

* LST = Limestone, **SST = Sandstone

Table 15B-5: Original slope angles of undercutting rock units.

Site	Stable Angle of Undercutting Unit	Site	Stable Angle of Undercutting Unit
JEF-7-6	36	WAS-77-15	36
	39		37
	36		39
	36		40
	34		35
	35		38
JEF-7-14	39		36
	36		45
	40		41
	39		43
	33		39
BEL-7-24	46		45
	44	BEL-70-1	38
	38		38
	30		39
COL-7-3	36		42
	40		39
	40		40
	37	JEF-22-8	36
	38		30
	37		40
	39		36
	36		42
	36		47
	34		42
			36
			36
			35
			34
			33
			42
			44
			42
			43

APPENDIX 15-C

HISTOGRAMS OF NON-TRANSFORMED DATA

Q-Q PLOTS OF TRANSFORMED DATA USED FOR BIVARIATE AND
MULTIVARIATE REGRESSION

SCATTER PLOTS FOR TRANSFORMED DEPENDENT AND
INDEPENDENT VARIABLES
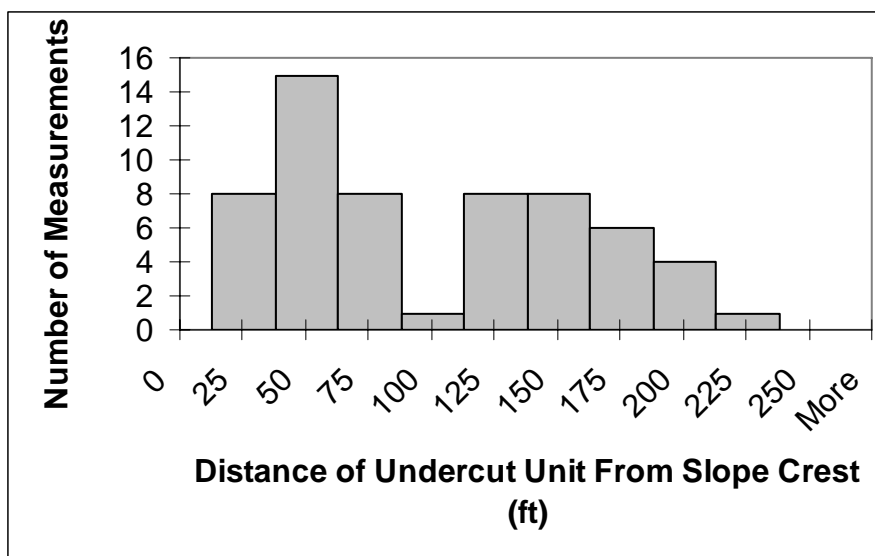
Figure 15C-1: Frequency histogram for non-transformed distance of undercut rock unit from slope crest.
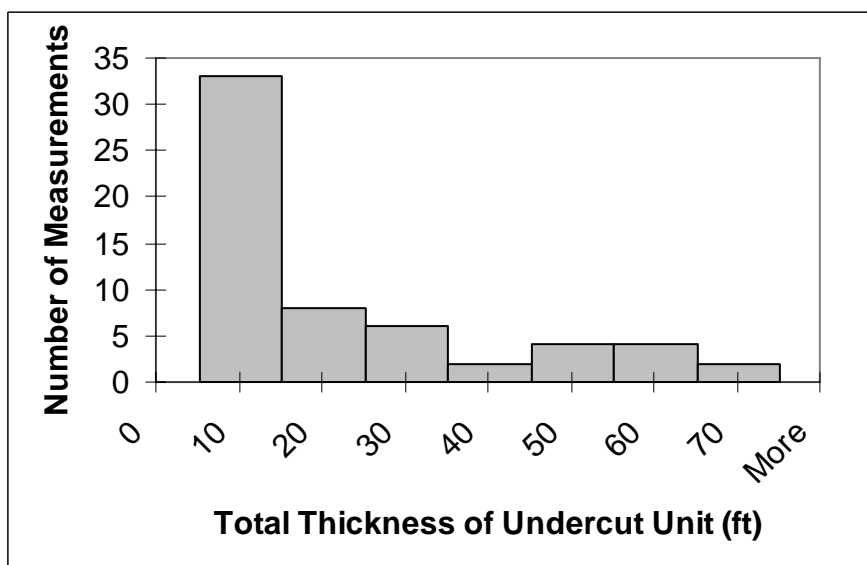
Figure 15C-2: Frequency histogram for non-transformed total thickness of undercut rock unit.
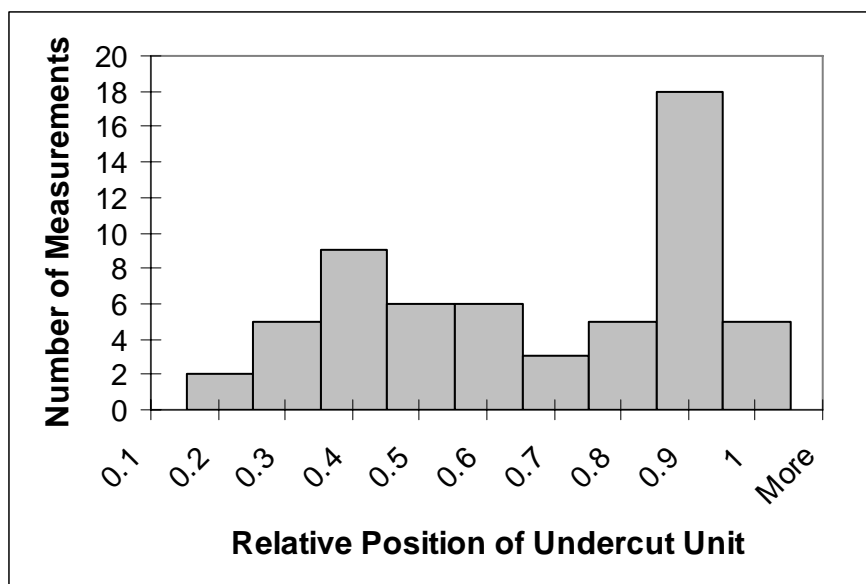
Figure 15C-3: Frequency histogram for non-transformed relative position of undercut rock unit from slope crest.
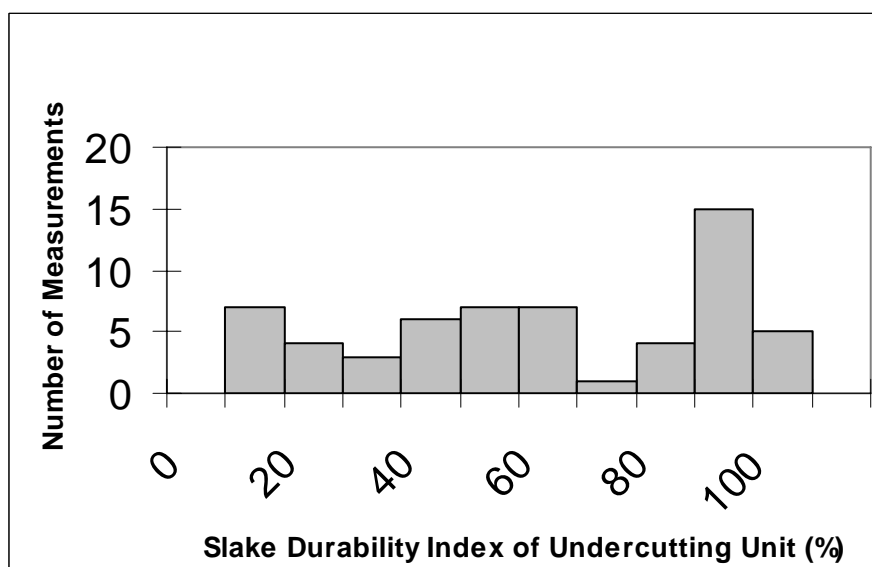
Figure 15C-4: Frequency histogram for non-transformed slake durability index of undercutting rock unit.
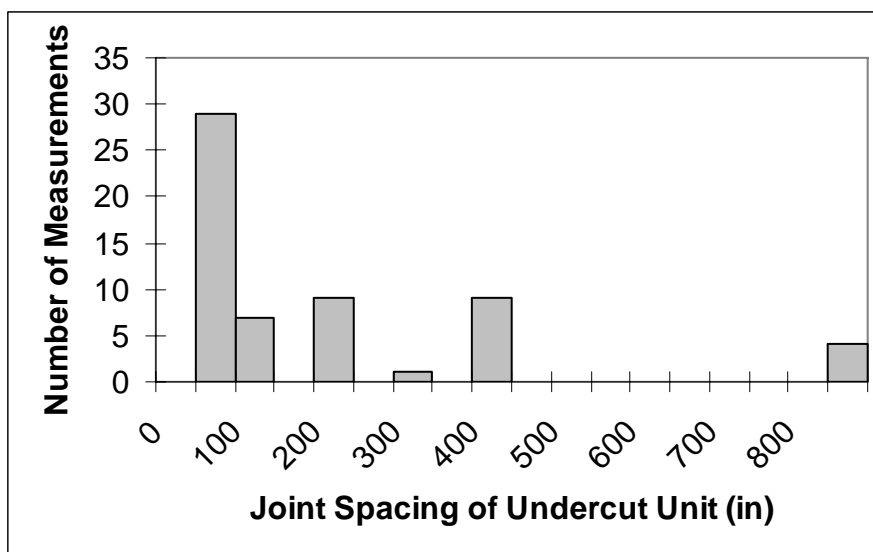
Figure 15C-5: Frequency histogram for non-transformed joint spacing of undercut rock unit.
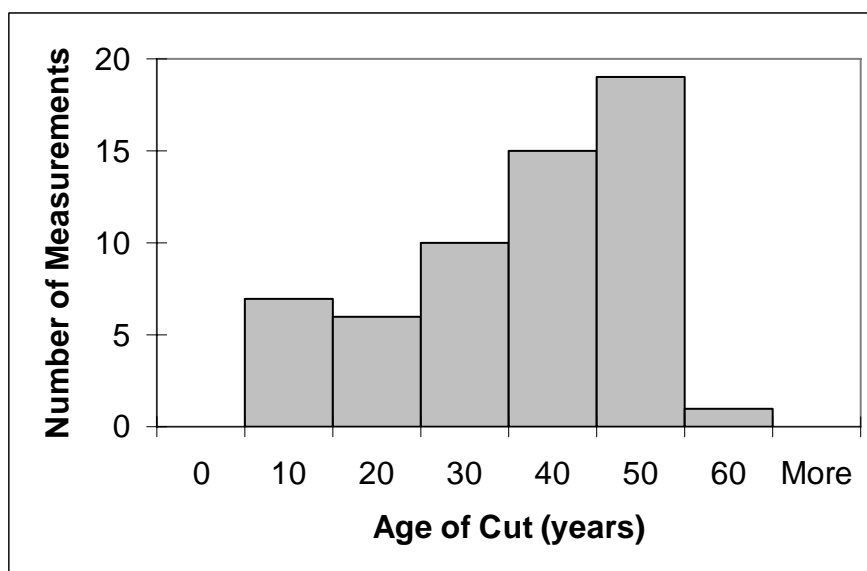
Figure 15C-6: Frequency histogram for non-transformed age of slope cut.
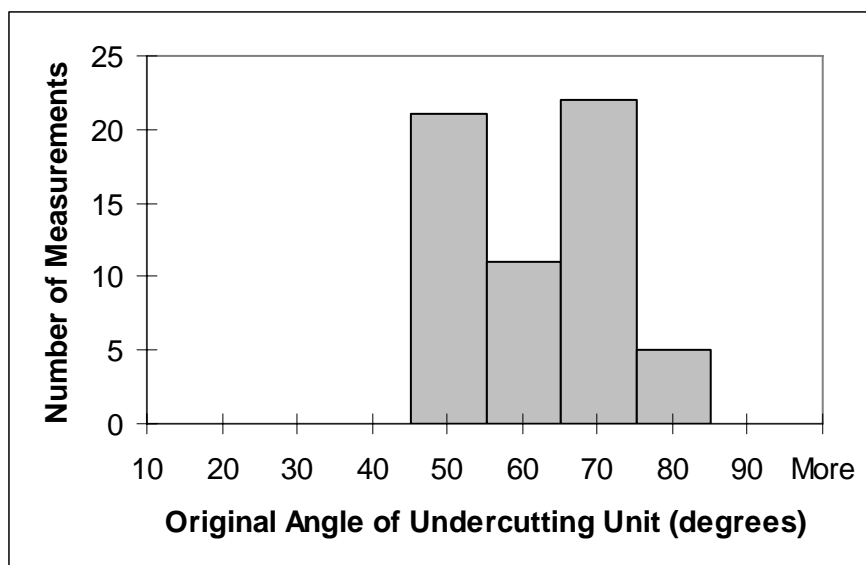
Figure 15C -7: Frequency histogram for non-transformed original slope angle of undercutting rock unit.
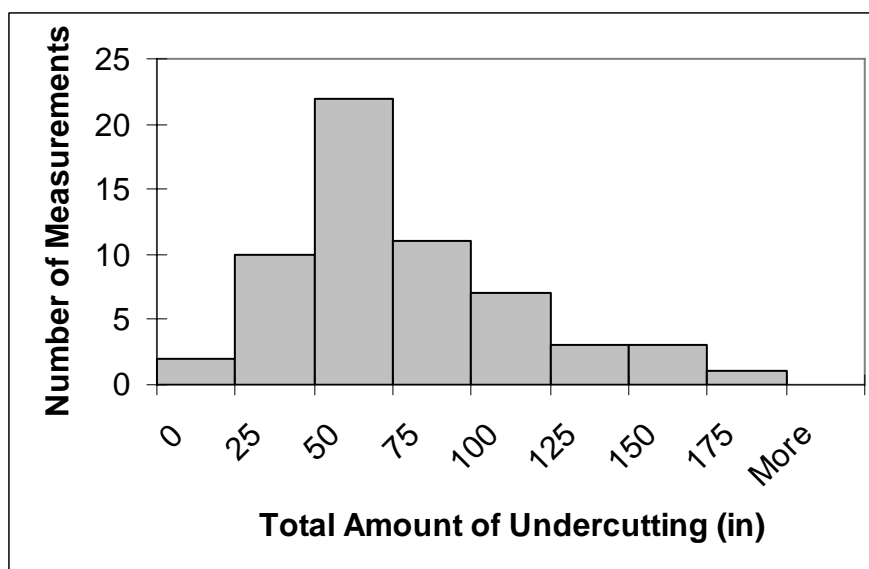
Figure 15C-8: Frequency histogram for non-transformed total amount of undercutting.
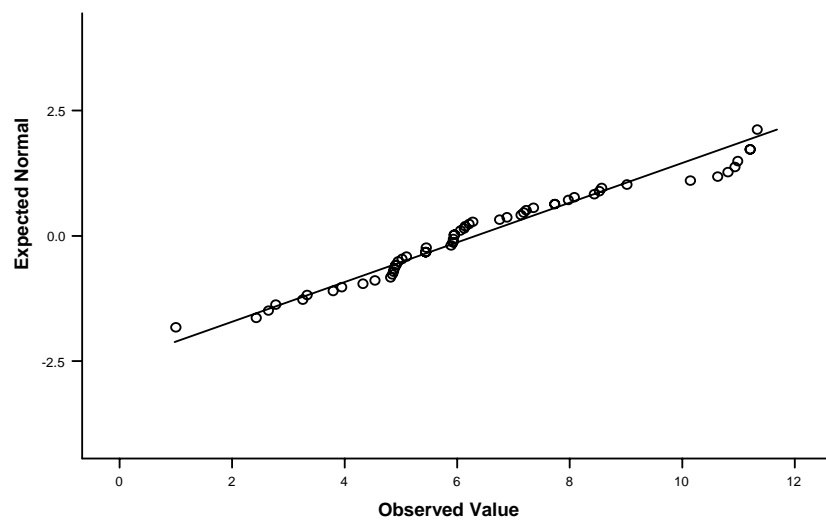
Figure 15C-9: Q-Q plot of distance of the undercut unit from the slope crest (adjusted SQRT).
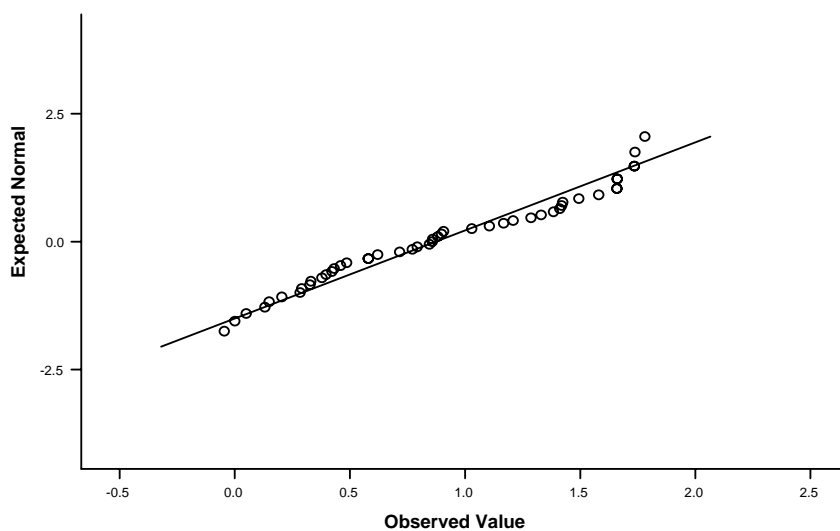
Figure 15C-10: Q-Q plot of total thickness of the undercut unit (log).
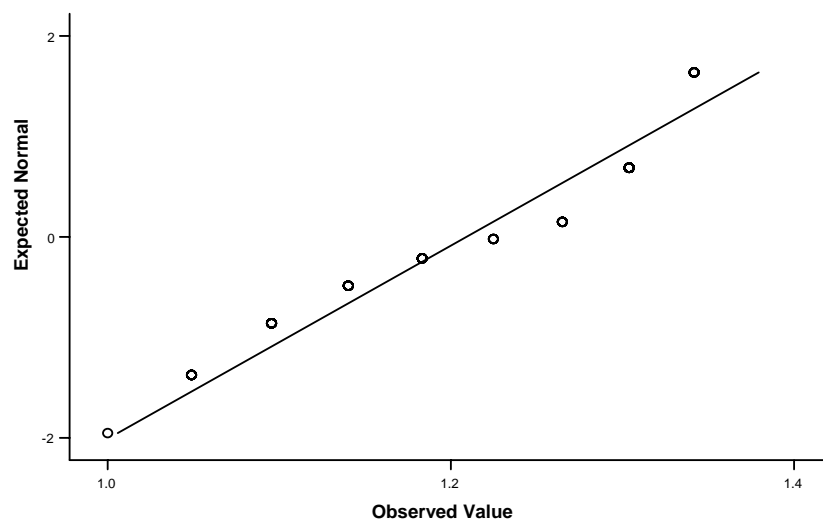
Figure 15C-11: Q-Q plot of relative position of the undercut unit from the slope crest (adjusted SQRT).
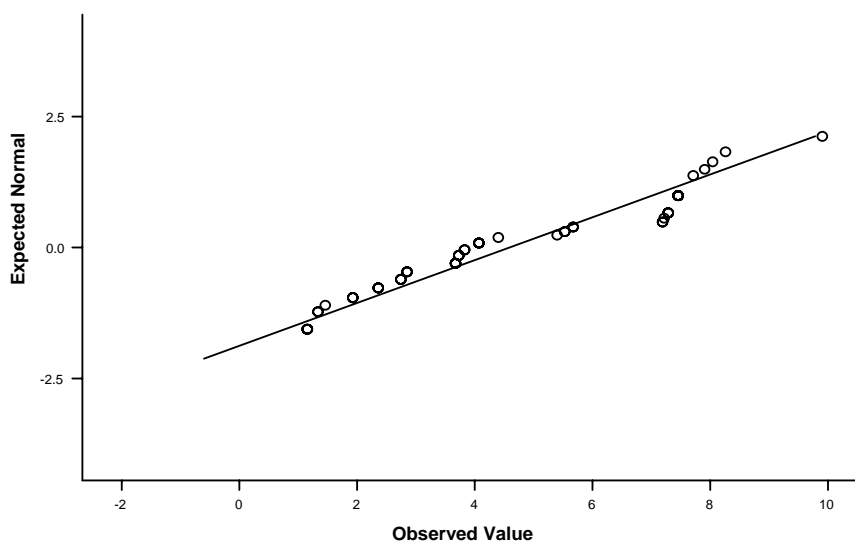
Figure 15C-12: Q-Q plot of slake durability index of the undercutting unit (reflected adjusted SQRT).
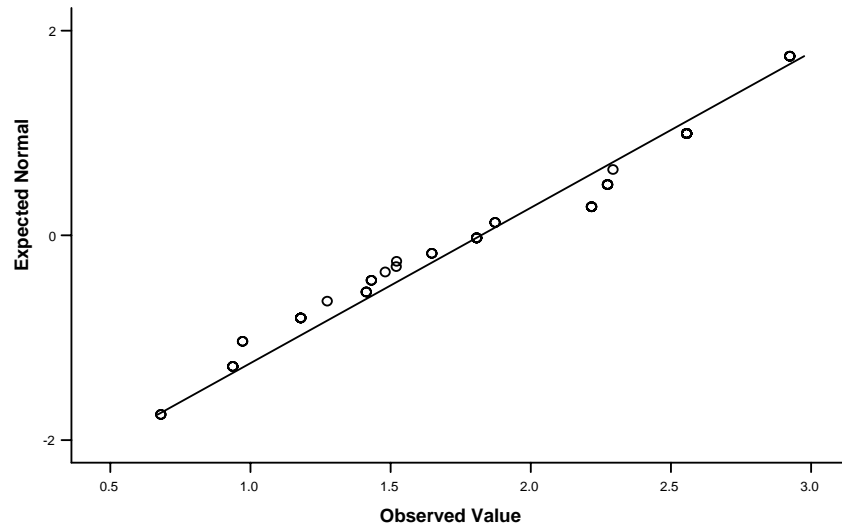
Figure 15C-13: Q-Q plot of spacing of orthogonal joints within the undercut unit (log).
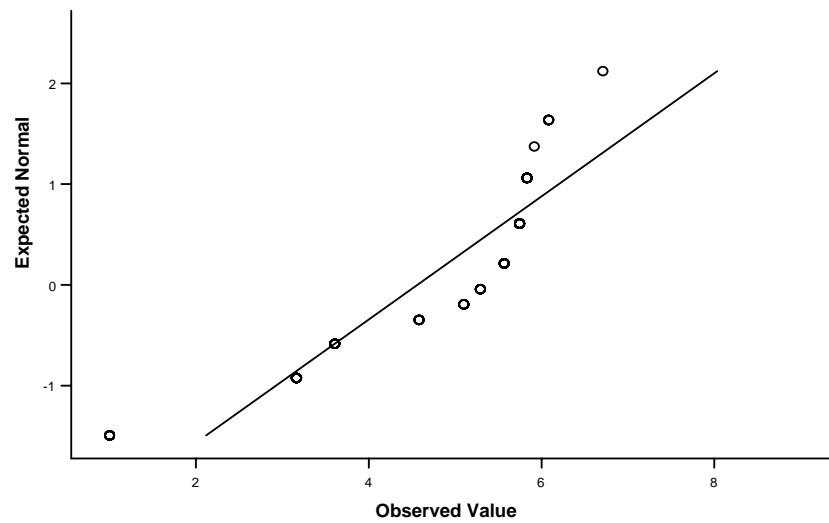
Figure 15C-14: Q-Q plot of spacing of age of road cut (adjusted SQRT).
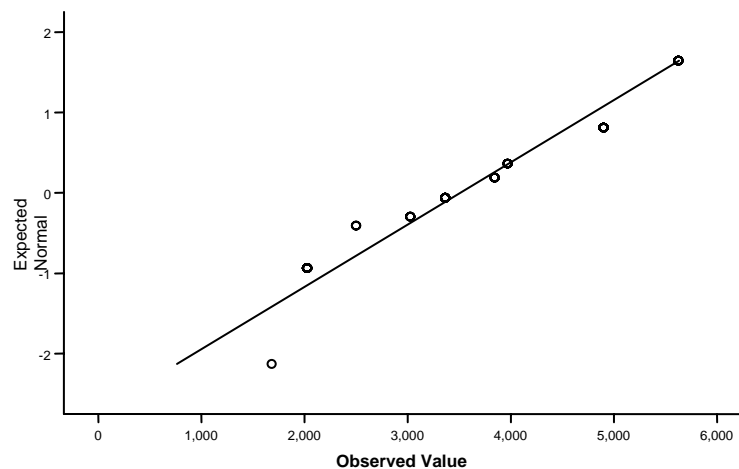
Figure 15C-15: Q-Q plot of original slope angle of the undercutting unit (squared).
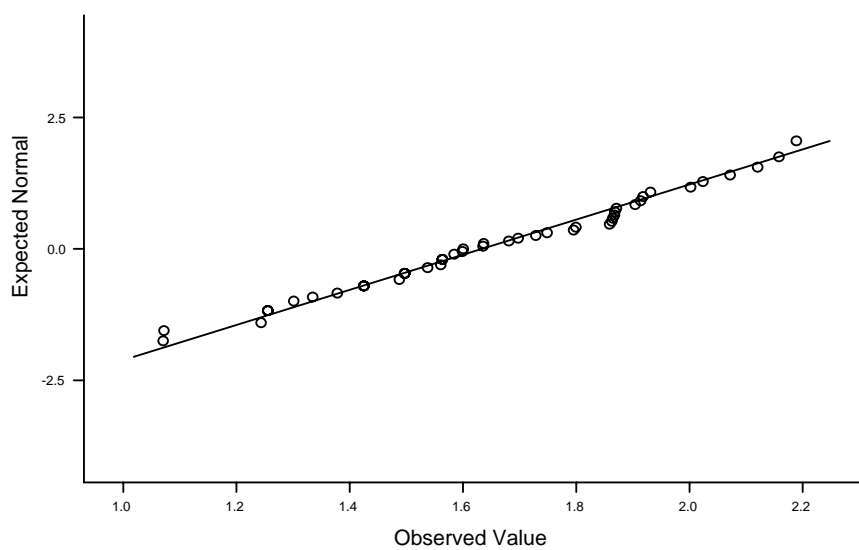
Figure 15C-16: Q-Q plot of total amount of undercutting (log).
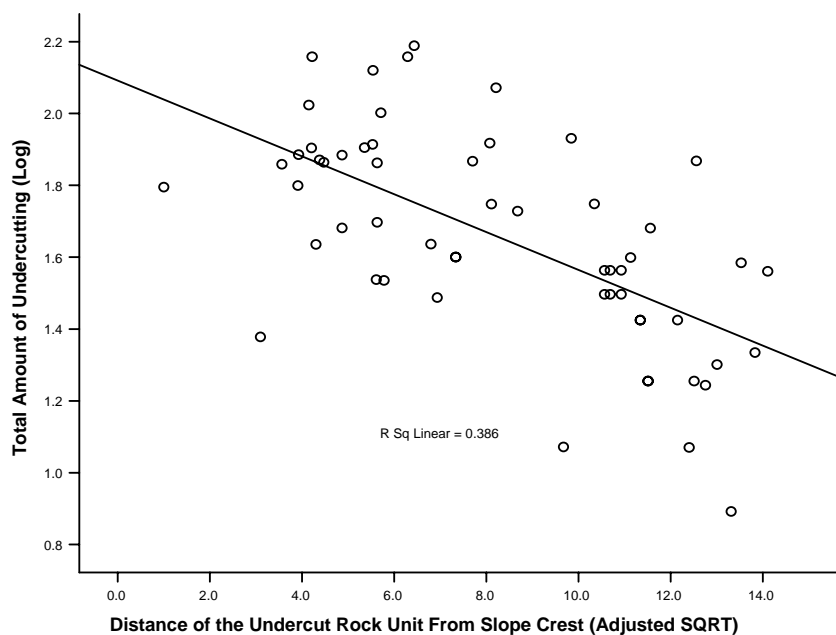
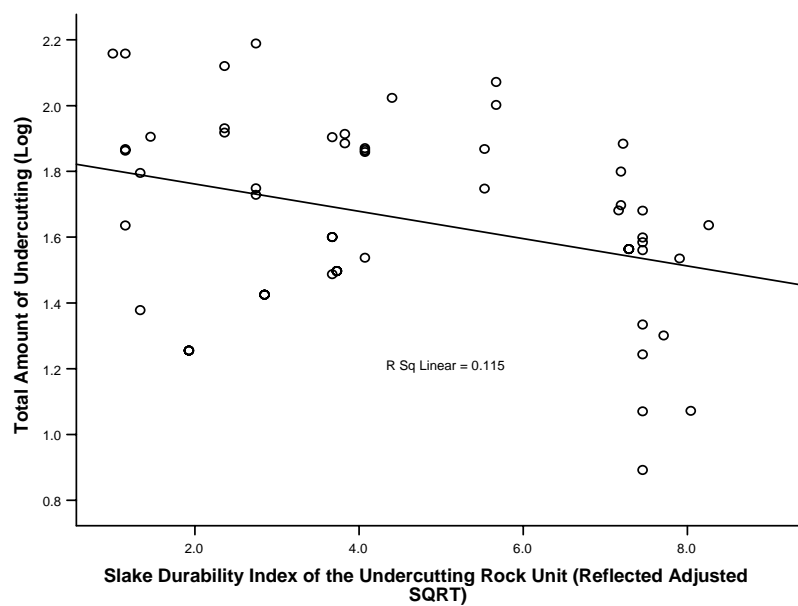Figure 15C-17: Scatter plot for total amount of undercutting and distance of the undercut rock unit from slope crest.
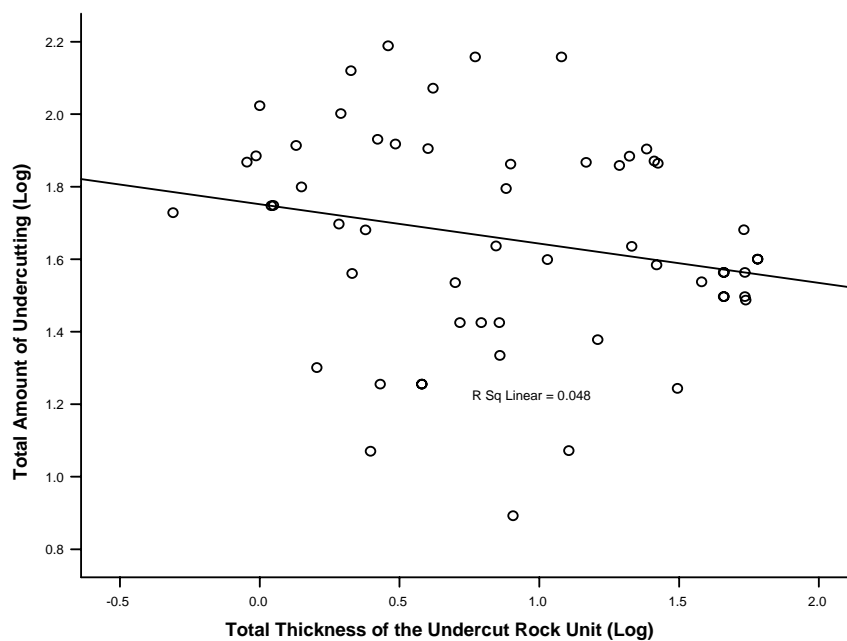
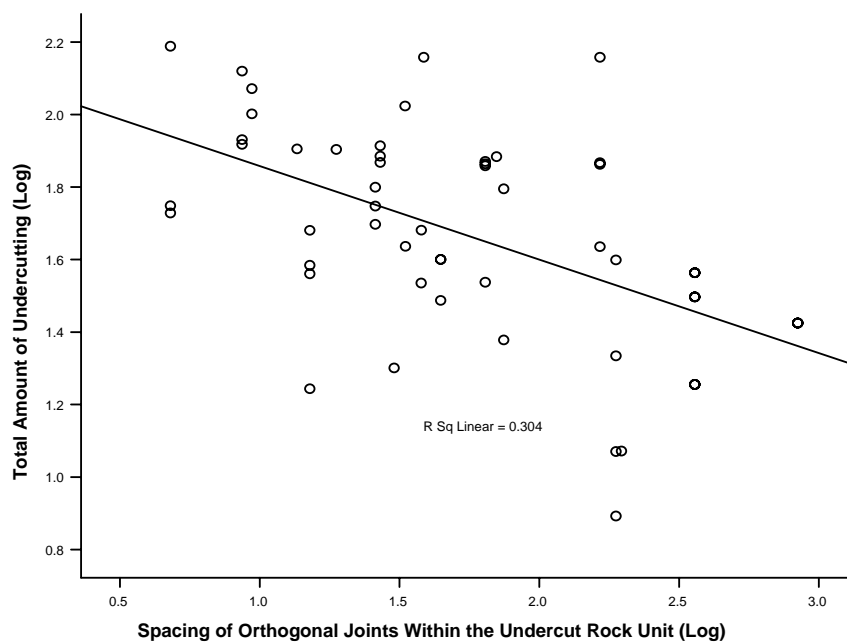Figure 15C-18: Scatter plot for total amount of undercutting and total thickness of the undercut rock unit.
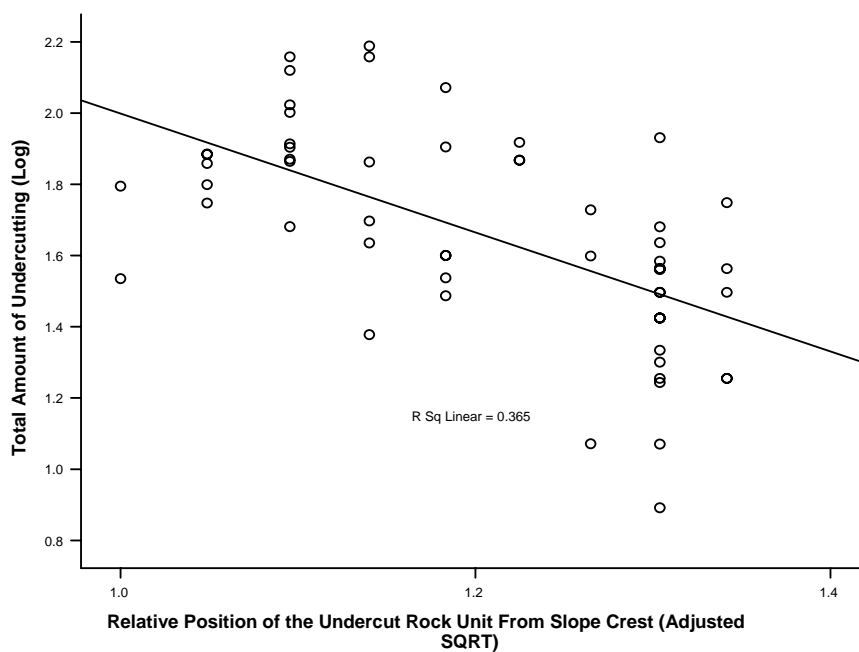
Figure 15C-19: Scatter plot for total amount of undercutting and relative position of the undercut rock unit from slope crest.

Figure 15C-20: Scatter plot for total amount of undercutting and slake durability index of the undercutting rock unit.

Figure 15C-21: Scatter plot for total amount of undercutting and spacing of orthogonal joints within the undercut rock unit.
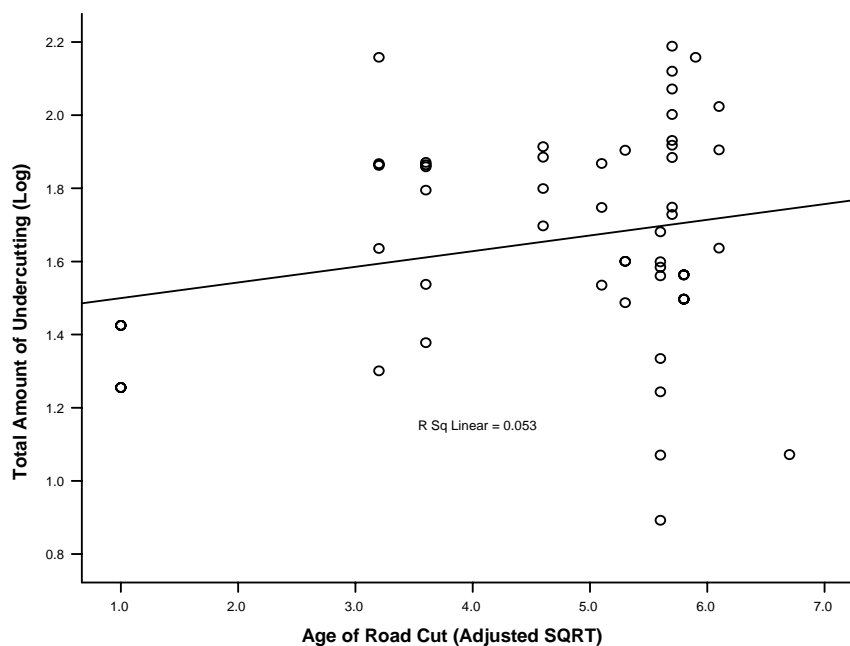

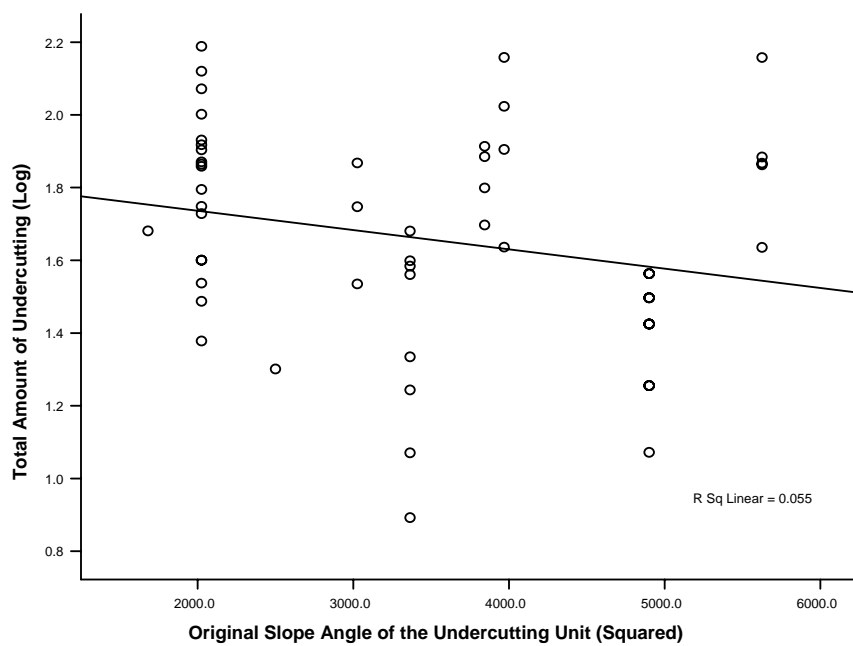Figure 15C-22: Scatter plot for total amount of undercutting and age of road cut.

Figure 15C-23: Scatter plot for total amount of undercutting and original slope angle of the undercutting rock unit.

APPENDIX 16

ODOT ROCK SLOPE DESIGN MANUAL