Evaluation of Guidelines for Subgrade Treatments

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16. Abstract

ODOT has recently developed guidelines for subgrade treatments to be used during plan development and construction. This study evaluates these guidelines by comparing them with existing guidelines developed elsewhere and validating them through comparison of the actual treatment methods and quantities used with those suggested by the guidelines. Soil boring data and construction record from 7 reconstruction and 2 new construction projects were obtained. Actual treatment methods and quantities were obtained from the project field offices. Dynaflect deflection data, when available, were analyzed to determine their usefulness in subsurface assessments. GB1 criteria for excess moisture content predicted the undercut quantity reasonable well, but the criteria for acceptable moisture content tend to under predict the undercut quantity in many cases, likely due to increased soil moisture content after removal of existing pavement. For reconstruction projects, the average undercut depths (i.e., the overall undercut quantities) versus the corresponding SPT N_L values seem to fall reasonably well within the upper bound provided in the Section 204 guidelines. However, the actual undercut depths vary significantly even for soils with similar or same N_L values. Actual undercut depth and quantity are somewhat correlated with the average SPT N_L value, Dynaflect W5 deflection, and soil moisture content. The regression equation developed has a coefficient of determination (or R-square value) as high as 0.71.

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Problem

Wet, unstable subgrade soil conditions are often encountered during new or reconstruction projects. The problems are often unidentified during plan development stage. Once the existing pavement is removed, the unstable subgrade must be modified or replaced to provide an acceptable surface for pavement construction. This often results in change orders for the additional work, causing significant cost overruns.

ODOT has recently developed guidelines for subgrade treatments to be used during plan development and construction. This study evaluates these guidelines by comparing them with existing guidelines developed elsewhere and validating them through comparison of the actual treatment methods and quantities used with those suggested by the guidelines.

Objectives

1. To evaluate the existing Guidelines for Plan Subgrade Treatments (GB1) and Subgrade Construction and Stabilization Guidelines (Section 204) by comparing them with existing guidelines used by other agencies.
2. To validate the guidelines by comparing actual and suggested treatment methods and quantities.
3. To recommend any improvements to the existing Guidelines.

4. To reduce the cost overrun caused by unanticipated subgrade treatment needs during construction.

Description of the Research

GB1 is used during design and Section 204 is used during construction. Both guidelines uses data from soil borings, particularly the Standard Penetration Test (SPT) blow count, N_L, to estimate the undercut location and quantity. Section 204 can utilize additional proof rolling and test pit data to determine the subgrade treatment method. Criteria for reconstruction and new construction projects are different. Subgrade investigation and treatment guidelines from other agencies were reviewed and compared with the current ODOT guidelines. Soil boring data and construction record from 7 reconstruction (major rehabilitation) and 2 new construction projects were obtained. Actual treatment methods and quantities were obtained from the project field offices. Dynaflect deflection data, when available, were analyzed to determine their usefulness in subsurface assessments.

Findings

Soil boring and subgrade treatment guidelines from other agencies are not significantly different from the current ODOT guidelines in terms of boring depth, locations, spacing, and other field and laboratory testing required. GB1 criteria for excess moisture content predicted the undercut quantity reasonably well, but the criteria for acceptable moisture content tend to under predict the undercut quantity in many cases, likely due to increased soil moisture content after removal of existing pavement. For reconstruction projects, the average undercut depths (i.e., the overall undercut quantities) versus the corresponding SPT N_L values seem to fall reasonably well within the upper bound provided in the Section 204 guidelines. However, the actual undercut depths vary significantly even for soils with similar or same N_L values. Actual undercut depth and quantity are somewhat correlated with the average SPT N_L value, Dynaflect W5 deflection, and soil moisture content. The regression equation developed has a coefficient of determination (or R-square value) as high as 0.71. A cost analysis shows the break point for complete stabilization is 30% undercut for reconstruction projects and 70% undercut for new construction projects. The cost of deflection testing is insignificant.

Conclusions & Recommendations

Subgrade soils are highly variable. Using point specific data from soil borings to predict the exact location of undercut is difficult. Dynaflect deflection, W5, is as good a predictor as SPT N_L in estimating soil undercut and can be performed at much closer spacing; therefore, it should be included in the GB1 guidelines for reconstruction projects. All the reconstruction projects studied have more than 30% undercut and both new construction projects have more than 70% undercut. Therefore, complete chemical stabilization should be considered for all new or reconstruction projects, unless boring or deflection data show very strong subgrade.

Implementation Potential

The results of this study can be implemented by ODOT without significant increases in cost or staff commitment.

INTRODUCTION

Wet, unstable subgrade soil conditions are often encountered during new or reconstruction projects, however the problems are often unidentified during plan development stage. Once the existing pavement is removed, the unstable subgrade must be modified or replaced to provide an acceptable surface for pavement construction. This often results in change orders for the additional work, causing significant cost overruns.

ODOT has recently developed guidelines for subgrade treatments to be used during plan development and construction. This study evaluates these guidelines by first comparing them with existing guidelines developed elsewhere. Secondly, using available design geotechnical data, the actual treatment methods and quantities used are compared with those suggested by the guidelines.

This study also evaluates the costs and benefits of various methods of subsurface investigation and subgrade treatment techniques. The final recommendations include considerations on the cost effectiveness of various subsurface investigation and subgrade treatments methods.

Background

The two subgrade treatment guidelines that are the focus of this study are:

1. *Interim Guidelines for Plan Subgrade Treatments* (dated November 1, 2001), which was subsequently updated and renamed *Geotechnical Bulletin GB1 on Plan Subgrad*es (July 11, 2003, updated July 14, 2004). This is referred to as GB1 for abbreviation.
2. *Subgrade Construction and Stabilization Guidelines* (dated April 18, 2002), which was subsequently renamed as Section 204 *Subgrade Compaction and Proof Rolling* in the *Construction Inspection Manual of Procedures* (2002). This is referred to as Section 204 for abbreviation.

The two guidelines are similar in the way subgrade treatments are determined. GB1 is intended to be used by the designer to apply the information from the subsurface exploration to determine reasonable limits and quantities of subgrade stabilization in the plan. Section 204 is meant to be used by construction field personnel to evaluate subgrade conditions primarily through proof rolling and to determine the appropriate subgrade treatment if necessary. The three subgrade treatment methods currently used by ODOT are: (1) soil undercutting and replacement, (2) lime stabilization, and (3) cement stabilization.

GB1 uses the following information from soil boring and subsequent laboratory testing to design subgrade treatment:

1. Average N_L (blow counts) from the standard penetration test (SPT).
2. Average Plasticity Index (PI).
3. Average moisture content (MC).

The standard penetration test measures the number blows (N) per foot required to drive the sampler through the soil and is an indicator of the soil's consistency and stiffness. The data are presented as number of blows required to penetrate each six-inch (150 mm) increment. The first six inches of the run is ignored, because the sampler may not be seated properly in the borehole or may be driven through disturbed soils. For example, SPT data shown as 1/2/3 has an N value of 5 blows per foot.

At each boring location, the lowest N value recorded within the top 5.0 feet (182 cm) of the proposed subgrade is denoted as $N_{L.}$ The average N_L value along a segment of the project that is considered relatively uniform is calculated. When N_L is greater than 30 blows per foot, a maximum N_L value of 30 is used when calculating the average.

Figure 1 shows an example of calculating N_L. In the figure, 'N_L' for the boring is the minimum of {14, 23, 17} = 14.

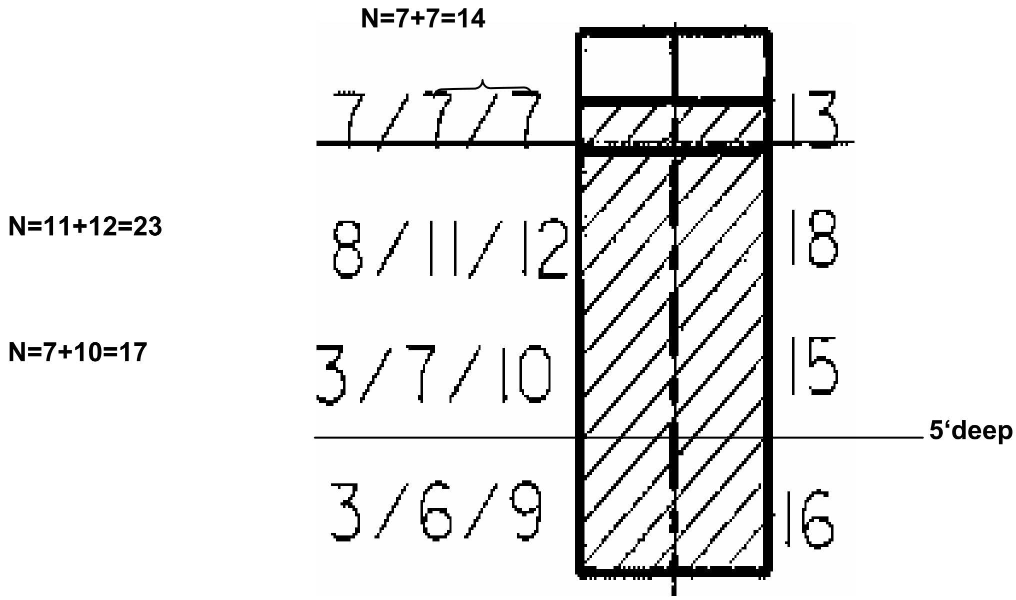


Figure 1. Definition of N_L

Figure 2 is obtained by plotting the subgrade treatment recommendations presented in Table B of GB1. The average NL value along the whole project or segments of the project with similar soil characteristics is used to estimate undercut depth.

Section 204 uses the following data to determine the appropriate corrective treatment action:

1. Soil boring information (particularly N_L)
2. Rut depth from proof rolling
3. Test pit data, which include soil type, layer thickness, observed condition, and unconfined compressive strength (UCS) estimated from a hand-held penetrometer.

Figure 3 shows the subgrade treatment chart included in Section 204. This chart summarizes the subgrade treatment recommended by the guideline. As shown in the chart, recommended undercut or stabilization depth can be determined from either unconfined compressive strength in ton/ft^2, SPT blow count (N value), or proof rolling rut depth in inches. For new construction projects, more time is available for the subgrade soils to be drained or otherwise dried through evaporation, therefore, the recommended undercut depth is smaller for reconstruction projects or projects with heavy hauling.

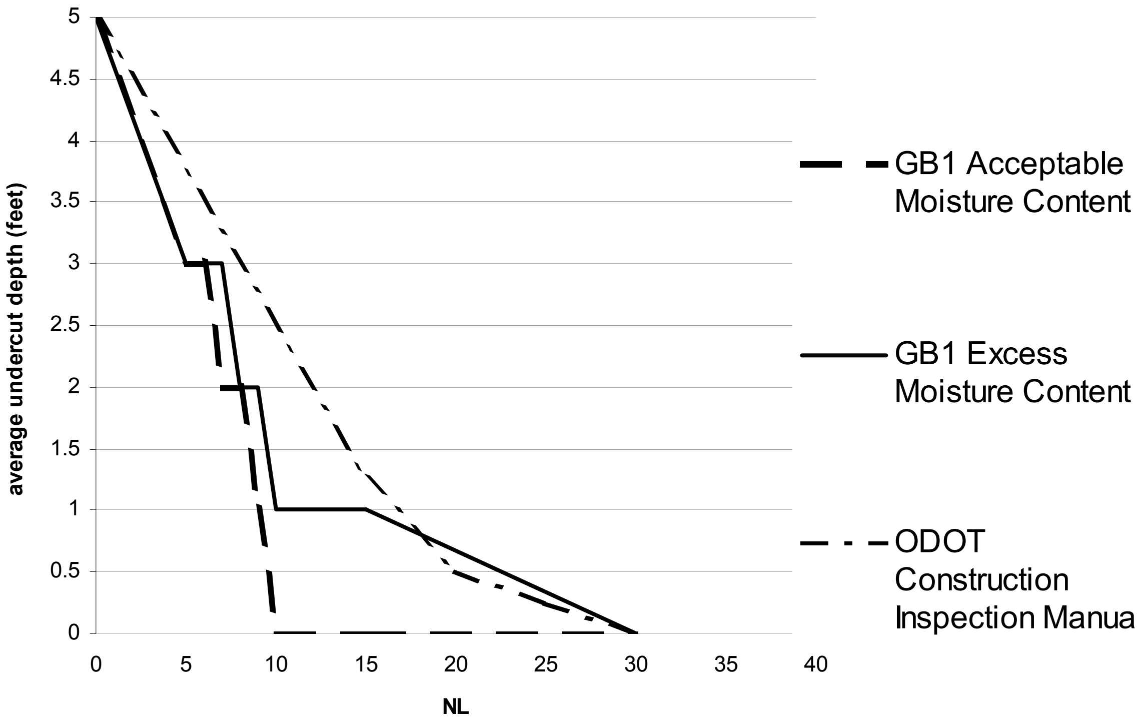


Figure 2. Undercut Depth Estimation (from Geotechnical Bulletin GB1 on Subgrades)

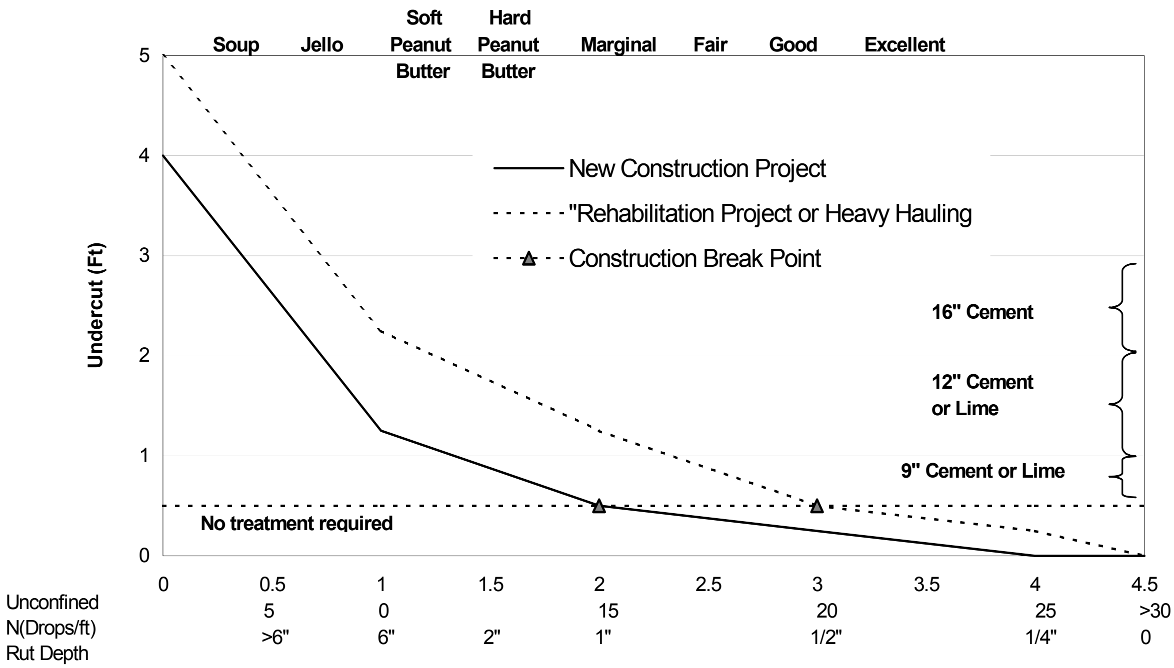


Figure 3. Subgrade Treatment Chart (from Section 204 of the Construction Inspection Manual of Procedures)

Identifying unstable subgrade conditions and the required remedial actions during design and construction is highly important to pavement engineers in reducing the overall cost of new pavement construction or major reconstruction projects. Because subgrade soil conditions are highly variable, there is no universal solution that can economically address all subgrade conditions to provide a satisfactory surface for pavement construction.

Many states, including Kentucky, Illinois, Minnesota, and others, have developed or are in the process of developing subsurface investigation and subgrade treatment guidelines. These and other existing guidelines have been reviewed and compared with ODOT's guidelines. New techniques, such as non-destructive testing methods may be used in conjunction with more traditional testing methods such as boring to help identify weak subgrade conditions under existing pavements.

The Mechanistic-Empirical (M-E) Pavement Design Guide proposed by NCHRP project 1-37A provides some guidelines and recommendations for characterizing pavement foundations, subsurface explorations, and foundation improvements and strengthening. The main purpose of these guidelines is to help evaluate the subgrade conditions in sufficient detail in order to develop economical and constructible treatment plans aimed at achieving an adequate foundation to build the pavement structure. Four critical subsurface conditions are addressed by the Guide, namely: a) collapsible or highly compressible soils, b) expansive or swelling soils, c) subsurface water flow and saturated soils, and d) frost susceptible soils. The Guide discusses in detail:

- The effect of these conditions on the design, construction and pavement performance
- Methods to identify these conditions in the soil
- Recommendations to treat the encountered soil condition

The treatment recommendations address issues such as the selection of borrow materials that can replace problem-soils, thickness of borrow materials, increase in structural layer thickness to account for strength reduction of subgrade material existing in undesirable conditions, and appropriate methods to improve subgrade strength.

The M-E Design Guide also recommends techniques to improve the strength and reduce the climatic variation of the foundation on pavement performance. The techniques discussed are classified as stabilization of weak soils, use of thick granular layers, use of subsurface drainage systems, and use of geotextiles. The Guide lays out the soil conditions under which each of these strengthening methods can be incorporated and their associated benefits. The most suitable strengthening technique depends on the soil classification, composition, soil chemistry, strength, plasticity, amount of fines, permeability, frost heave-susceptibility, etc. In addition, the consideration of the overall pavement design plays an important role in the selection of a suitable treatment.

OBJECTIVE OF THE RESEARCH

Objective of the Study:

The objectives of the proposed study are:

1. To evaluate the existing Interim Guidelines for Plan Subgrade Treatments (now Geotechnical Bulletin GB1 on Plan Subgrades) and Subgrade Construction and Stabilization Guidelines (now Section 204 of the Construction Inspection Manual of Procedures) and comparing them with existing guidelines used by other agencies.
2. To validate the guidelines by comparing actual and suggested treatment methods and quantities.
3. To recommend any improvements to the existing Guidelines for Subgrade Treatment and Specifications for Subsurface Investigations.
4. To reduce the cost overrun caused by unanticipated subgrade treatment needs during construction.

GENERAL DESCRIPTION OF RESEARCH

The research study was divided into the following tasks.

Task 1. Review of Existing Guidelines

Subgrade investigation and treatment guidelines from other agencies, including the NCHRP project 1-37A on Mechanistic-Empirical Pavement Design Guide, Illinois DOT, Pennsylvania Turnpike, Pennsylvania DOT, Michigan DOT, Kentucky DOT, Indiana DOT, Wisconsin DOT, and Minnesota DOT were reviewed when available. Telephone interviews were part of the efforts to obtain summary information. Comparison with the current ODOT guidelines were made. This task was performed with the assistance of the subcontractor, ERES Consultants, Inc. of Champaign, Illinois.

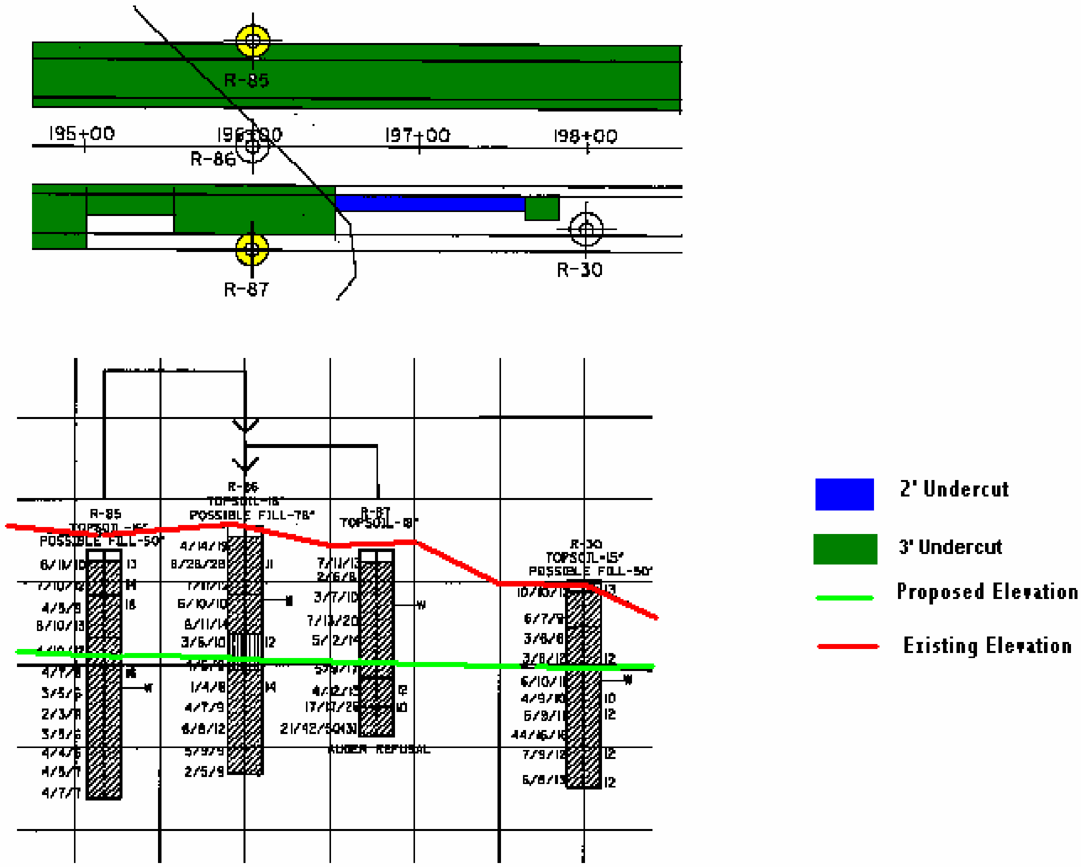
Task 2. Comparison of Field Results

With the assistance of ODOT engineers, geotechnical investigation data and construction records for 7 reconstruction (major rehabilitation) and 2 new construction projects were obtained. Table 1 shows a summary of these projects. Additional projects were initially considered, but some projects did not have sufficient amount of SPT data, and others did not have actual undercut data available in time to be included in the analysis. In the end, those projects listed in Table 1 were analyzed in detail. Boring locations, depth, soil testing data such as classification, moisture content, PI, and SPT blow counts (N values) were obtained from the plans. Actual subgrade treatment methods and quantities were obtained from the project field offices. Dynaflect deflection data were available for some projects and those were analyzed to determine their usefulness in subsurface assessments. Figure 4 shows a typical section where locations and depths of undercut are summarized along with boring locations. Undercuts are often not performed across the entire pavement width, but on spot locations. Therefore, average undercut depth across the entire pavement area is subsequently used to represent the undercut quantity. All data were entered into a master spreadsheet for analysis.

Table 1. Summary of Undercut Projects Investigated

Project ID	District	Unit	Length (ft)	No. of Useful Borings	No. of SPT	No. of W5 Data Available	New or Rehab
Fairfield US33-7.28	5	ft	31,364	86	86	0	Rehab
Franklin I70-14.49	6	ft	54,500	112	112	102	Rehab
Fayette US62-13.67	6	ft	6,400	12	12	0	Rehab
Lucas SR2 21.15	2	ft	31,500	72	72	0	Rehab
Lucas I280-1.64	2	ft	2,500	8	0	8	Rehab
Lucas I280-4.64	2	ft	4,200	17	17	0	Rehab
Medina I71-5.78	3	ft	56,140	136	136	122	Rehab
Jackson US32-27.63	9	m	900	2	2	0	New
Ross US35-25.17	9	ft	50,000	64	64	0	New

(1 foot = 0.30 meters)



(1 foot = 0.30 meters)

Figure 4. Typical Undercut Data Gathered

Evaluation of a Test Procedure or Parameter

Prior to construction, engineers must rely on soil borings to obtain estimation of underlying soil characteristics. Boring data are point data and therefore do not provide the complete picture of subsurface soil conditions. Soil information obtained from the borings such as soil classification, moisture content, SPT N_L value provide, in varying degree, estimation of the stiffness of the soils underneath and whether or not the subgrade soil must be replaced (undercut) or stabilized in order to provide adequate support for the pavement structure and carrying the construction and in-service traffic. Nondestructive deflection measurements using Dynaflect or Falling Weight Deflectometer (FWD) are also point data, but can be performed at much closer spacing than soil borings and are relatively inexpensive to perform. However, they are typically only used on reconstruction projects since the test requires a flat and smooth surface area, which is often not encountered for new projects during design stages.

The high variability of soils and the high sensitivity of fine grained soils to moisture content makes it difficult to accurately predict the undercut quantity and location during the design stage. The existing guidelines are developed based on empirical experience and this study attempts to evaluate the accuracy of these guidelines.

The Receiver's Operating Characteristic Curve (ROC Curve) method is used in this study as a way to evaluate a given parameter or procedure in their ability to predict the actual condition. ROC curve method was developed in the 1950's as a by-product of research into deciphering radio signals contaminated by noise. ROC Curve analysis has frequently been used in the medical field to determine the ability of a particular test in identifying the actual situations.

The ROC curve method determines the optimal threshold of a given diagnostic test. The ROC curve displays the relationship between the True Positive Rate (TPR) to the False Positive Rate (FPR), across all the possible threshold values that define the possibility of a condition. The trade-offs between TPR and FPR is calculated for each threshold level. A curve is generated between the various True Positive Rates and False Positive Rates to determine the optimal threshold value. The optimal threshold is often determined by finding the threshold that yields the maximum value of: True Positive Rate + (1 − False Positive Rate).

Figure 5 below shows the ROC curves of two different tests. Test B is a slightly better test than test A because the area under test B's ROC curve is larger than the area under test A's.

Perfect Test: A perfect test has an area under the ROC curve equal to 1.0, and has the True Positive Rate of 100% and the False Positive Rate of 0%, which is the best possible scenario.

50-50 Test: A 50-50 (coin toss) test is a test with its ROC curve overlapping the diagonal line. The area under the ROC curve is 0.5, which is the worst possible condition. Essentially, the test is equivalent to a coin toss.

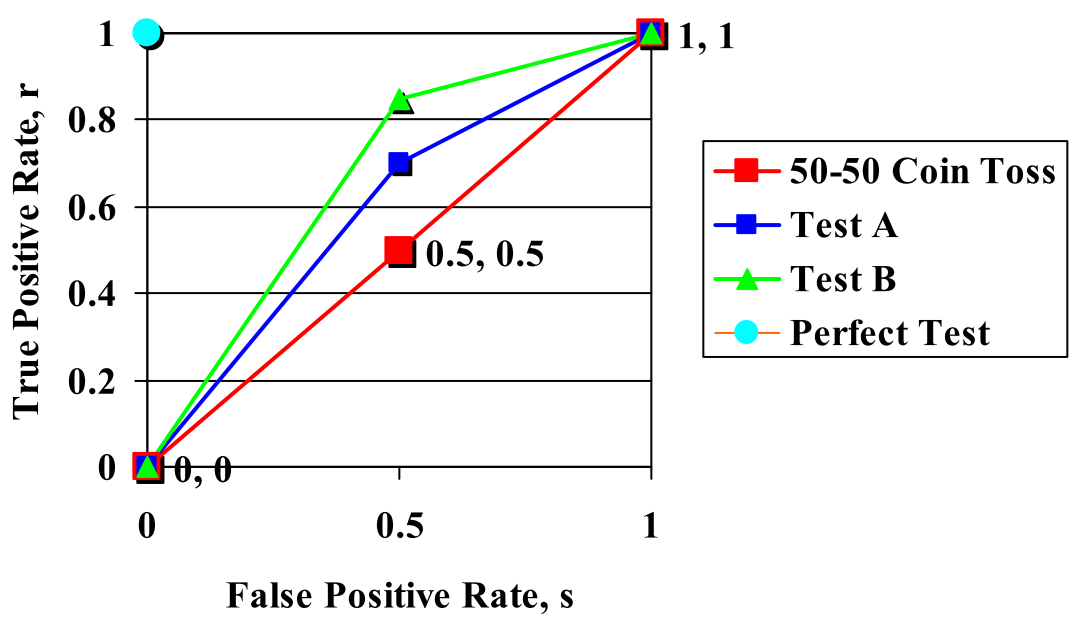


Figure 5. ROC Curves of Different Hypothetical Tests

To illustrate the ROC curve, the following is a numerical example:

A project has one hundred borings. Based on a certain criteria, (i.e. $N_L < 10$), 60 of the boring locations are predicted to require undercut. In the end, 75 boring locations actually require undercut, with 50 of the 75 being originally among the 60 predicted to require undercut. Another 25 boring locations predicted to require no undercut actually need undercut. Table 2 summarizes the calculation.

Table 2. Summary of ROC Calculations

Total of 100 borings	75 boring location actually undercut (True)	25 boring locations no undercut (False)
60 out of 100 predicted to require undercut (positive)	50 of the 60 predicted positive ones actually require undercut: True Positive Rate = 50/75 = 0.67	10 of the 60 predicted positive ones require no undercut: False Positive Rate = 10/25 = 0.40
40 out of 100 predicted to require no undercut (negative)	25 out of the 40 predicted negative ones require undercut 25/75 = 0.33	15 out the 40 predicted negative ones require no undercut 15/25 = 0.60

A good test or a good predicator is such that the true positive rate is high, while the false positive rate is low. In other words, when the actual result is known, the ones that actually require undercut should be all predicted to require undercut. On the other hand, those that do not require undercut should have none predicted to require undercut.

If the threshold value for predicting undercut is set differently, say $N_L < 30$. Then likely all boring would be predicted to require undercut (since the maximum N_L value is assumed to be 30), and no boring would be predicted to require no undercut. The True Positive Rate would be 1.0 (= 75/75), but the False Positive Rate would also increase to 1.0 (25/25).

The other extreme would be the threshold for predicting undercut being set very low (say, $N_L < 1$). Thus most of the prediction would have been no undercut, resulting in a low True

Positive Rate (TPR) and a low False Positive Rate (FPR). Therefore, by selecting different threshold values, different pairs of (TPR, FPR) can be computed. The optimal threshold of the parameter can be determined by finding the (TPR, FPR) values that yield the highest [TPR + (1 − FPR)]. Figure 6 illustrates the ROC curve for the example problem.

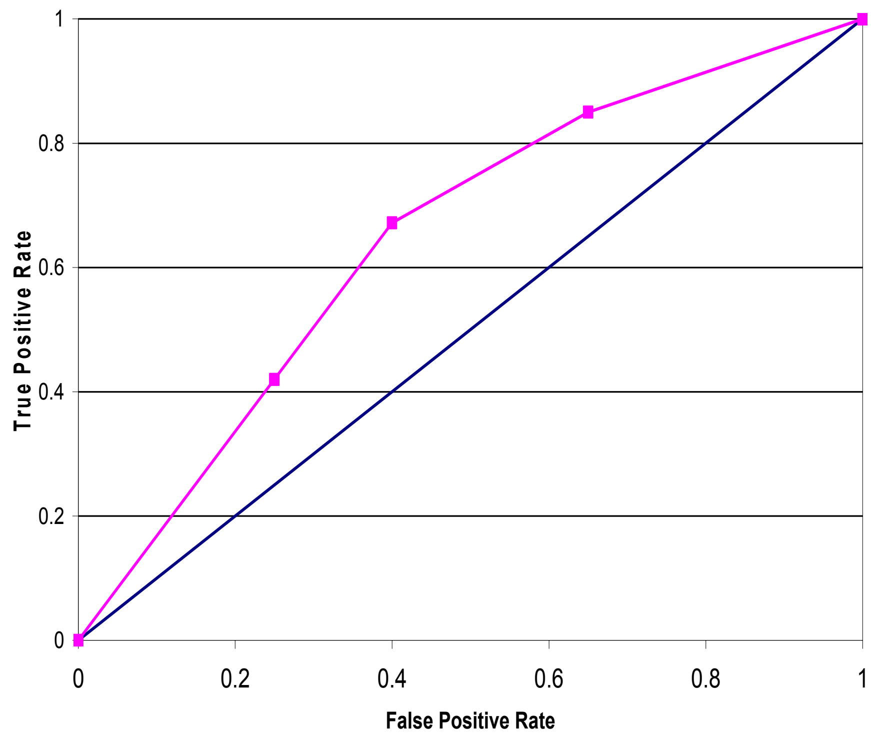


Figure 6. ROC Curve of the Numerical Example

Task 3. Cost-Benefit Analysis

Based on cost data of soil boring, deflection testing, undercutting, and lime or cement stabilization, a comparison of the cost of obtaining additional data versus that of inaccurate estimation is made. Subsurface investigation costs are relatively small compared with the subgrade treatment costs. If additional investigation helps to reduce change orders, or results in an overall less expensive treatment method, then the additional expenses on investigation would be worthwhile. From such cost-benefit analysis, recommendations on the methods of investigation before and during construction, frequency of boring or deflection testing, and the most cost-effective subgrade treatment strategy are made.

FINDINGS OF THE RESEARCH EFFORT

The findings of this study are reported in this section. They include:

Task 1. Review of Existing Guidelines

Given below is a summary of guidelines recommended by the Mechanistic Empirical Pavement Design Guide (M-E Design Guide) developed under project NCHRP 1-37A. Also provided are summaries of guidelines from other states and their comparison to ODOT guidelines.

SUMMARY OF M-E DESIGN GUIDE RECOMMENDATIONS

The subgrade layer is characterized by its resilient modulus in the M-E Design Guide analysis and design process for new, reconstructed, and rehabilitated pavements. Depending on the hierarchical input level being used, input value for the layer modulus can be obtained through laboratory resilient modulus tests, or back calculation of NDT data for rehabilitation designs, or through correlations with other physical properties.

Subsurface Explorations

The design process considers the effects of soil types, moisture contents, densities and water table depth in the design process, hence an appropriate subsurface exploration test plan to collect this information is necessary to fully benefit from the capabilities of this design procedure. The M-E Design Guide, developed as a national-level design procedure, does not explicitly state the specific activities to be conducted in the subsurface exploration program for each project. However, it states that the extent of exploration program should be dependent on the nature and magnitude of the project, and the site-specific subsurface conditions so that the variability in the soil conditions can be well defined both vertically and horizontally along the project length. Representative soil layers where transition in key material properties including shear strength, consolidation, and resilient modulus is expected to be selected for laboratory testing.

Borings

The M-E Design Guide does not offer rigid rules for the number of borings and spacing. In fact, it recommends that agency guidelines should not establish rigid rules for these aspects of testing as conditions vary across different geographic locations. Testing should be performed in reasonable detail to obtain basic engineering properties of the overburden and bedrock formations that will affect the future pavement design and performance. The county soil maps should be referred to provide an overview of the spatial variability of soil series within a county. The depth of borings should be chosen depending on the nature of subsurface condition, and magnitude and distribution of traffic loadings being applied on the pavement.

General Guidelines for Boring Depth

- Where light cut and fill are made with no special problems, explorations should extend to a minimum of 5 ft (1.5 m) below the proposed subgrade elevation. Some borings should extend to a depth 20 ft (6.0 m) below the planned surface elevation.
- Where deep cuts are to be made, large embankments are to be constructed, or subsurface information indicates the presence of weak (or water-saturated) layers, the boring depth should be increased.
- Where unsuitable foundation strata (for example, unconsolidated fill, highly organic materials, or soft, fine-grained soils) are encountered, borings should extend to reach relatively hard or compacted materials of suitable bearing capacity.
- Where potentially compressible fine-grained strata of great thickness exist, borings should extend to a depth where the stress from superimposed traffic loads or a thick embankment is so small that consideration will not significantly influence surface settlement.

- Where stiff or compact soils are encountered at the surface and the general characteristics and location of rock are known, borings should extend into sound rock.
- Where the location and characteristics of rock are unknown or where boulders or irregularly weathered materials are likely to be found, the boring penetration into rock should be increased.

Laboratory Testing

The M-E Design Guide recommends laboratory testing of samples for material classification and strength properties. The extent of the laboratory program depends on the criticality of the design and the complexity of the soil conditions.

Typical tests recommended

- Moisture Content and Dry Unit Weight
- Atterberg Limits
- Gradation
- Shrink Swell
- Permeability
- Consolidation
- Shearing and Bearing Strength
- Resilient Modulus

Subgrade Treatment

The M-E Design Guide addresses four critical soil conditions for considering subgrade treatment and provides guidelines for their identification and treatment. The conditions are as follows:

- Collapsible or highly compressible soils.
- Expansive or swelling soils.

- Subsurface water flow and saturated soils.
- Frost-susceptible soils.

The M-E Design Guide recommends five techniques to improve subgrade strength or reduce the effects of climatic variations on pavement performance:

1. Stabilization of weak soils (highly plastic or compressible soils).
2. Thick granular layers.
3. Subsurface drainage systems.
4. Geosynthetics.
5. Soil encapsulation.

Stabilization

Stabilization is provided for two purposes:

i. To provide a stable construction platform for wet soils and to facilitate compaction of the upper layers
ii. To strengthen a weak soil and restrict volume changes with changes in moisture conditions of the soil.

General Recommendations for Stabilization

- Lime is recommended for clayey soils (CH and CL type) and granular soils containing clay binder (GC and SC). Lime treatment and stabilization should be considered for soils with a Plasticity Index (PI) above 10.

- Portland cement treatment is recommended for non-plastic soils. Note that chemical stabilization can change physical properties of the soil that can result in soils with frost heave problems.

- **Lime treatment**: Lime treatment is achieved by applying 1 to 3 percent hydrated lime to improve compaction and remove excess moisture. This aids in expediting construction but does not contribute to the structural strength of the structure and does not alter design.

- **Lime stabilization**: Lime stabilization improves the strength of the material; the improvement is significant in fine grained soils and marginal in coarse grained soils. Soils classified as CH, CL, MH, ML, SM, SC, and GC with a plasticity index greater than 10, and with 25 percent passing the No. 200 sieve potentially are suitable for stabilization with lime.

  The recommended lime content for stabilization of clay is 3 to 8 percent of the dry weight of the soil, with an increase in compressive strength of at least 50 psi (345 kPa) after a 28-day curing period at 73 degrees Fahrenheit (22 Celsius). The lime content should be optimized using laboratory unconfined compressive strength tests and the Atterberg limit tests. The lime-stabilized subgrade layer should be compacted to a minimum density of 95 percent, as defined by AASHTO T99. National Lime Association guidelines are recommended for designing lime content.

- **Cement stabilization**: Soils stabilized with cement should have a PI of less than 20 and greater than 45 percent passing the # 40 sieve. Soils with higher PI can be treated with cement after a pretreatment with lime or fly ash. For cement stabilization of granular and/or nonplastic soils, the cement content should be 3 to 10 percent of the dry weight of the soil, and the cured material should have an unconfined compressive strength of at least 150 psi (1000 kPa) within 7 days.

- **Asphalt stabilization**: Asphalt stabilization is provided only for base or subbase material treatment. The durability of asphalt-stabilized is dependent on water absorption characteristics.

Thick Granular Layers

The use of a thick granular layer improves the structural capacity and therefore is a design and construction consideration. The M-E Design Guide recommends that the soil be improved as opposed to increasing thickness of the surface layers of the pavement in order to meet design requirements. Thick granular layers are generally greater than 18 inches (45 cm) in thickness, and they enhance natural soil foundation and pavement performance as they:

1. Improve drainage
2. Control moisture related and seasonal damages
3. Provide stronger support to the overlying layers

Recommendations for Thick Granular Layer

The material used for the thick granular layer should be a high quality aggregate with good drainage characteristics. The material should have a CBR value above 20, corresponding to a resilient modulus of 17,500 psi (120 MPa), and associated with AASHTO A-1 and A-2. The fines content should be limited to 10 percent. The optimal thickness of the granular layer is between 1.5 to 5 feet (0.5 to 1.5 m) depending on the soil type. Note that higher thicknesses do not necessarily contribute to added structural capacity.

Subsurface Drainage

Subsurface drainage is recommended by the M-E Design Guide to:

- Lower the ground water level,
- Intercept the lateral flow of subsurface water beneath the pavement structure
- Remove the water that infiltrates the pavement's surface.

Recommendations for Subsurface Drainage

- Install deep under drains, greater than 3.3 feet (1.0 m) deep, for groundwater problems

- The geotechnical investigation will encompass, among other things, the design and placement of these under drains
- To address water infiltrating from above, place edge drains under the shoulder at shallower depths

Geosynthetics

The M-E Design Guide also contains recommendations for conditions when the use of geosynthetics are appropriate.

SUMMARY OF ILLINOIS DOT GUIDELINES

The Illinois Department of Transportation (IDOT) provides guidelines in the "Subgrade Stability Manual," which puts major emphasis on subgrade stability during construction. The manual also addresses design and long-term pavement performance considerations.

IDOT recognizes that the distribution of soil types does not change over time, and that it is not practical to accurately predict the field moisture content or strength as a function of location, depth, and time. Poor soil conditions, if not detected during the investigation process, can be identified during construction. Therefore, the assessment of soil type and condition has to be carried out both before and during construction. Furthermore, the suction-water content relationships, which greatly influence the field equilibrium moisture content, are insensitive to the density and moisture content at the time of placement. As a result, the moisture content can increase in the subgrade during the pavement service life even if the material is compacted to optimum or dry of optimum at the time of construction.

IDOT provides rather restrictive guidelines for subgrade stability during construction because construction loads on the subgrade cause higher deflections, stresses and strains during the construction phase than those caused by traffic loading during the pavement service life. Nevertheless, subgrade stability is vital for good performance of the pavement during its service life. IDOT provides subgrade stability requirements during the construction phase based on control of rutting and material compaction.

Requirements during Construction

The finished grade should have a CBR of at least 6 to minimize rutting. To limit the rut depth to 1/2 and 1/4 inch (13 and 6 mm), the soil CBR should be in the ranges of 5.5 to 8.5 and 8.0 to 8.5, respectively, depending on the tire pressure. The tire pressures considered in this specification are between 50 and 80 psi (345 and 550 kPa).

Requirements for Performance

The fundamental requirement is that the subgrade stability after the completion of project is equal to or more than the value used in the pavement design process. The in-situ strength should be consistent with the design values used. The design process should in turn consider the effect of changes in climate on the soil modulus or soil support value.

Remedial Actions

Remedial actions are recommended for situations when the compacted soil does not meet the strength and stiffness requirements for the project. The most effective remedial actions are undercut and backfill, and lime treatment as they offer improvement in subgrade properties during construction and in the long term. The remedial actions can sometimes include the provision of subsurface drainage. Proof rolling is not considered a remedial procedure. Details of the specifications for the two remedial actions, undercut and backfill, and lime treatment are discussed below.

Undercut and Backfill

The fundamental requirement for backfill material to be satisfied is that the selected thickness should be sufficient to adequately distribute the pressure over the soft subgrade, and it should be able to withstand the repeated wheel loads without excessive rutting. Thickness requirement for the backfill material is based on a modified Corps of Engineers design approach, expressed as:

$$t = F\left[P\left(\frac{1}{8.1*CBR} - \frac{1}{p*\pi}\right)\right]^{\frac{1}{2}} \qquad (1.)$$

where t = layer thickness (inches)

P = single wheel (or equivalent single wheel) load (lbs.)

CBR = CBR of existing soil underlying the granular layer

p = tire contact pressure (psi)

F = 0.23 log C + 0.15

C = Number of load repetitions

The above equation was originally developed for flexible pavement thickness requirements, but has been extended to determine granular backfill layer thickness. The optimum thickness for granular layer is approximately 60% of that determined from equation 1. The following summarizes the granular layer thickness

- For CBR above 8, remedial action is not necessary
- For CBR between 6 and 8, remedial action is optional
- For CBR below 6, remedial action is necessary. Recommended thicknesses are approximately 23, 16, 13, 12, 10, 9, 9, and 9 inches for CBR values of 1 through 8 respectively.
- Granular backfill material should have adequate shear strength, which is typical in crushed material with high maximum size aggregates, good gradation and size distribution, less fines, and low PI of the fines content.

Geotextile

IDOT allows the use of a geotextile for subgrade stability by preventing the intrusion of fines into the granular layer. Currently, IDOT Bureau of Materials and Physical Research performs the design of granular layer thickness in the event a geotextile is used. Approximately, the granular layer is reduced by 33% with the use of a geotextile underneath the layer.

Compaction Specifications

IDOT specifies that the moisture content of the top 2 feet (0.60 m) of all embankments is not greater than 120 percent of AASHTO T-99 optimum water content. It also requires that the entire subgrade has to be compacted to no less than 95 percent of the standard laboratory density. However, meeting the above two conditions does not secure and guarantee subgrade stability, and therefore a qualitative control of moisture content is necessary. It is recognized that quantitative values of compaction moisture content should be added to the current specification

Lime Treatment

Lime treatment is used to improve the strength, stiffness, plasticity, and durability properties of the subgrade soil. The selected lime treatment should prevent shear failure of the layer, and should have sufficient thickness to prevent subgrade failure. The following are recommended by IDOT for lime treatment:

- The minimum CBR for lime treated soil is 10.
- The thickness of the lime-modified soil mix can be selected from the same charts used for selecting the thickness of backfill granular layer.
- If the immediate CBR of lime-modified soil is less than 10, then a granular surface layer should be added. The combined thickness of the granular layer and the lime-modified layer can be considered as the equivalent thickness of the granular layer above the underlying soil for design and construction specification purposes.

- The minimum thickness of the lime-modified layer should be 8 inches (20 cm).
- For a working platform, the soil should be lime-reactive, gain an additional 50 psi (345 kPa) compressive strength after lime treatment, and have a minimum strength of 100 psi (690 kPa).
- The layer thickness can be selected based on Table 3, and sufficient time should be allowed for the material to gain design strength.

Table 3. IDOT Requirements for Lime-stabilized Soil Layers

Subgrade Strength			Minimum lime-soil layer thickness, inch	
Modulus of subgrade reaction, k, psi/inch	CBR	Cone index	Unconfined compressive strength 100 psi	Unconfined compressive strength 200 psi
50	2	80	12	9
125	4	160	12	9
150	6	240	9	8
200	8	320	9	8

(1 inch = 2.54 centimeters) (1 psi = 6.9 kPa)

Illinois uses a minimum of 12" (30 cm) stabilization for all reconstruction projects. DCP tests are performed during construction. If the CBR is greater than 4, then the stabilization provided is considered adequate. If CBR is less than 4, then additional stabilization is provided or thickness is added. Illinois also collects boring log data every 300-600 feet (90 – 180 m). For rubblization, Illinois uses DCP test data to verify the feasibility for rubblization on a project-by-project basis.

Choice of Remedial Procedure

IDOT guidelines indicate that the remedial procedure to be adopted for a project should be based on the following considerations:

1. Subgrade stability requirement for each option (moisture density control levels, thickness of undercut and backfill, lime percentage required for treatment)

2. Assess the potential of each option (construction feasibility, cost-benefit, energy, performance of the treatment for the particular situation)
3. Selection of best option based on comprehensive assessment.

SUMMARY OF GUIDELINES AND PRACTICES FROM OTHER AGENCIES

Pennsylvania Turnpike

Pennsylvania Turnpike undertakes reconstruction projects which involve the removal of pavements that were built more than 5 decades ago and that have been in service since then. In their experience, they have often found the preconstruction evaluation, especially with boring logs, to show a more favorable soil condition than the actual. Their practice is to conservatively estimate quantities for stabilization based on prior experience and make more definite decisions during the reconstruction stage. Because it is their experience that problem areas are not "normally" distributed, i.e. they can be pocketed and skewed, DCP tests are performed along the stations at 20 m (approximately 65-70 feet) intervals. A uniform stabilization of 9 percent lime and 9 percent cement for 15 inch (38 cm) depth is provided. This stabilization is considered adequate to withstand construction traffic and hauling trucks.

Pennsylvania DOT

The Pennsylvania DOT has revised its subsurface exploration procedure due to cost overruns during the construction phase. The subsurface exploration procedure includes soil boring, sampling, and laboratory testing for gradation, in-place density, moisture, and CBR. The subsurface investigation procedures are also followed for considering rubblization during the reconstruction design and construction. The CBR of the soil is the controlling factor in selecting remedial options for subgrade improvement. Soils with a CBR below 5 are enhanced either with a cut and backfill or stabilization.

Michigan DOT

Michigan has some occurrences of wet and unstable subgrades. The subsurface exploration does not include extensive testing on a routine basis. Michigan DOT has undertaken very few reconstruction projects involving pavement removal. MDOT uses an 18-inch (45 cm) granular layer on the subgrade in all pavement projects. This practice has been in place since the 1950s.

Kentucky DOT

Kentucky encounters frequent occurrences of wet and unstable subgrades. Kentucky has relied on NDT methods for evaluating the condition of the subgrade soil and complements it with boring spaced at 400-500 feet (120 – 150 m) accompanied with lab tests. The most typical remedial procedure for treating unsuitable soils is undercut. More recently, lime and cement stabilization are being used. For selecting the appropriate option, the agency has switched from encumbrance method to cash balance basis to avoid overruns.

Indiana DOT

Indiana DOT commonly faces occurrences of wet or unstable subgrade. INDOT uses data from soil borings taken at 500 – 800 feet (150 – 240 m) intervals and laboratory tests conducted on undisturbed samples. Subgrade treatments are a single bid item in the contract and gives the contractor three options: 2-ft (0.60 m) compaction undercut, 16-inch (40 cm) chemical treatment, or 12-inch (30 cm) undercut with aggregate replacement. The new specification has significantly reduced cost overruns.

Wisconsin DOT

Occurrences of wet and unstable subgrades are common in Wisconsin. There is no statewide subsurface exploration procedure specified. The District Soils Engineer determines the need for investigation, usually 4 to 5 borings per mile, sampling and laboratory testing. The treatment consists of subgrade drying or removal and replacement when in-place moisture is nearing the liquid limit. Sand, breaker run stone, or stabilization methods are also used as treatment methods. There has been a significant reduction in problems associated with cost overruns because of improved testing and investigation practices.

Minnesota DOT

In Minnesota, the subsurface exploration activity consists of taking borings every 100 feet (30 m) intervals, and sampling for classification and moisture content. Follow-up sampling is conducted when and where necessary. Cut and backfill is most common treatment option and lime treatment is adopted only subject to the approval of the project engineer. In the event that it is demonstrated that the soil cannot be dried with conventional methods due to excessive moisture and uncooperative weather conditions, lime treatment can be used after approval from the District Soils or Materials Engineer. Recent problems cited in the State were as a result of swamp excavation, not wet soils.

Other

Washington State uses data from FWD testing every 1/500th of a mile for all rehabilitation and reconstruction projects. Some cores are also taken for analysis. There is no state-wide subgrade treatment guideline.

Florida has no state-wide guideline for subgrade treatment. FWD analysis is used extensively for testing existing pavement and decisions are made on a project-to-project basis.

Table 4 shows a summary of the subgrade investigation guidelines from various agencies. Boring depth and spacing guidelines from ODOT are comparable, and fall in the middle of range, with that from other agencies.

Table 4. Summary Comparison of Subsurface Investigation Guidelines from Various Agencies

	Boring Depth			Boring Spacing[5]		Field Testing	Laboratory Testing
	Cuts	Fills	Others[1]	Uniform	Others		
Ohio DOT	10ft (3m)[2]	10ft (3m)[3]	5ft(1.5m) to 10 ft (3m) into the stiff soils	400ft (120m)	50ft(15m) to 400ft(120m)	Ground water determination, Standard penetration test (SPT)	Visual Description[4], Classification (moisture content, particle size, Atterberg Limits); Strength and/or Consolidation (utilize the appropriate test methods from: unconfined compressive strength (UCS), direct shear, triaxial compression, one-dimensional consolidation, specific gravity)
NCHRP I-37A	5ft(1.5m)-20ft(6m)		into the hard material	Dependent on the project, not specified		Ground water determination	Classification, Shrink Swell, Permeability, Consolidation and Strength, Resilient Modulus, etc.
US DOT	10ft (3m)	Twice the embankment height	into the stiff soils	500ft (150m)	200ft (60m)	SPT; Cone penetration test (CPT)	Classification, Permeability, Remolded density, CBR, UCS, Consolidation, etc.
Indiana DOT	7ft (2.1m)	6 ft(1.8m) or 2/3 of the embankment height	3ft(1m)-6ft(1.8m) into the stiff soils	500ft(150m) to 830ft(250m)	100ft(30m) to 300ft(90m)	Ground water determination, SPT, Field vane shear test	Classification, pH test, Moisture-density, CBR, UCS, Consolidation, Loss on ignition test, etc.
Alberta DOT	6.7ft (2m)	Equal to the fill height, minimum 6.7ft (2m)	10ft(3m) to 33ft(10m)	667ft (200m)	167ft(50m) to 333ft(100m)	sPT, CPT, Dynamic CPT, Vane test, Pressure meter test(PMT), Dilatometer test(DMT)	Visual classification, Classification, Durability and strength, Consolidation, Swell, Dispersion, Hydraulic conductivity, etc.
FHWA training course	6.7ft (2m)	Twice the embankment height	16.7ft (5m) below at the ditch line	200ft(60m) to 400ft(120m)	200ft (60m)	SPT, CPT, Field vane test, PMT, DMT, Plate load test	Classification, CBR, UCS, Consolidation, Permeability, Resilient modulus, etc.
Georgia DOT	5ft (1.5m)	5ft (1.5m)	to the bottom of soft soils	300ft (90m)	50ft(15m) to 100ft(30m)	Ground water determination	Classification, Volume change, Maximum dry density, Strength and Consolidation, Permeability, etc.
Tennessee DOT	10ft (3m)	Twice the embankment height	10ft(3m) into refusal	600ft (180m)	100ft(30m) to 400ft(120m)	Ground water determination	Classification, UCS, CBR, Consolidation, etc.

1.Such as sidehill cut sections, sidehill cut-fill sections, compressible and low strength soils, peat and muck deposits, etc. 2. below proposed grade or ground, 5ft (1.5m) for rehabilitation or widening projects. 3. When embankment height >10ft (3m), the depth is 10ft (3m) plus one half of the embankment height. 4. Never visually classify a soil as A-2-5, A-4b, A-5, or A-7-5 within the top 3 feet of the proposed subgrade. 5. The borings spacing for other states: Minnesota (100ft), Kentucky (400-500ft), Wisconsin (4 to 5 borings per mile). DCP, moisture content and soil classification tests are commonly used in the subsurface investigation.

Task 2. Comparison of Field Results

Table 5 is a summary of the soil investigation and actual undercut depth data obtained for this study. In this report, an average undercut depth is calculated for the entire pavement area adjacent to a boring in order to summarize different undercut depths between two borings. For example, if 30% of the project area adjacent to a boring (within 200 ft.(60 m) in each direction) was undercut at a uniform depth of 1 foot (0.30 m), then the reported average undercut depth is 0.3 ft (0.10 m) for this area. Alternatively, if 20% of the area was undercut, with 10% at one ft. deep and 10% at 2 ft (0.60 m). deep. The average undercut depth would still be 0.3 ft. (since 10%*1+10%*2 results in the same total quantity as 30%*1). This was done out of necessity, because at a boring location, multiple undercut depths may be presented in the immediately surrounding area. Even at the same station, undercut depths are often different across the full width of the pavement.

The results in Table 5 show that among the reconstruction projects, Franklin I70-14.49 has the strongest subgrade, indicated by its relatively high average N_L, low average moisture content above the optimal, and low average W5. However, the average undercut depth is still 0.33 ft (0.10 m), equivalent to 33% of the project area had one foot undercut. All other reconstruction projects studied have at least as much or significantly more undercut than the Franklin I70 project. The other reconstruction projects all have lower average N_L value, higher moisture content above the average, and higher Dynaflect W5 defelction.

Among the two new construction projects, Jackson US32-27.631 and Ross US35-26.17, the latter has higher average NL, lower moisture content above the average, and lower undercut depth. However, both projects have significant amount of undercut. These two new projects have much more cuts and fills than the reconstruction projects. Therefore, undercut depth is often deep (sometimes 3~5 ft) (1 ~ 1.5m), resulting in the average undercut depth equivalent to the entire project being undercut 2 ft. (0.60 m) or 1.15 ft (0.35 m), respectively, even though some areas of the projects have no undercut.

Table 5. Summary of Subgrade Investigation and Undercut Results

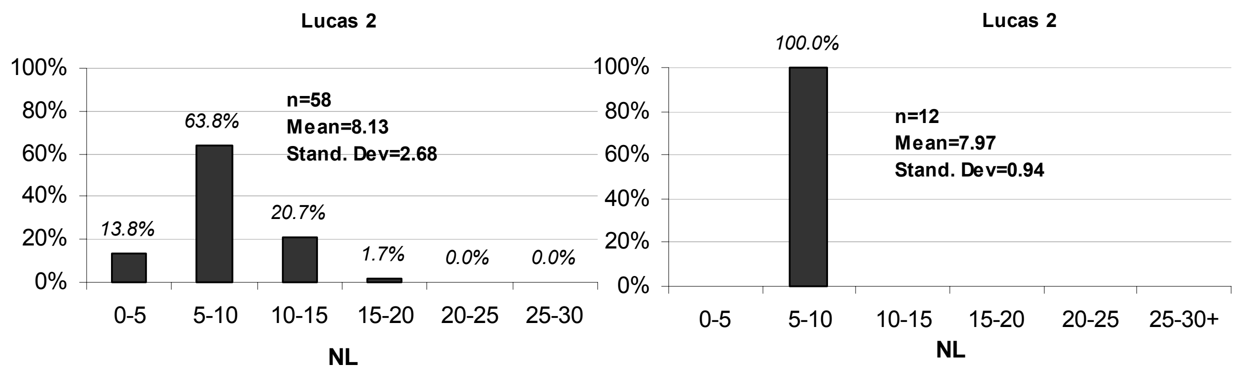
PROJECT ID	Soil Classification	Average N_L	Average Moisture Content Above Optimum (%)	Average W5 (mils)	Average Undercut Depth (ft)
Fayette US 62-13.67	No Data Available	7.5	No Data Available	No Data Available	2.26
Franklin I70-14.49	A3: 5% A4a: 4% A4b: 3% A6a: 42% A6b:42% A7-6:5%	19.76	1.9	0.16	0.33
Medina I71-5.78	A4a:31% A6a: 60% A6b:4% A7-6: 5%	13.84	4	0.27	0.94
Lucas SR2-21.15	A3: 1% A4a:2% A6a: 9% A6b: 45% A7-6: 43%	7.0	5.9	No Data Available	0.33
Lucas I280-1.64	No Data Available	No Data Available	No Data Available	0.18	2
Lucas I280-4.64	A6a: 92% A6b: 8%	7.5	1.5	No Data Available	1.3
Jackson US32-27.631*	A7-6:100%	7	8	No Data Available	2
Ross US35-26.17*	A3(or better): 50% A6a: 18% A6b: 14% A7-6: 18.18%	16.8	2.0	No Data Available	1.15

* JAC32 and ROS35 are new construction projects, and others are re-construction projects.

(1 mil = 1/1000 inch = 0.0025 cm) (1 foot = 0.30 meters)

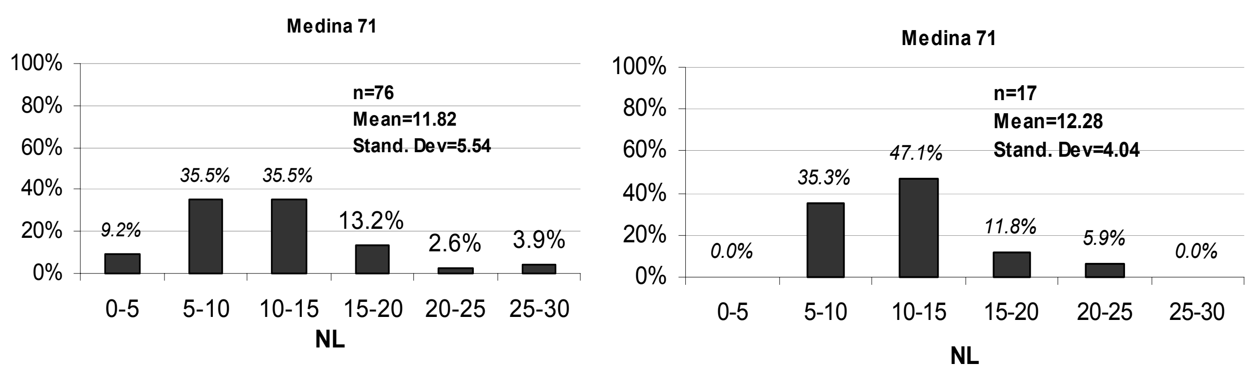
The current guidelines use the SPT N_L value as a primary indicator of soils stiffness and consistency. The average N_L value is used in the GB1 guidelines to estimate the required depth of undercutting or chemical stabilization.

Figures 7 through 11 show the distribution of average N_L values for each project investigated. The average N_L every 500 ft. (152 m) typically represent a individual boring, whereas average N_L every 2500 ft. (762 m) is an average of typically 5 to 6 borings. These figures show that within each project, there is a high variability of the N_L values (Note: the projects that seem to be more uniform have relatively few data points).



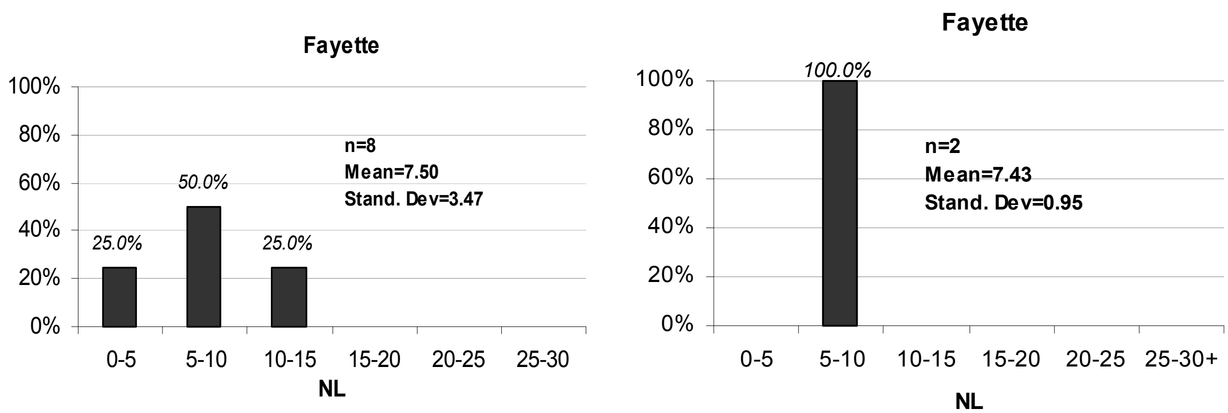
(a) Average N_L every 500 ft (152 m) (b) Average N_L every 2500 ft (762 m)

Figure 7. Frequency Distribution of N_L in Lucas SR-2 Reconstruction Project



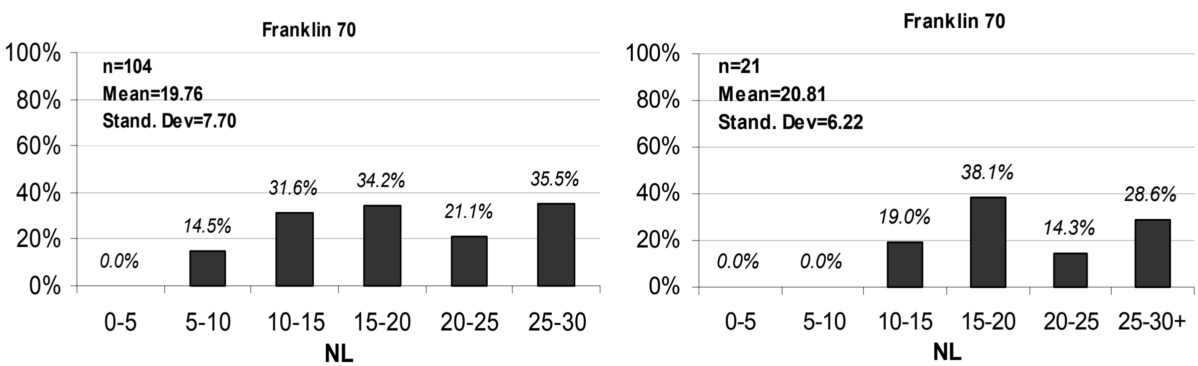
(a) Average N_L every 500 ft (152 m) (b) Average N_L every 2500 ft (762 m)

Figure 8. Frequency Distribution of N_L in Medina I-71 Reconstruction Project



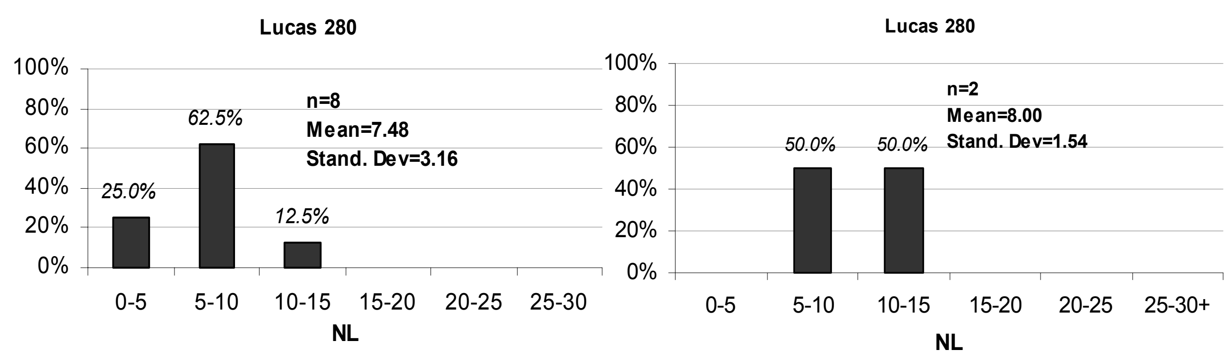
(a) Average N_L every 500 ft (152 m) (b) Average N_L every 2500 ft (762 m)

Figure 9. Frequency Distribution of N_L in Fayette US-62 Reconstruction Project



(a) Average N_L every 500 ft (152 m) (b) Average N_L every 2500 ft (762 m)

Figure 10. Frequency Distribution of N_L in Franklin I-70 Reconstruction Project

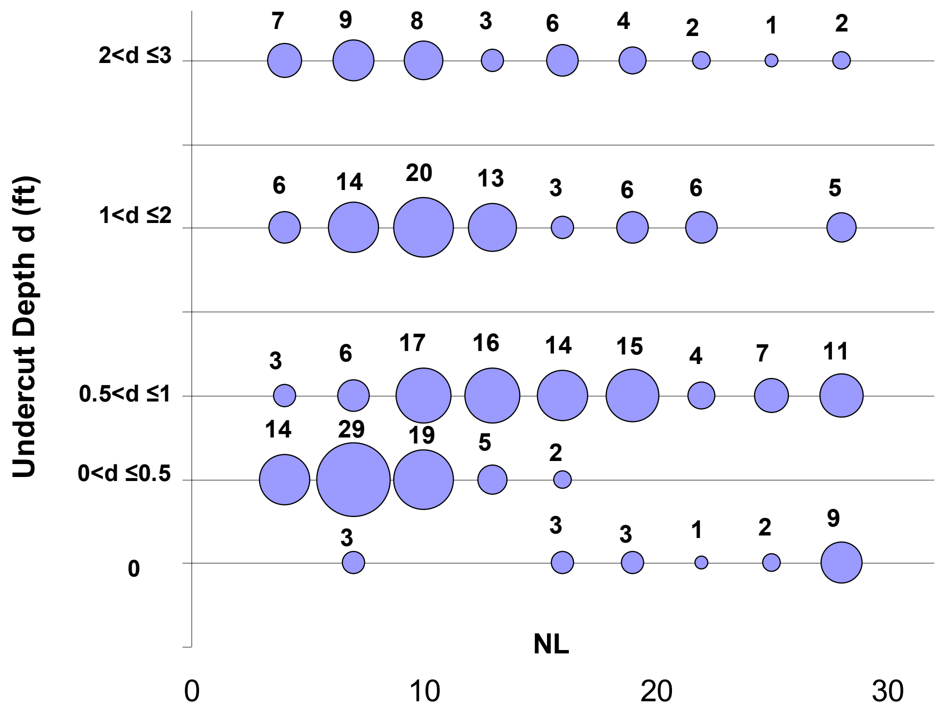


(a) Average N_L every 500 ft (152 m) (b) Average N_L every 2500 ft (762 m)

Figure 11. Frequency Distribution of N_L in Lucas I-280 Reconstruction Project

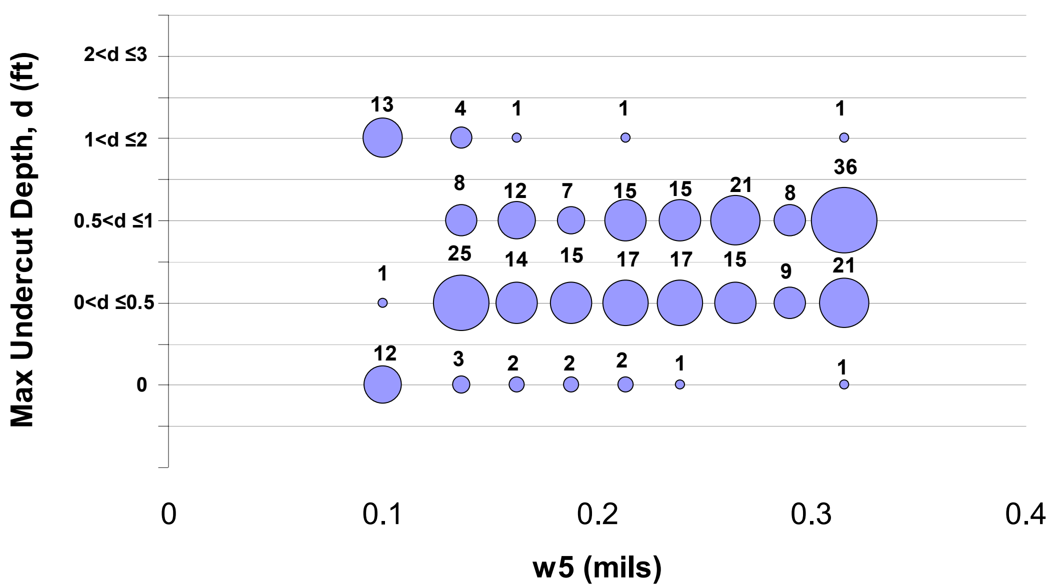
Figure 12 shows the bubble (or cluster) plot of N_L value versus the actual undercut depth based on combined data from all projects studied. The size of each bubble represents the number of data points at that location, which is also indicated by the number next to each bubble. In contrast, Figure 13 shows the bubble cluster plot of Dynaflect sensor #5 deflection (W5) versus the actual undercut depth.

These two figures show that, in general, lower N_L and higher W5 values correspond to weaker soils, therefore, more undercut quantity may be expected. However, actual data from the projects studied are rather scattered as shown in these graphs, indicating that actual undercut depth can not be predicted with great accuracy, with either of these two parameters.



(1 mil = 1/1000 inch = 0.0025 cm) (1 foot = 0.30 meters)

Figure 12. N_L Values, Actual Undercut Depths and Number of Occurrences per Interval

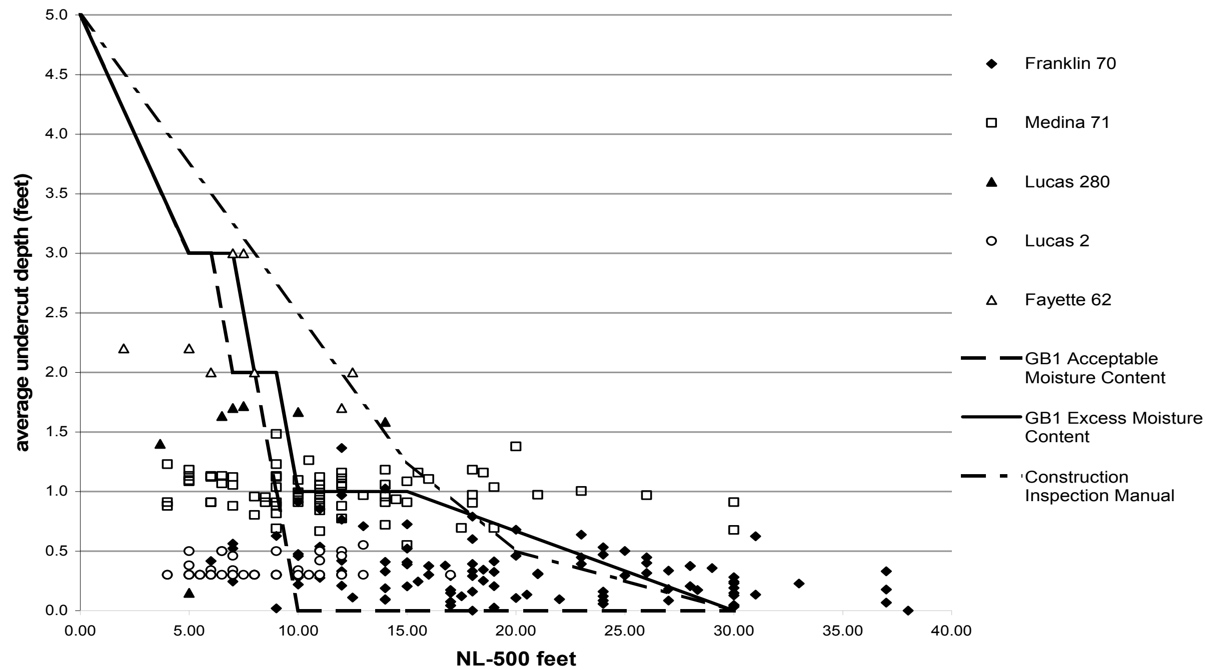


(1 foot = 0.30 meters) (1 mil = 1/1000 inch = 0.0025 cm)

Figure 13. Dynaflect W5 Deflections, Actual Undercut Depths and Number of Occurrences per Interval

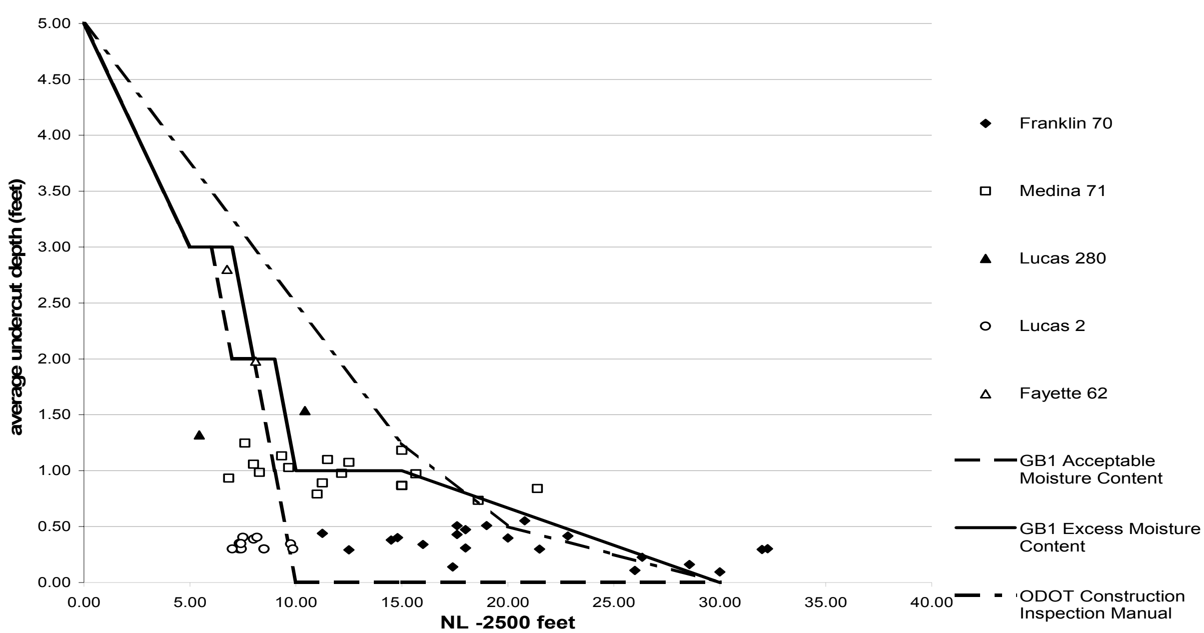
Figure 14 shows the average undercut depth versus the NL values for all projects as compared with the current guidelines. Notice the average undercut depth for the Medina I-71 project was almost always about one foot deep, regardless of the N_L values. Sometimes a decision could be made to undercut the entire project despite some localized spot of soils with high stiffness (and high N_L values). This could be beneficial in ensuring a more uniform subgrade support. Excluding a few data points with very high N_L values, the guidelines in the Section 204 of the Construction Inspection Manual seem to provide a rather accurate upper bound of the required undercut depth. Figure 15 shows that this is particularly true when average N_L values of adjacent borings (every 2500 ft. (762 m)) are used instead of the individual N_L values.

Figures 16 and 17 show that a somewhat positive correlation between W5 deflection and average undercut depth can be observed, especially when the average W5 every 2500 ft. (762 m) is used. Higher W5 deflections correspond to weaker subgrade, thus higher average undercut depth.



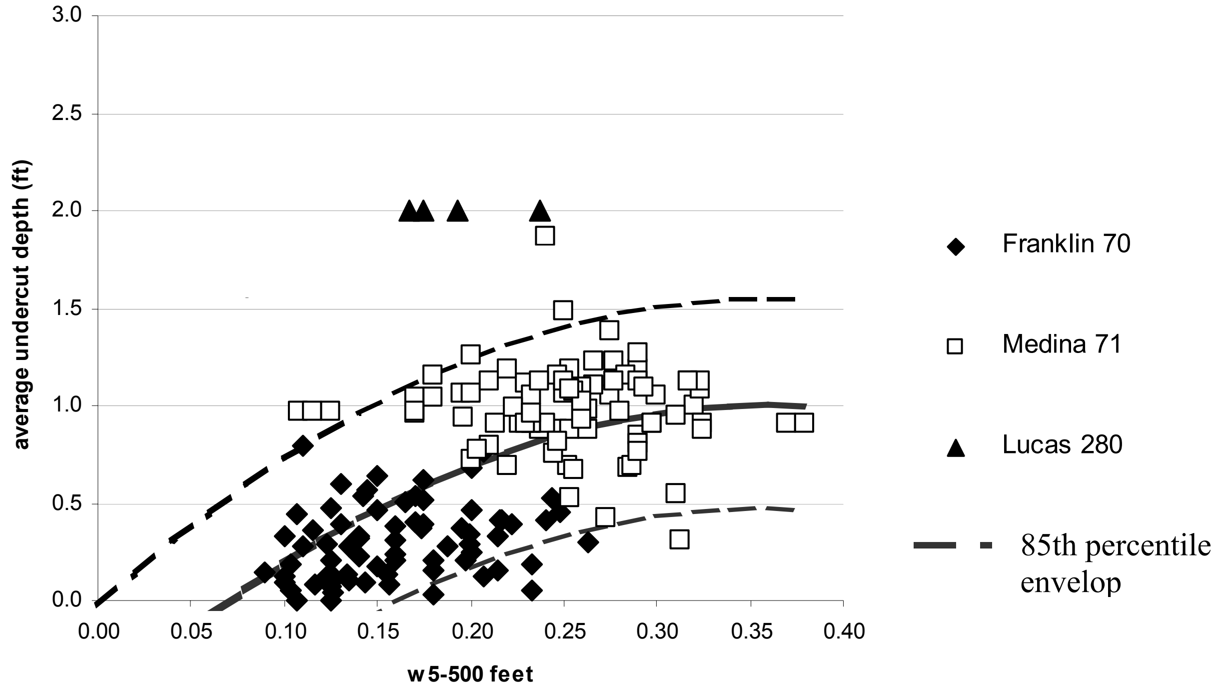
(1 foot = 0.30 meters)

Figure 14. N_L versus Actual Undercut Depth



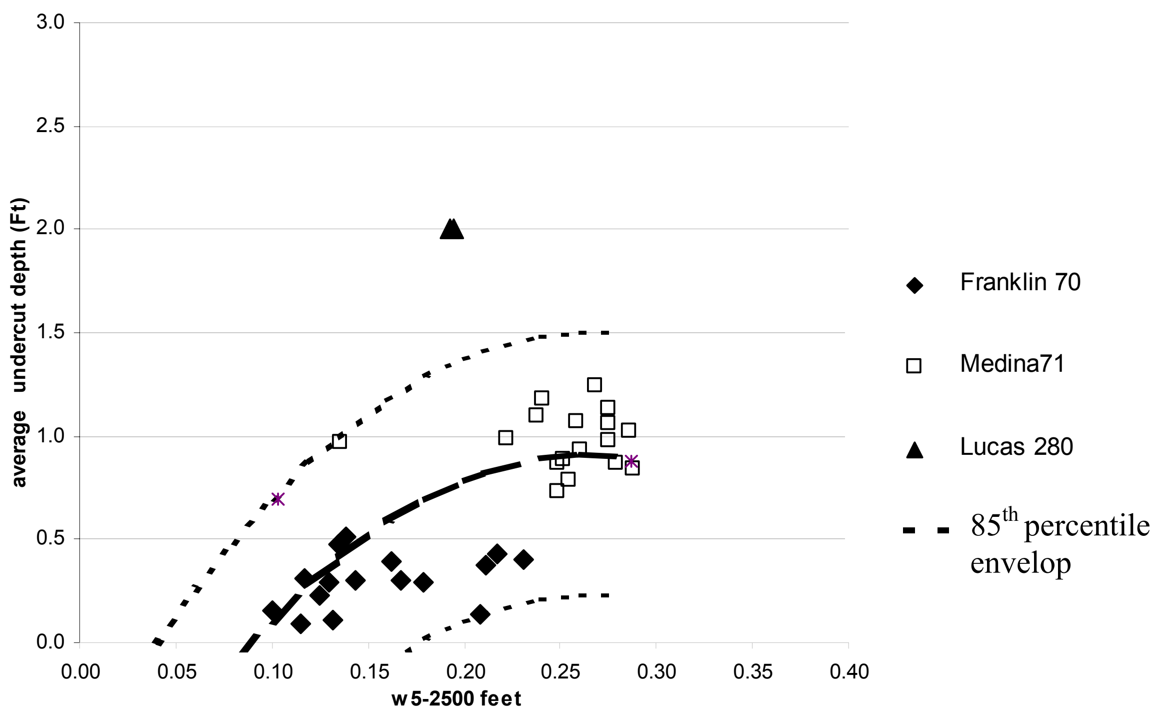
(1 foot = 0.30 meters)

Figure 15. Average N_L Every 2500 ft versus Actual Undercut Depth



(1 foot = 0.30 meters)

Figure 16. Dynaflect W5 Deflection versus Actual Undercut Depth



(1 foot = 0.30 meters)

Figure 17. Average W5 Every 2500 ft versus Actual Undercut Depth

Figure 18 shows that moisture content affects both N_L values and undercut depth. Soils with moisture content more than 3% below the optimum moisture content (OMC) is denoted as having 'dry' moisture content. Moisture content within 3% of the OMC is considered adequate moisture content and moisture content more than 3% above the OMC is considered excessive moisture content. Soils with dry moisture content have higher N_L values, and the average undercut depth is 0.28 ft. (8.5 cm) (or equivalent to 28% of the area received 1 ft. undercut). The average undercut depth for borings with adequate moisture content is 0.58 ft. (18 cm), and for excessive moisture content is 0.67 ft (20.4 cm), respectively.

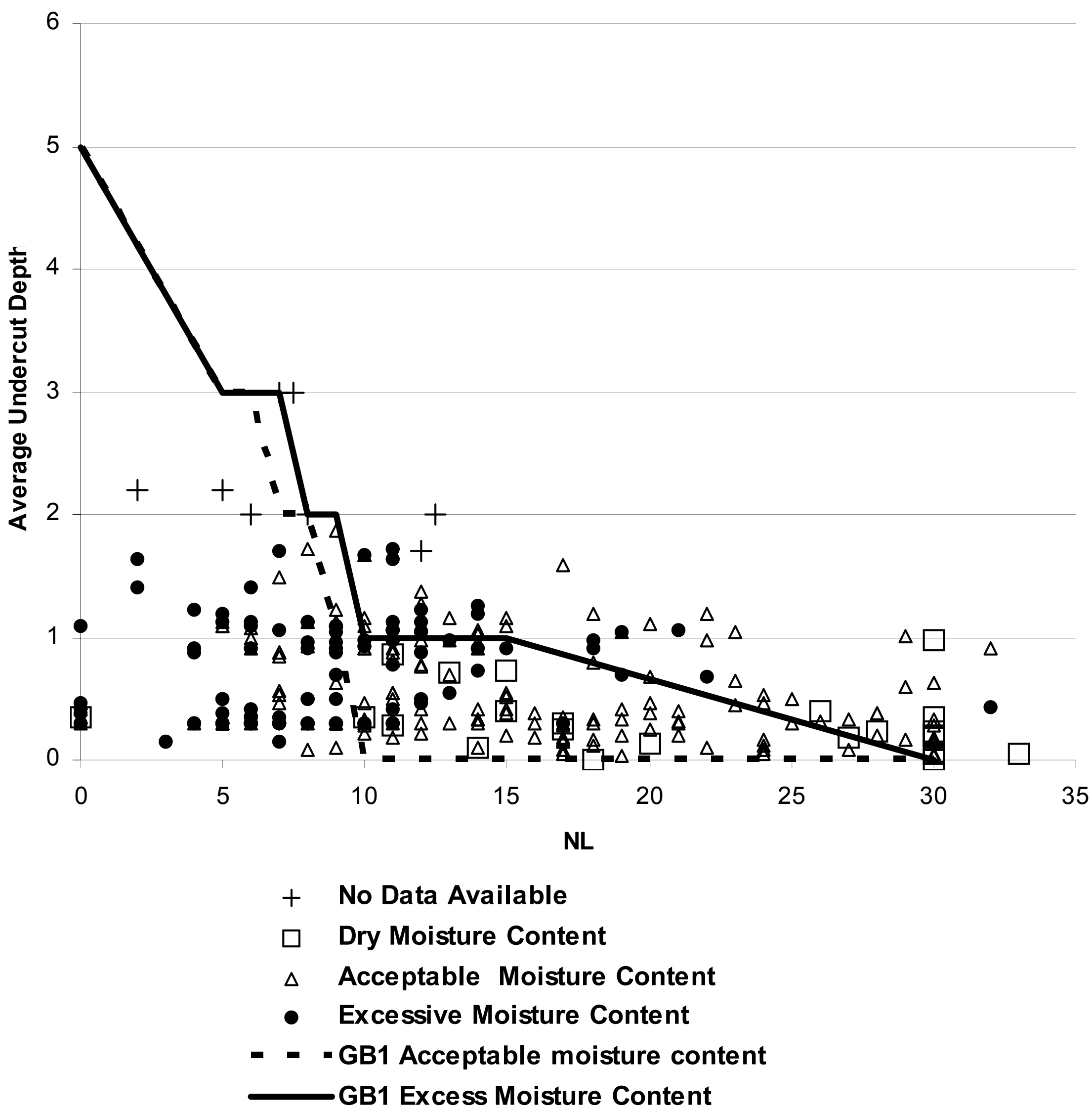
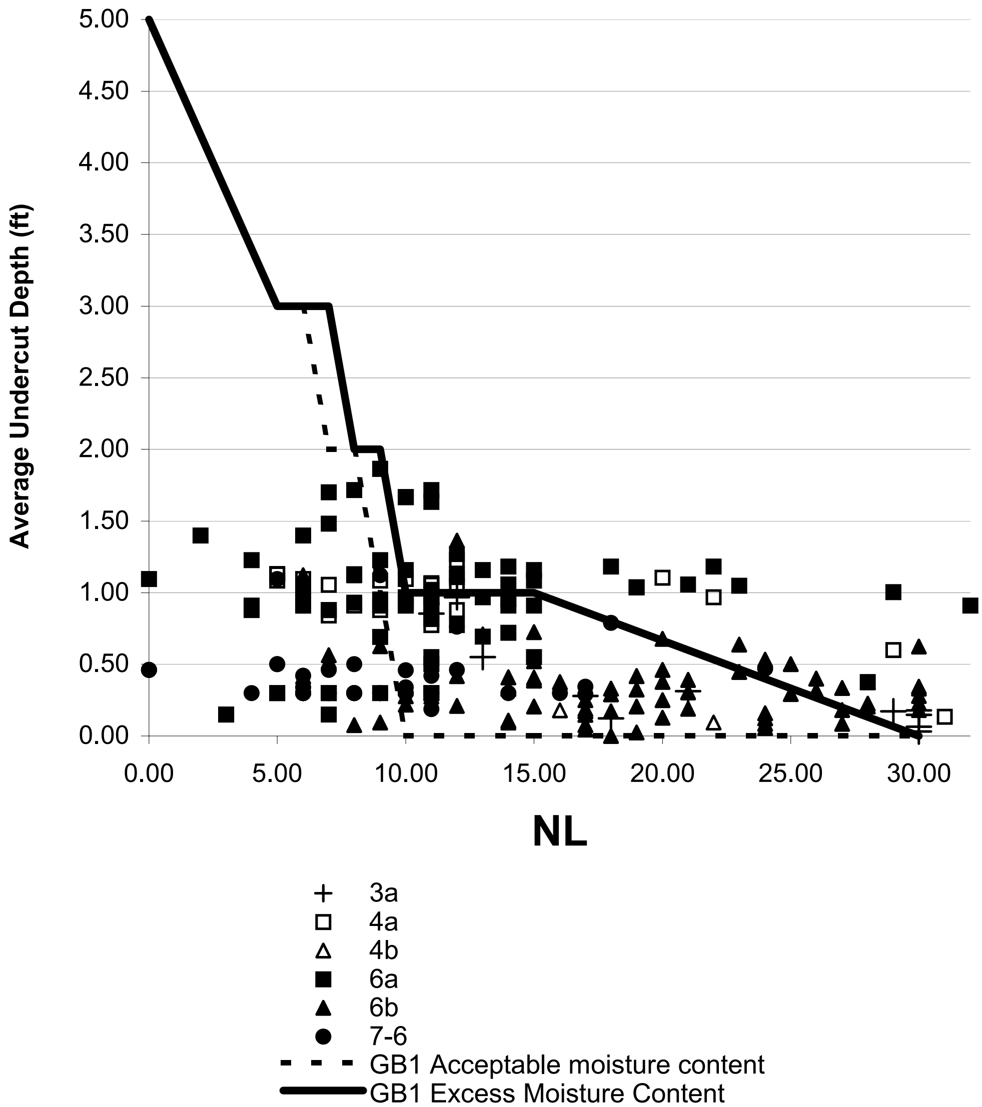


Figure 18. Moisture Content, N_L, and Average Undercut Depth Relationships

Figure 19 shows that soil classification is also somewhat correlated with N_L and average depth. Finer grained soils generally have lower N_L values and are more likely to require undercut than coarser-grained soils. Still, actual data show quite a few exceptions to this general trend.



(1 foot = 0.30 meters)

Figure 19. Soil Classification, NL, and Average Undercut Depth Relationships

Threshold Determined by ROC Curve Method

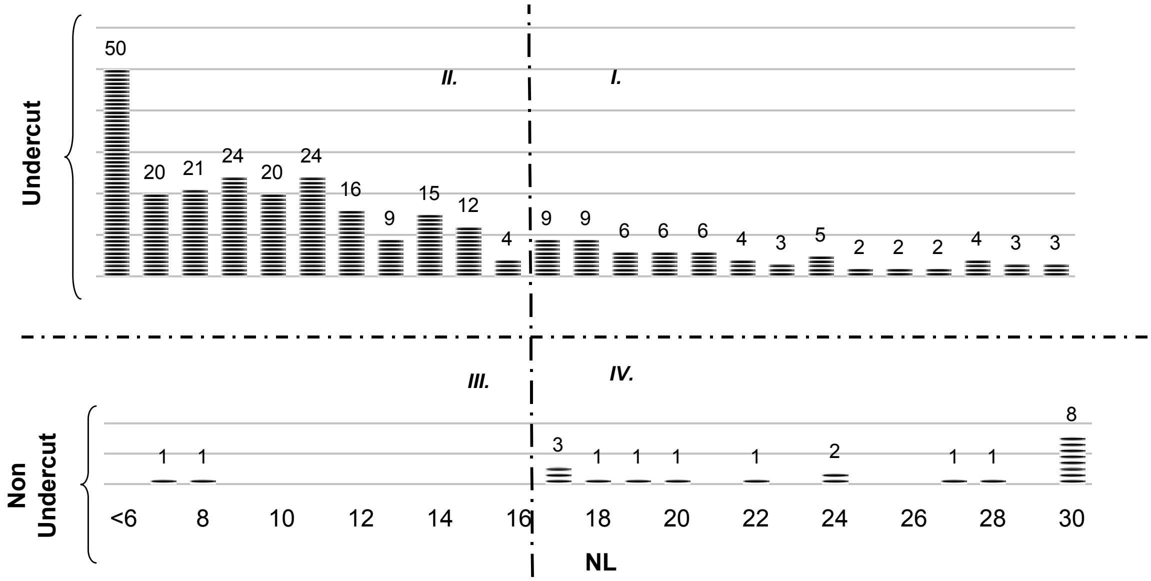
Figure 20 shows that when a N_L threshold value of 16 is selected (i.e., N_L less than 16 would required undercut), the combined data from all reconstruction projects can be divided into four quadrants: I: Predicted no undercut, actual undercut, II: Predicted undercut, actual undercut, III: Predicted undercut, actual no undercut, IV: Predicted no undercut, actual no undercut.

The number of data in quadrant II divided by the total number of data in quadrants I and II (actually undercut) yields the True Positive Rate (TPR). The number of data in quadrant III divided by the total number of data in quadrant III and IV (actual no undercut) is the False Positive Rate (FPR).

Different threshold values of N_L will result in different pairs of (TRP, FPR). Figure 21 shows the resulting ROC curve for N_L values, based on data from all projects combined. The optimal threshold value for N_L is approximately 17. This means that when the N_L value is below 17, undercut is likely required.

Figures 22 and 23 show the ROC curve for W5, based on data from all projects. The optimal threshold value for W5 is around 0.18. That is, when W5 deflection measurement is above 0.18, undercut is likely required.

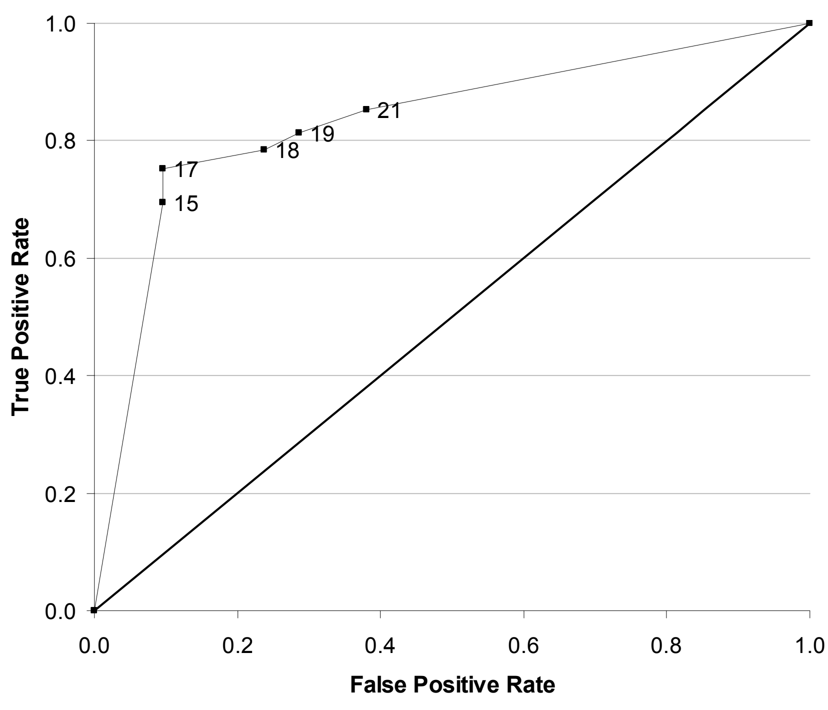
Note that the actual undercut decision is made by project engineer, and can be somewhat subjective. For example, it is desirable to have a more uniform undercut depth than have many varying depths. Or, it may be beneficial to undercut an entire segment rather than leaving small sections out. Moisture contents and proof rolling test results can also vary rapidly due to precipitation or inadequate drainage. Therefore, the 'True' or 'False' states in the ROC Curve analysis are not necessarily perfectly defined. As a result, the threshold values determined by the ROC Curve method are, at best, approximations.



I. Predicted no undercut, actual undercut. II. Predicted undercut, actual undercut.

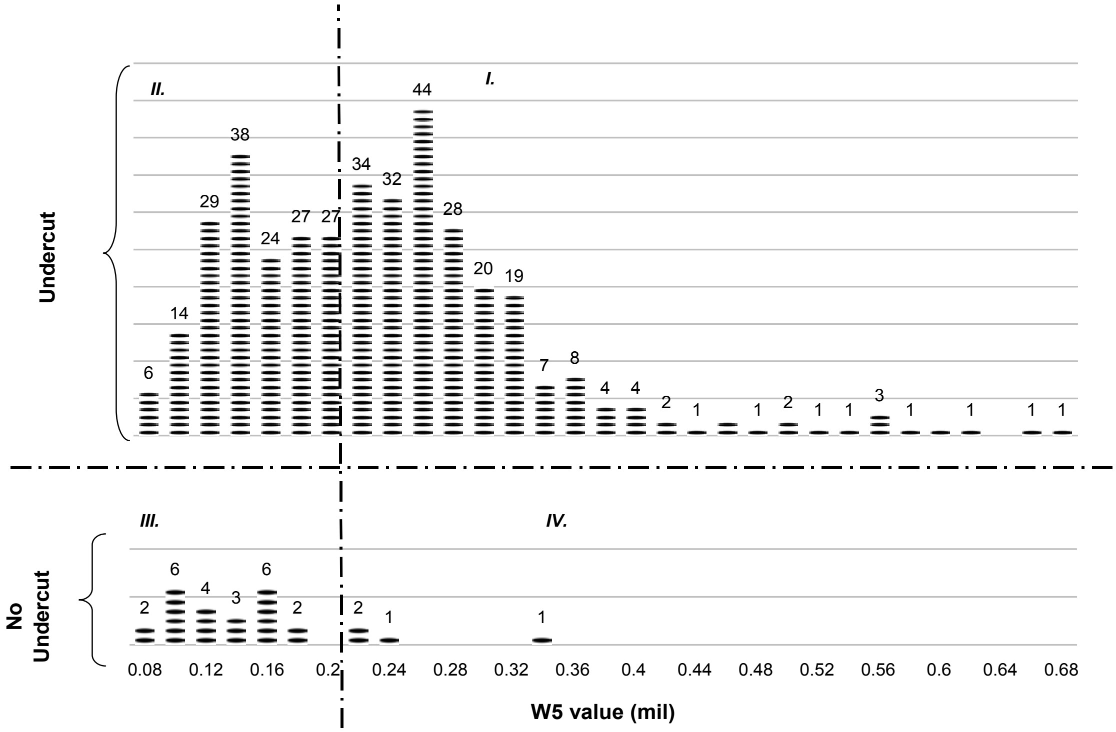
III. Predicted undercut, actual no undercut. IV. Predicted no undercut, actual no undercut

Figure 20. Determination of N_L Threshold for Undercut Prediction



Optimal Threshold for $N_L \sim 17$

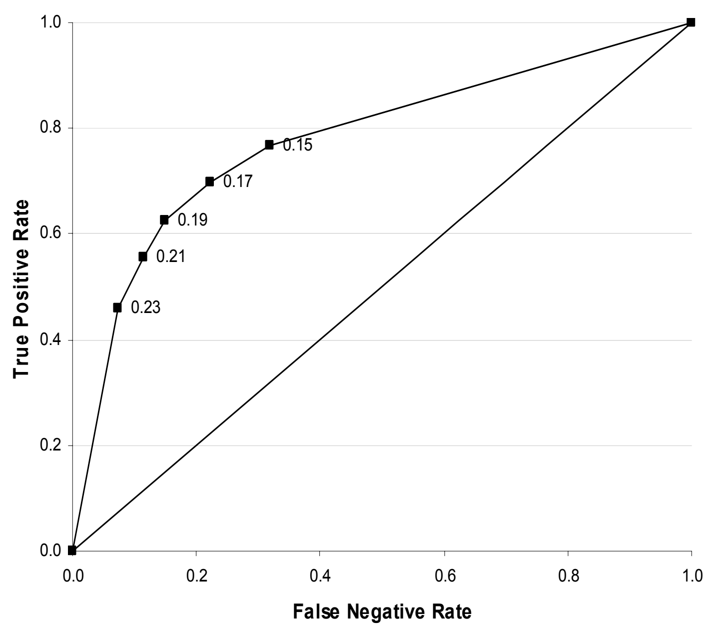
Figure 21. ROC Curve for N_L



I. Predicted undercut, actual undercut. II. Predicted no undercut, actual undercut.

III. Predicted no undercut, actual no undercut. IV. Predicted undercut, actual no undercut

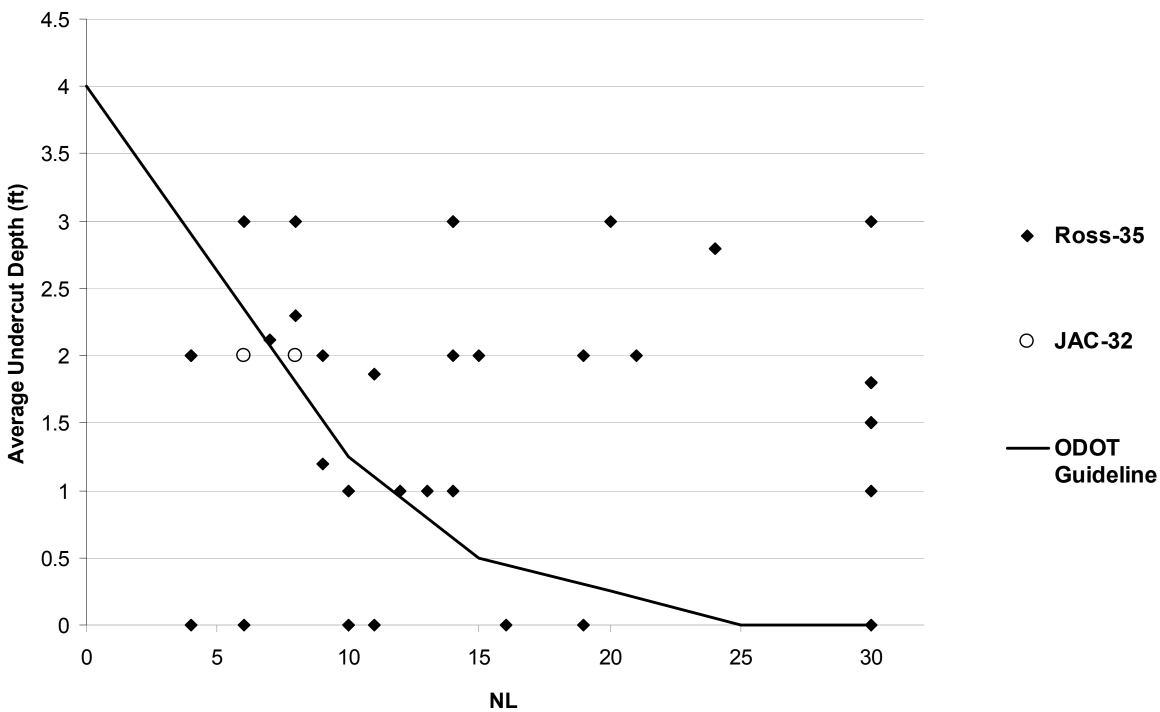
Figure 22. Determination of W5 Threshold for Undercut Prediction



Optimal Threshold for W5 ~ 0.18 mil

Figure 23. ROC Curve for W5

Figure 24 below shows the undercut and N_L data from the two new construction projects. It seems that for the data from ROS-US35 project, actual undercut depths are nearly unrelated to the N_L values. This is attributed to the fact that this new construction project has many cut-and-fill sections; only those near the eventual grade were used for analysis and represent only a small portion of the entire project. Therefore, predicting undercut depth from the SPT N_L value alone is not reliable, particularly for new construction projects.



(1 foot = 0.30 meters)

Figure 24. N_L versus Average Undercut Depth for New Construction Projects

Figures 25 and 26 show the undercut depth, N_L value, moisture content above the optimal (M-OMC), and Dynaflect W5 deflection along the Franklin I-70 and Median I-71 projects. These two projects have the most complete data among the projects studied.

A regression analysis was performed to correlate undercut depth with the available parameters. From the data available, moisture content above the optimal was found to be not a significant parameter in predicting undercut depth. The following regression equations were obtained:

Table 6. Regression Equations to Predict Undercut Depth

<table>
<tr><th></th><th>Based on Data from Every Boring</th><th>Based on Average Data Every 2500 ft. (762 Meters)</th></tr>
<tr><td>Data from All five Reconstruction Projects Combined</td><td>D* = $0.763 – 0.012\ N_L$
(n**=279, R^2 =0.075)</td><td>D = $1.072 – 0.029\ N_L$
(n= 54, R^2 =0.168)</td></tr>
<tr><td rowspan="3">Data from Franklin and Medina Projects</td><td>D = $1.069 – 0.0221\ N_L$
(n= 154, R^2 =0.319)</td><td>D = $1.313 – 0.039\ N_L$
(n= 33, R^2 =0.574)</td></tr>
<tr><td>D = 0.27 + 1.737 W5
(n= 154, R^2 =0.170)</td><td>D = -0.261 + 4.296 W5
(n= 33, R^2 =0.508)</td></tr>
<tr><td>D = $0.711 – 0.0195\ N_L$+ 1.266 W5
(n= 154, R^2 =0.405)</td><td>D = $–0.417 – 0.0223\ N_L$+ 2.956 W5
(n= 33, R^2 =0.710)</td></tr>
</table>

*D = average undercut depth in ft.

**n = number of data points

Not all data are available for every project. Most of the deflection data came from the Franklin I-70 and Medina I-71 projects. These two projects also have the most complete undercut information. Regression results based only on data from these two projects are much better than other data are included, possibly due to some undercut data from the Lucas SR-2 project are not complete – the low NL values are not associated large quantities of undercut.

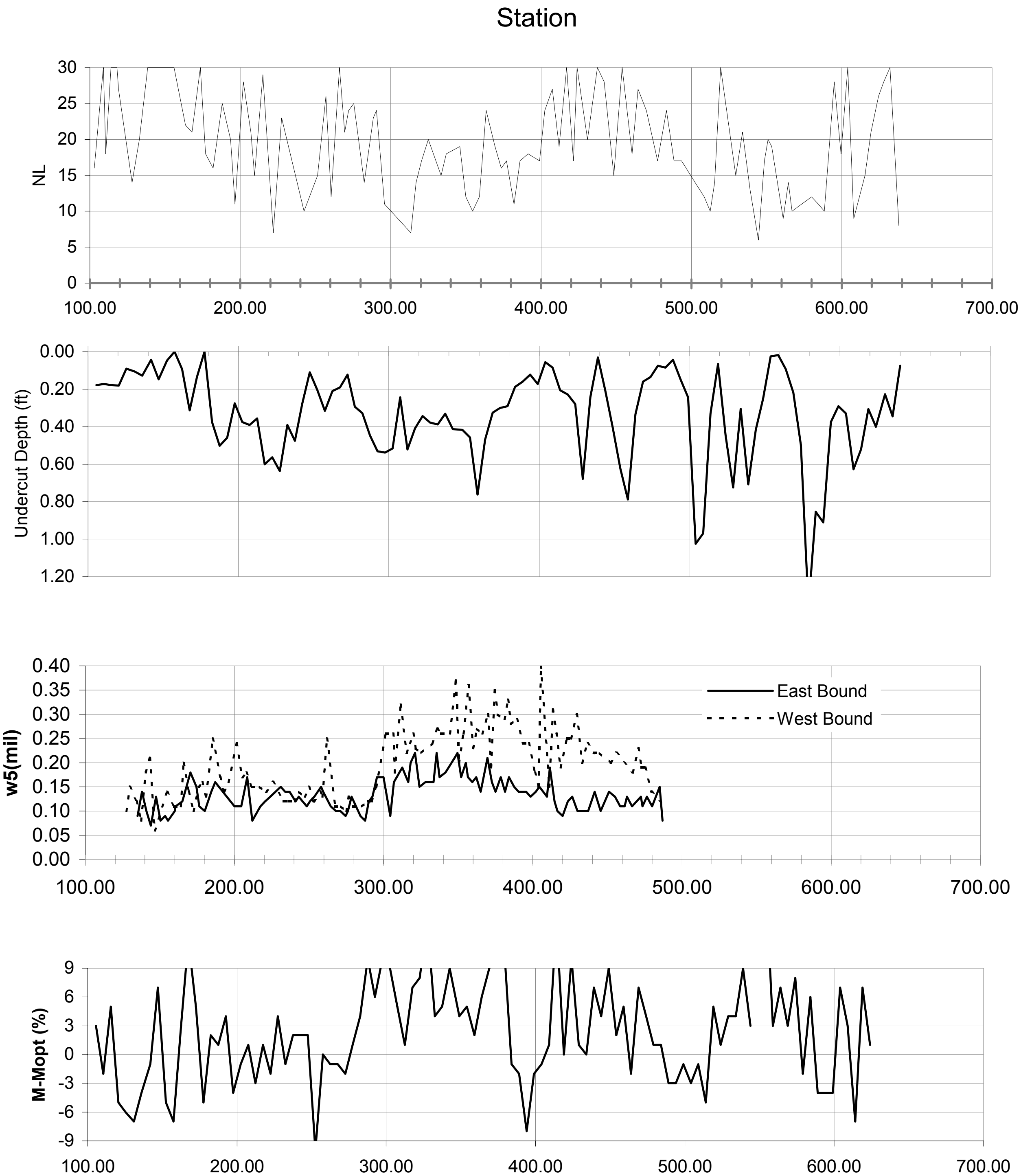


Figure 25. Undercut Depth, N_L, Moisture Content above Optimum, and W5 Deflection along the Franklin I-70-14.49 Project

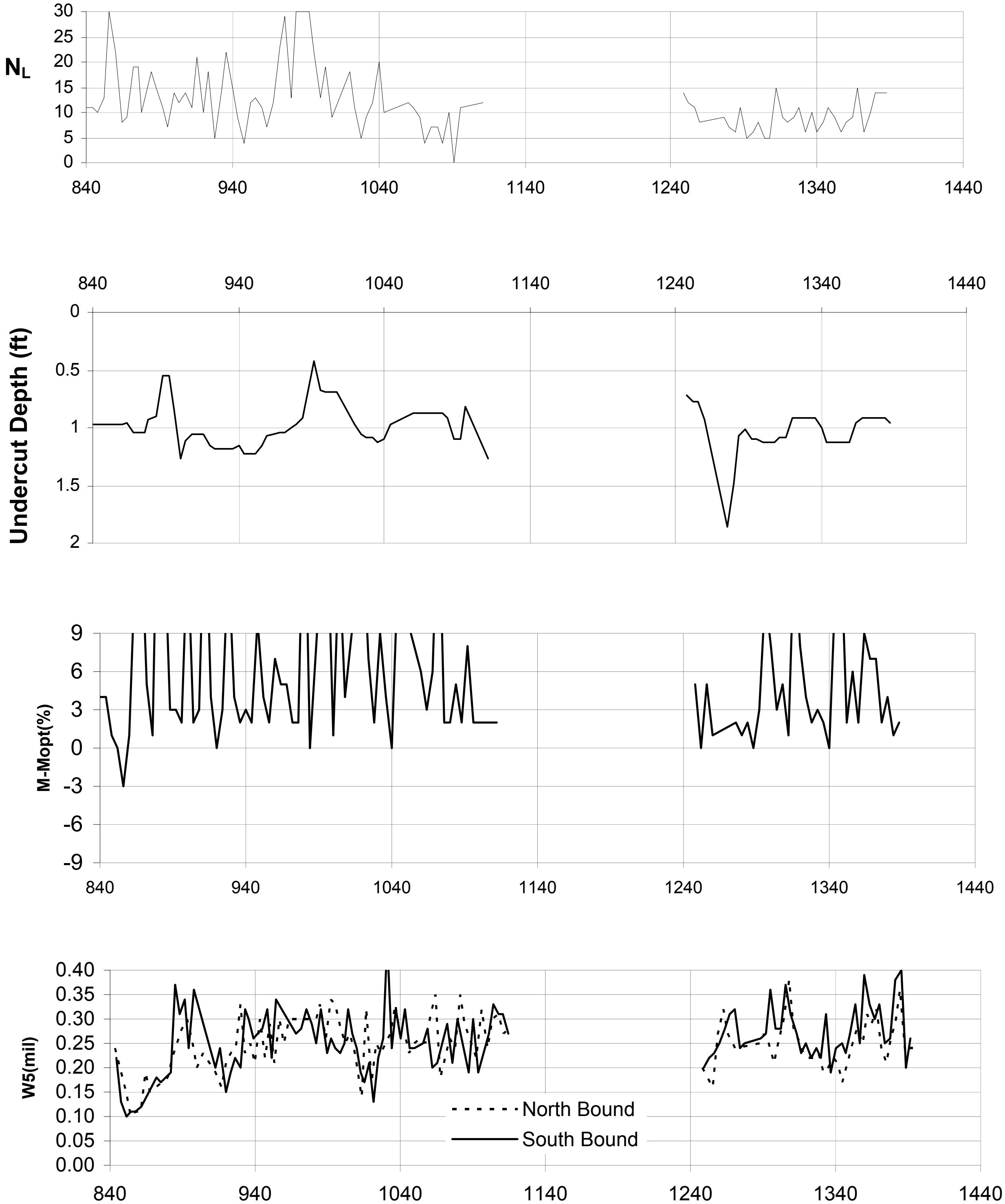


Figure 26. Undercut Depth, N_L, Moisture Content above Optimum, and W5 Deflection along the Medina I-71-5.78 Project

The low R-square values from the regression equations indicate the prediction of undercut depth at each boring location can not achieve very high accuracy, although including N_L and W5 as predictors improves the prediction.

Figure 27 shows a scatter plot of the predicted versus actual undercut depths using data from the Franklin and Medina projects, based on data for every boring, and both NL and W5 as the predicting parameters. That is: $D = 0.711 - 0.0195 N_L + 1.266 W5$ ($n = 154$, $R^2 = 0.405$). The regression model in this case is probably biased due to a few data points where soils were likely very stiff based on N_L and W5, but some undercut was still performed. As a result, the prediction equation based on every boring overall end up over predicting when the soil is stiff and under predicting when the soil is strong.

Figure 28 shows a scatter plot of the predicted versus actual undercut depths using data from the Franklin and Medina projects, based on data for every 2500 ft average, and both NL and W5 as the predicting parameters. That is, $D = -0.417 - 0.0223 N_L + 2.956 W5$ ($n = 33$, $R^2 = 0.710$). Given the highly variable nature of soils, the coefficient of determination (i.e., R-square value) of 0.71 seems fairly good. Additional data from future projects may be added to further refine this model.

The highly variable nature of soils, both spatially and with time, in addition to the fact that soil boring and deflection data are point specific, makes it very unlikely to have a very accurate prediction. Unless technological advances permit soil investigation to gather complete information covering the entire project area and depth, uncertainty and inaccuracy will continue to be part of the design process.

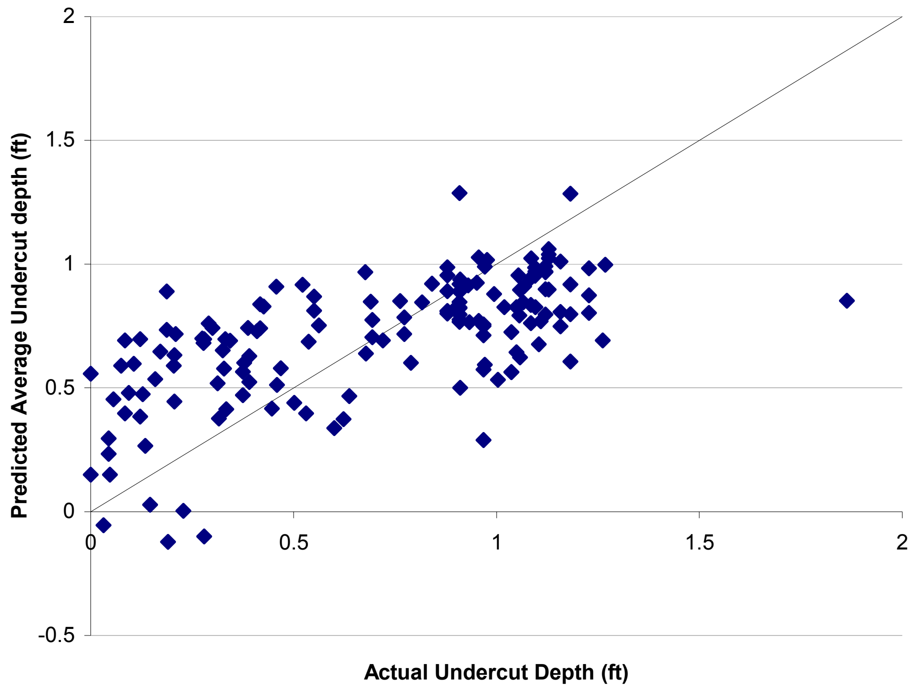


Figure 27. Predicted versus Actual Undercut Depth, 400 ft Section

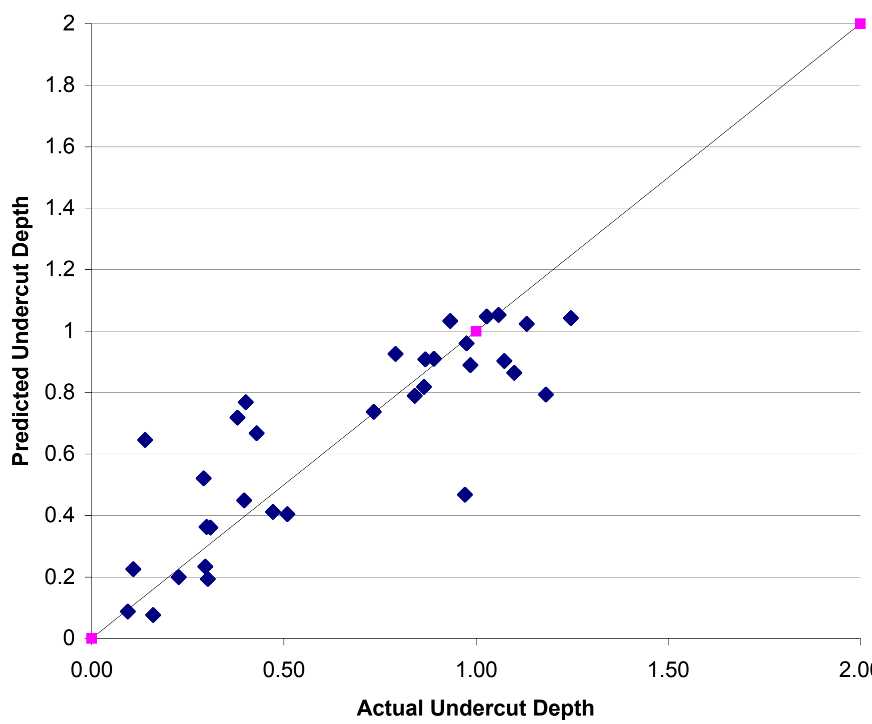


Figure 28. Predicted versus Actual Undercut Depth, 2500 ft Sections

TASK 3. COST BENEFIT ANALYSIS

Figure 29 is generated based on cost data analysis of recent projects done by ODOT Geotechnical Engineering staff. This figure shows that for reconstruction projects, when the total undercut quantity reaches 30% of the total project area, the cost of undercut is about break even with performing soil stabilization for the entire project area. For new construction projects, the cost of stabilizing the entire project area is equivalent to undercutting about 70% of the project area. Undercutting cost is much higher for reconstruction projects due to the need to maintain existing traffic flow and accessibility issues both to haul away removed soils and to bring in suitable backfill materials, whereas for new construction projects suitable materials are more readily available.

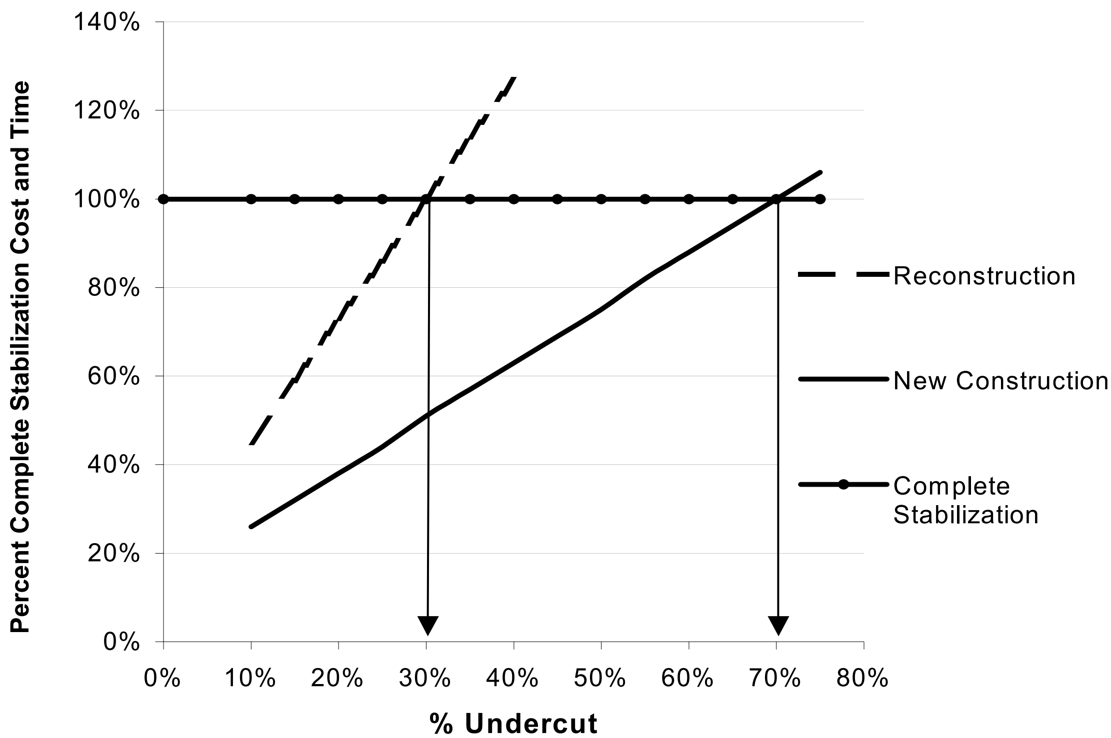


Figure 29. Break Even Cost of Undercut versus Complete Stabilization

The cost of subsurface investigation is estimated at about $90 per foot of boring. Therefore, for a typical five-foot deep boring for subgrade investigation, the cost is about $450. At 400 ft. spacing per boring (at alternating side of highway), the cost of current boring scheme is about $6,000 per mile (~5280/400*450). Dynaflect deflection measurement cost is estimated at about $730 per day ($650 for labor and $80 for traffic control equipment). Given a production rate of about 100 deflection measurements a day, and deflection measurement at every 50 foot, the cost of deflection testing is about $ 730 per mile.

Table 7 shows the costs and production rates for undercut and stabilization and new and reconstruction projects.

Table 7. Production Rates and Costs for Undercut and Stabilization on New and Reconstruction Projects

			Undercut New Construction (On Site Borrow Locations)	Undercut Reconstruction (Off Site Borrow Locations)
Undercut	Cost	Excavation	$5/ cu yd	$10/ cu yd
		Granular Material	$10/ cu yd	$20/ cu yd
		Subgrade Compaction	$0.75/ sq yd	$1/ sq yd
		Fabric	$1/ sq yd	$1.25/ sq yd
	Production Rate		1000 cu yd/day	400 cu yd/ day
Stabilization	Cost			
	12" Deep	Cement Total Cost	$5/ sq yd	$5/ sq yd
		Lime Total Cost	$4/ sq yd	$4/ sq yd
	16" Deep	Cement Total Cost	$ 6/ sq yd	$6/ sq yd
		Lime Total Cost	$5/ sq yd	$5/ sq yd
	Production Rate			
		12" Deep	9500 sq yd/day	9000 sq yd/day
		16" Deep	9000 sq yd/day	8500 sq yd/day

*Source: Correspondence with Randy Morris, ODOT Office of Construction

** If material is on site, the cost could be lower and production rate could be higher

The cost of undercut is dependent upon whether or not the borrow location is on site (as typically in the case of new construction) or off site (typical in the case of reconstruction). Production rate for on site borrow location is 1000 cubic yard a day, while for off site borrow locations is 400 cubic yard a day. For new construction, the cost of undercut includes \$5/yd^3 for excavation, \$10/ yd^3 for granular material, \$0.75/yd^2 for subgrade compaction, and \$1/yd^2 for fabric. The total estimated cost, assuming a width of 60 feet and a depth of one foot, is about \$237,600 per mile and require 12 days to complete. If 30% of the area require undercut, then the cost is about \$71,280 per mile, and it takes about 4 days.

For reconstruction projects, the cost for excavation is \$10/yd^3, for granular material, \$20/yd^3, subgrade compaction, \$1/yd^2, and fabric is \$1.25/yd^2. The total cost is about \$431,200 per mile and requires about 30 days to complete at the production rate of 400 cubic yards per day assuming a pavement width of 60 feet and at 1 foot depth. If 30% of the area require undercut, the cost is \$129,360 per mile, and it requires about 9 days.

The cost of stabilization on new construction is about \$140,800 per mile for 12 inches of lime stabilization or \$176,000 per mile for 12 inches of cement stabilization. The production rate is 9500 sy/day for 12 inches of stabilization, therefore, to stabilize an entire mile will take about 4 days. For 16 inches deep of stabilization, the cost of lime stabilization increases to \$176,000 per mile. For 16 inches of cement stabilization, the cost is about \$211,200. The production rate is reduced to 9000 sy/day. Therefore, it takes about 4 days to stabilize a mile.

For reconstruction projects, the cost is the same as for new construction, but the production rate for 12 inch deep stabilization is 9000 sy/day, and for 16 inch deep stabilization is 8500 sy/day. Therefore, it may take just over four days to stabilize an entire mile if 16 inches of stabilization is being done.

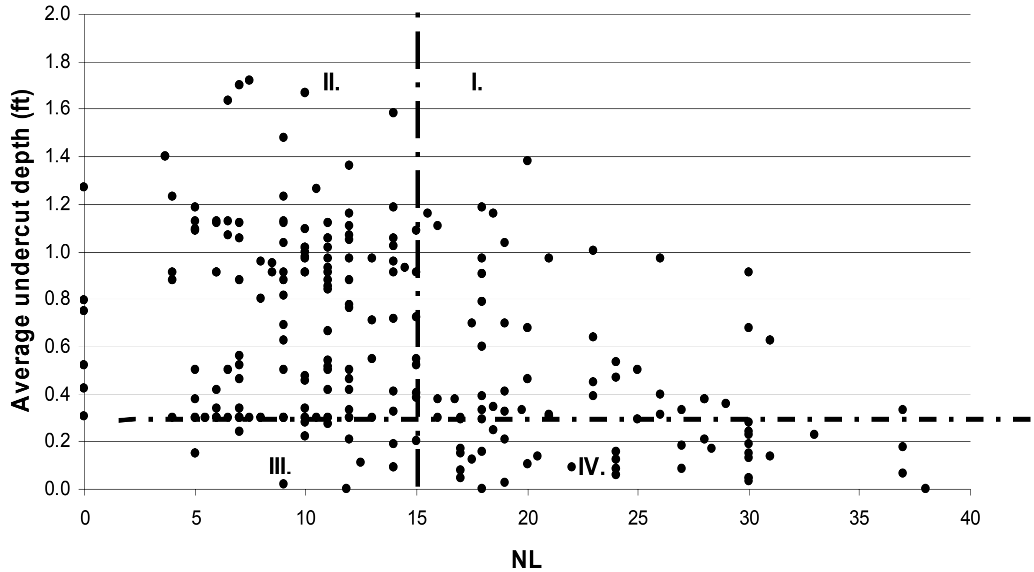
The above calculation shows that for new construction projects, the cost of performing undercut is relatively low. Therefore, it does take about roughly 70% of undercutting the entire area to be break even with the cost of stabilization with lime.

For reconstruction projects, the 30% break even point between undercut and stabilization is also fairly accurate. It seems that there is a significant time advantage to perform stabilization, particularly when the area requiring undercut is more than 30%. However, lime or cement stabilization requires up to 5 days of curing. When the curing time is included, the time required to perform stabilization is about the same as the time required to perform 30% undercut.

Predicting Whether or Not to Perform Complete Stabilization

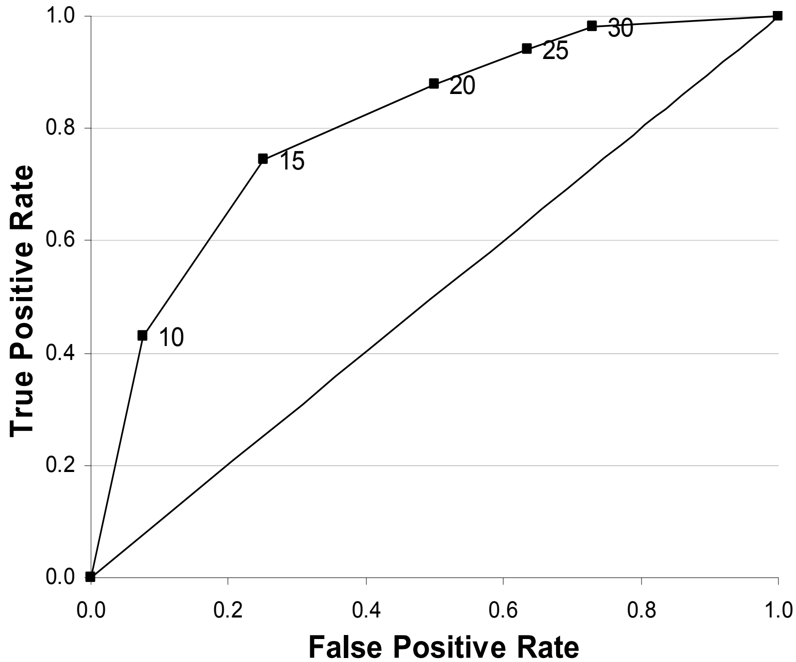
Figure 30 shows that the average N_L value may be used to predict whether or not the required undercut quantity will exceed 30 percent of the total project area, making complete undercut a better choice. The data are divided into four quadrants using a particular N_L threshold value and the 30% undercut line. The four quadrants are: I. Predicted less than 30% undercut, actual undercut more than 30%; II. Predicted more than 30 % undercut, actual undercut more than 30%; III. Predicted more than 30% undercut, actual undercut less than 30%; and IV. Predicted less than 30% undercut, actual undercut less than 30%. Figure 31 shows the corresponding ROC curve, which indicates that when the average N_L value is less than 15, more than 30% of the area is predicted to end up requiring undercut. Compared with Figure 20, where when average N_L is less than 17, some undercut is predicted.

Similarly, Figure 32 shows that the average W5 value may be used to predict whether or not the required the undercut quantity exceed 30 percent of the total project area. The data are divided into four quadrants using a certain W5 threshold value and the 30% undercut line:



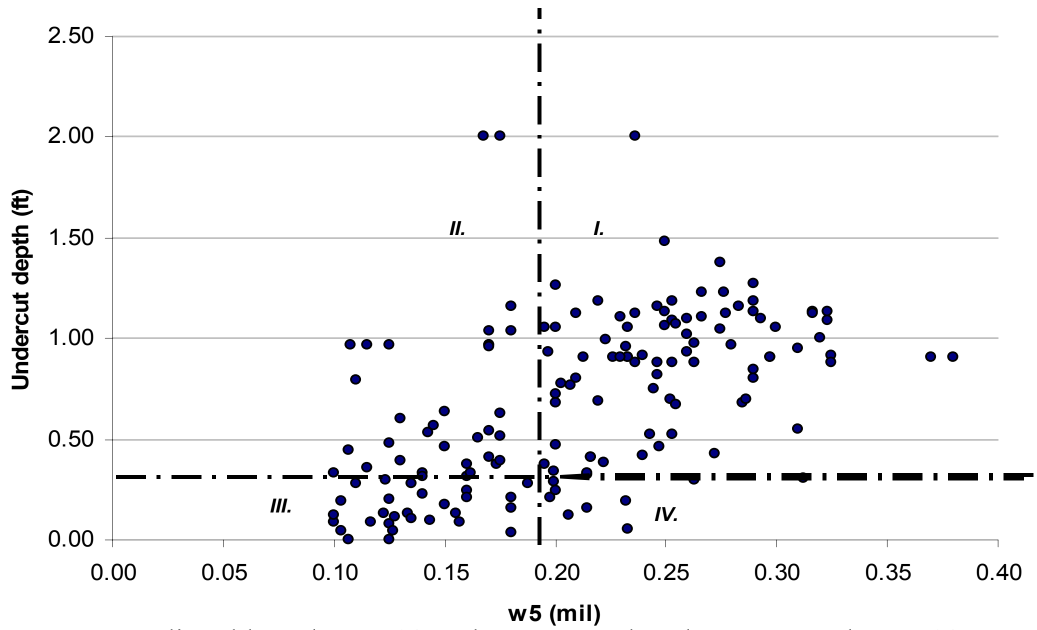
i. Predicted less than 30% undercut, actual undercut more than 30%.
ii. Predicted more than 30 % undercut, actual undercut more than 30%.
iii. Predicted more than 30% undercut, actual undercut less than 30%
IV. Predicted less than 30% undercut, actual undercut less than 30%
(1 foot = 0.30 meters)

Figure 30. NL versus Average Undercut Depth



Optimal Threshold for $N_L \sim 15$

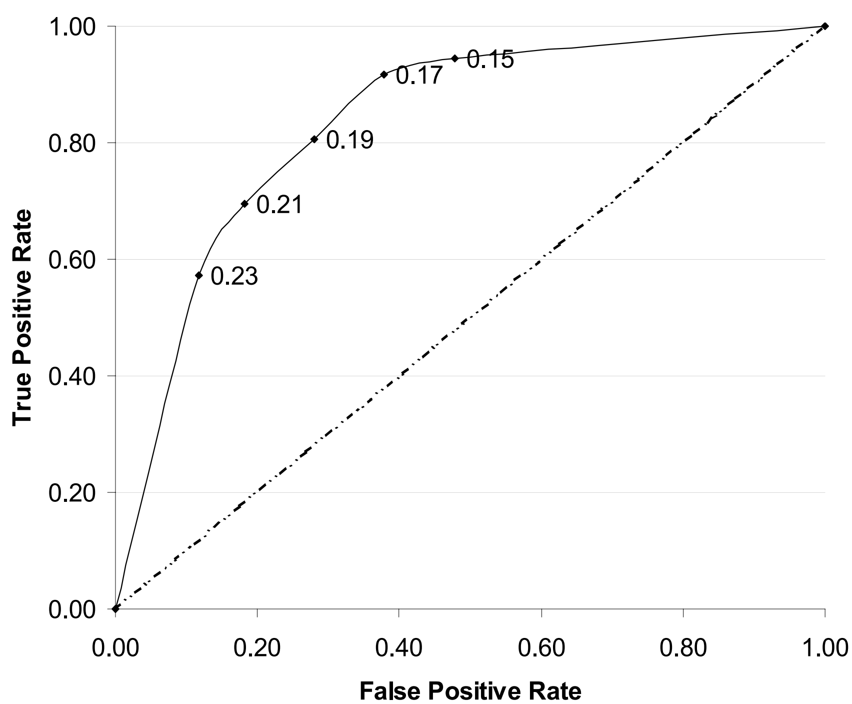
Figure 31. ROC Curve for Predicting 30% Undercut Using N_L



I. Predicted less than 30% undercut, actual undercut more than 30%.
II. Predicted more than 30 % undercut, actual undercut more than 30%.
III. Predicted more than 30% undercut, actual undercut less than 30%
IV. Predicted less than 30% undercut, actual undercut less than 30%

(1 foot = 0.30 meters)

Figure 32. W5 versus Average Undercut Depth



Optimal Threshold for W5 ~ 0.19 mil

Figure 33. ROC Curve for Predicting 30% Undercut with W5

The four quadrants are: I. Predicted less than 30% undercut, actual undercut more than 30%; II. Predicted more than 30 % undercut, actual undercut more than 30%; III. Predicted more than 30% undercut, actual undercut less than 30%; IV. Predicted less than 30% undercut, actual undercut less than 30%. Figure 26 shows the corresponding ROC curve, which indicates that when the average W5 value is greater than 0.19, then it is likely more than 30% of the area will end up having undercut. Note in Figure 22, the threshold is that when average W5 is greater than 0.18, some undercut will likely be required.

Comparing the results of predicting any amount of undercut versus predicting undercut amount exceeding 30% of the project, the two threshold values are not that different (for average N_L: 15 versus 17, and for average W5: 0.19 versus 0.18). This is due to the fact that nearly all projects studied have more than 30% undercut, despite the Franklin I-70 project had an average N_L value of about 19, higher than the threshold of 15. Therefore, except for cases where very high N_L or very low W5 are obtained, it seems reasonable to consider complete stabilization for all reconstruction projects.

Fewer amounts of data are available to allow a similar analysis and the threshold to justify complete stabilization is higher for new construction projects, yet the two projects studied both have more than 70% average undercut depth, therefore it would have been less expensive if complete stabilization were employed.

Complete stabilization may not address all the problems of wet and soft subgrade, since the stabilization depth is typically limited to 16 inches (40 cm) deep. Weak soils deeper than this depth still must be replaced. Presumably, this situation may not be wide spread. Complete chemical stabilization provides another benefit of added structural support to the pavement, resulting in thinner pavement layer thickness. More details on quantifying this structural benefit can be found in the recently completed report on “Structural Support of Lime or Cement Stabilized Subgrade Used with Flexible Pavements” (Report No. FHWA/OH-2004/017).

CONCLUSIONS AND RECOMMENDATIONS

This study was originated to evaluate the two existing guidelines for estimating the subgrade treatments: (1) the *Interim Guidelines for Plan Subgrade Treatments* (dated November 1, 2001), later updated as *Geotechnical Bulletin GB1 on Plan Subgrad*es (last updated July 14, 2004). (2) the *Subgrade Construction and Stabilization Guidelines* (dated April 18, 2002), subsequently included as Section 204 *Subgrade Compaction and Proof Rolling* in the *Construction Inspection Manual of Procedures* (2002).

The GB1 guideline is intended to be used during the design stage, prior to construction. GB1 utilizes data from soil borings, particularly the Standard Penetration Test (SPT) blow count, N_L, to estimate the extent of required subgrade treatment. Two sets of criteria depending on soil moisture content are provided.

The Section 204 guideline is for field construction personnel to determine the proper subgrade treatment actions during subgrade construction. Therefore, it can utilize boring data as well as available proof rolling and test pit data to determine the subgrade treatment method and extent. Criteria for reconstruction and new construction projects are different.

Based on the findings of this study, the following conclusions can be made:

1. Subgrade soils typically show high variability. The coefficient of variation (CV), defined as the standard deviation divided by the mean value, can be as high as 30% to 50%. In order to accurately determined the locations of weak soils spots and the quantity of undercut or stabilization, continuous data along the entire pavement area are required. Current technology does not provide such level of accuracy. Soil boring data provide only point specific information.

2. Nondestructive deflection data are also point specific, but because deflection tests are nondestructive, and are relatively fast and inexpensive to perform, they can be performed at much closer spacing, therefore, providing much more detailed information on subgrade

soil underneath than soil borings. The analysis on available data of the last sensor of Dynaflect deflection, W5, shows it is as good a predictor as SPT N_L value for soil undercut. Deflection data are also used in pavement thickness design. One drawback of the deflection test is that it requires a flat and smooth surface to perform, therefore, its use is generally limited to reconstruction (i.e., major rehabilitation) projects.

3. Based on the data available to this study, the GB1 criteria for excess moisture content predicted the undercut quantity reasonably well, but the criteria for acceptable moisture content tends to under predict the undercut quantity in many cases. Moisture content of the soil varies over time. The level of saturation of the soil at the time of construction can be very different from that at the time of boring. For reconstruction projects, after removal of the existing pavements, moisture content of subgrade often increases due to direct exposure to precipitation. Therefore, using the excess moisture content criteria as a default seems to be more representative of the likely field conditions.

4. Most of the data available for this study are from reconstruction projects. The average undercut depths (i.e., the overall undercut quantities) versus the corresponding SPT N_L values seem to fall reasonably well within the upper bound provided in the Section 204 guidelines for reconstruction projects. However, the actual undercut depths vary significantly even for soils with similar or same N_L values.

5. Subsurface investigation (soil boring) and treatment guidelines from other agencies are not significantly different from the current ODOT guidelines in terms of boring depth, locations, spacing, and other field and laboratory testing required. Current ODOT guidelines also have sufficient flexibility to deal with situations where more borings are required.

6. The analyses performed in this study show that actual undercut depth and quantity are correlated with both the SPT N_L value and Dynaflect W5 deflection, although the correlations are far from perfect. A regression analysis shows using average SPT N_L and

W5 deflection from every 2500 ft sections as parameters, average undercut depth in the section can be estimated with a coefficient of determination (or R-square value) of 0.71.

7. All the reconstruction projects studied end up having more than 30% of the project area receiving undercut, even for the Franklin I-70 project, which had a rather high average N_L value of about 19, indicating relatively stiff subgrade. Since 30% undercut is the break even point cost-wise compared to performing chemical stabilization for the entire project, it seems that specifying complete chemical stabilization would be a reasonable choice for most, if not all, reconstruction projects. However, note that chemical stabilization may not solve all subgrade problems; especially those caused by soft soils encapsulated more than 16 inches below grade surface.

8. For new construction projects, the cost break-even point is 70% undercut versus complete stabilization. Therefore, soil boring at closer spacing may be justified before specifying complete stabilization. However, both of the two new construction projects studied have more than average undercut depth of greater than 0.7 ft (0.2m). Therefore, it is likely to cost more to undercut than to stabilize. Chemical stabilization by lime or cement also provides structural support to the pavement, resulting in thinner pavement layer thickness as detailed in a recently completed study on “Structural Support of Lime or Cement Stabilized Subgrade Used with Flexible Pavements” (Report No. FHWA/OH-2004/017). Therefore, complete stabilization may also be considered on new construction projects.

The following recommendations are made based on the findings of this study:

1. Nondestructive surface deflection data, such as those by Dynaflect or Falling Weight Deflectometer, should be obtained on all reconstruction projects, at least as supplemental information to the soil boring data, to help identify the weak soil areas and estimate the quantity of required undercut or stabilization.

2. Pavement deflection is a promising approach to identify the presence of weak subgrade and estimating the quantity and location of likely undercut for reconstruction projects. This study shows when the W5 is greater than about 0.18 mils (0.0046 mm), undercut is very likely required. However, the deflection data available for this study are mostly from two projects: Franklin and Medina. Further study is recommended to investigate the effect of pavement thickness on measured deflections, and to confirm the findings of this study and establish more detailed criteria based on additional data.

3. The developed regression equation may be used by ODOT and should be verified and revised as more data become available. No other major changes to both existing guidelines seem necessary.

4. Complete chemical stabilization should be considered for all new or reconstruction projects. This recommendation coincides with the recommendation in the recently completed study on "Structural Support of Lime or Cement Stabilized Subgrade Used with Flexible Pavements". Soil stabilization provides a stable construction platform to facilitate construction traffic, which is the focus of the current study. Stabilization also provides long term structural support to the pavement to carry service traffic loadings, which is addressed by the other study.

5. ODOT should consider developing a geotechnical information database to store, in a consistent and easily retrievable format, all available soil investigation data as well as the eventual subgrade treatment methods and quantities for the entire State highway network. This database will be very useful in providing data for any future refinement of the subgrade treatment guidelines. It will also provide valuable information in connection with pavement performance evaluation.

6. Additional study to research or develop advanced technologies or devices that can provide continuous measurement of soil stiffness/density/moisture content prior to construction should be considered.

IMPLEMENTATION PLAN

The results of this research study can be implemented by ODOT as follows:

1. The recommendation to obtain detailed deflection data on reconstruction projects can be implemented without significant additional cost. Such deflection data would also benefit pavement design in addition to being used to identify the presence and extent of weak subgrades.

2. ODOT staff can use the findings of this study to revise the existing guidelines.

3. The average undercut depth prediction equation developed in this study may be used by ODOT staff and verified or refined as more data become available in future reconstruction projects.

4. The recommendation to consider using soil stabilization routinely for all new or reconstruction projects is consistent with recommendation in a previous study on lime or cement stabilized subgrades, and may be adopted as a departmental policy.

APPENDIX A. Soil Investigation and Undercut Information for Fayette US62-13.67

Table A1. Soil Investigation and Undercut Information for Fayette US62-13.67

Project ID Fayette US62-13.67	Standard Penetration							Undercut Depth(ft)	
Boring Location	n2	n3	N	n2	n3	N	N_L	WB	EB
221.00									
222.00	8	10	18	5	11	16	16	0	3
223.00								0	3
224.00	4	5	9	5	3	8	8	0	3
225.00								1	3
226.00								1	3
227.00	8	10	18	4	5	9	9	1	3
228.00								1	3
229.00								1	3
230.00	7	9	16	9	12	21	16	1	3
231.00								1	3
232.00								1	3
233.00	1	1	2	1	2	3	2	3	3
234.00								1	3
235.00								1	3
236.00								1	3
237.00	3	4	7	5	8	13	7	1	3
238.00								1	3
239.00								1	3
240.00	3	2	5	6	8	14	5	1	3
241.00								1	3
242.00	5	3	8	4	6	10	8	1	3
243.00								1	3
244.00								1	3
245.00								1	3
246.00								1	3
247.00								1	3
248.00								1	3
249.00								1	3
250.00	2	3	5	10	13	23	5	1	3
251.00								3	3
252.00								3	3
253.00	5	2	7	6	7	13	7	3	3
254.00								3	3
255.00								3	3
256.00								3	3
257.00								3	3
258.00	7	8	15	4	5	9	9	3	3
259.00								3	3
260.00								3	3
261.00	2	4	6	8	10	18	6	3	3
262.00								3	3
263.00								3	3
264.00								3	3
269.00								3	3

(1 foot = 0.30 meters)

APPENDIX B. Soil Investigation and Undercut Information for Franklin I70-14.49

Table B1. Soil Investigation and Undercut Information for Franklin I70-14.49

Project FRA I 70 - 14.49				Physical Characteristics														Moisture			Deflection Data		UD(ft)
B #	Boring Location	Nmin	LL			PI			% Silt			% Clay			Pass 200			M			WB	EB	
	89+33																					0.08	
	91+49																				0.04		
	91+97																					0.05	
	93+55																				0.06		
	94+45																					0.08	
	95+19																				0.06		
	97+25																						
	98+00																						
	100+75																						
1	103+00	16	21	22	22	6	6	6	36	37	40	29	28	27	65	65	67	11	13	11			
	105+00																						
	105+50																						**0.18**
	106+90																						**0.18**
	107+50																						**0.18**
109	108.50	29							9	7	6	5	3	3	14	10	9	9	12	15			**0.17**
2	109+18	38	25	22	23				35	17	37	30	14	28	65	31	65	8	8	8			**0.17**
3	110+80	18	24	25	25	16	17	17	25	30	28	53	63	59	78	93	87	21	16	12			**0.17**
	112+00																						**0.17**
	112+70																						**0.18**
	113+00																						**0.18**
111	113+20	41	NP	NP	NP	NP	NP	NP	6	7	5	7	4	5	5	11	10	19	11	16			**0.18**
	114+08																						**0.18**
	115+00																						**0.18**
	117+00																						**0.18**
110	118+00	33	24	24	0	22	0	0	32	36	0	36	28	0	36	64	0	10	10	0			**0.18**
4	118+20	27	23	22	NP	16	16	NP	33	37	40	28	31	27	61	68	67	10	10	11			**0.18**
	118+50																						**0.18**
	120+00																						**0.18**
5	123+00																						**0.09**
5	WB																						**0.09**
	124+00																						**0.09**
	125+52																						**0.09**
	126+25																						**0.09**
	127+56																					0.10	**0.11**
6	128+00	14	27	NP	NP	18	NP	NP	36	43	44	31	18	18	67	61	62	9	8	10			**0.11**
6	EB																						**0.11**
	129+00																						**0.11**
	130+00																						**0.11**
	130+73																					0.15	**0.11**
7	133+00	20	25	21	23	17	16	16	36	35	37	29	30	29	65	65	66	9	9	9			**0.13**
7	WB																						**0.13**
	133+95																					0.12	**0.13**
	134+69																				0.09		**0.13**
	137+11																					0.08	**0.13**
	137+75																				0.14		**0.13**
8	138+40	33	22	22	22	16	16	16	39	39	39	28	27	27	67	66	66	8	10	12			**0.04**
	140+23																					0.18	**0.04**
	140+81																				0.10		**0.04**
9	143+15	35	NP	NP	NP	NP	NP	NP	23	8	6	14	4	4	37	12	10	9	4	5			**0.04**
	143+40																					0.21	**0.04**
	144+03																				0.07		**0.15**
	145+45																						**0.15**
	146+62																					0.06	**0.15**
	146+75																						**0.15**
	147+00																				0.13		**0.15**
10	148+50	39	22	NP	0	15	NP		18	8	0	14	6	0	32	14		19	14	0			**0.15**
10	EB																						**0.15**
	149+10																						**0.05**
	150+16																				0.08		**0.05**
11	153+00	38	NP	25	25	NP	17	17	25	38	36	19	27	27	44	65	63	10	11	10			**0.05**

11	WB																						**0.05**
	153+59																				0.09		**0.05**
	156+65																					0.14	**0.00**
	156.76																				0.08		**0.00**
12	158+00	38	24	24	23	23	16	16	34	34	36	34	36	34	36	70	70	11	11	7			**0.00**
12	EB																						**0.00**
	159+87																					0.11	**0.09**
	160+13																				0.10		**0.09**
	161+30																				0.11		**0.09**
	162+00																						**0.09**
13	163+00	22	NP	NP	NP	NP	NP	NP	38	34	11	8	17	8	46	51	19	13	10	6			**0.09**
	163+14																					0.11	**0.09**
	164.73																				0.12		**0.31**
	165+50																						**0.31**
	166+20																					0.20	**0.31**
	167+50																						**0.31**
14	168+00	21	NP	NP	NP	NP	NP	NP	7	11	19	6	7	8	13	18	27	6	11	24			**0.31**
14	EB																						**0.31**
	169+64																					0.14	**0.31**
	170+00																						**0.13**
	170+75																				0.18		**0.13**
	171+00																						**0.13**
	172+86																					0.10	**0.13**
	173+00																						**0.13**
15	173+15	31	NP	NP	NP	NP	NP	NP	20	30	26	10	10	10	30	40	36	9	14	15			**0.13**
15	WB																						**0.13**
	174+07																				0.15		**0.13**
	176+19																					0.15	**0.00**
	177+35																				0.11		**0.00**
16	177+80	18	NP	24	25	NP	17	18	48	36	39	13	29	35	61	65	74	11	9	11			**0.00**
16	EB																						**0.00**
	179+25																					0.16	**0.00**
	180+36																				0.10		**0.38**
	182+00																						**0.38**
	182+31																					0.13	**0.38**
17	182+75	16	24	23	NP	16	17	NP	37	42	64	27	25	19	64	67	83	11	12	18			**0.38**
17	WB																						**0.38**
	183+63																				0.14		**0.50**
	185+53																					0.25	**0.50**
	186+64																				0.16		**0.50**
18	188+10	25	29	38	35	18	21	21	34	29	33	39	51	43	73	80	76	0	17	14			**0.50**
18	EB																						**0.50**
	188+25																						**0.50**
	188+65																						**0.46**
	189+17																					0.17	**0.46**
	190+50																						**0.46**
	192+34																					0.14	**0.46**
19	192+85	20	NP	NP	26	NP	NP	18	36	36	34	23	28	30	59	64	64	12	20	15			**0.46**
	193+05																						**0.46**
	194+71																						**0.46**
	195+00																						**0.28**
	195+88																					0.16	**0.28**
20	198+00	11	20	20	21	15	15	16	34	36	38	34	28	26	68	64	64	12	11	11			**0.28**
20	EB																						**0.28**
	200+75																						**0.28**
	201+75																						**0.28**
	202+10																						**0.38**
	202+48																				0.11		**0.38**
	202+96																					0.24	**0.38**
21	203+00	28	23	21	18	15	15	14	32	29	33	28	24	22	60	53	55	13	9	9			**0.38**
21	WB																						**0.38**
	205+00																						**0.38**
	205+86																				0.11		**0.39**
	206+33																					0.17	**0.39**
	207+00																						**0.39**
22	208+00	21	23	31	0	16	17		34	34	0	29	41	0	63	75		12	17	14			**0.39**
	209+00																						**0.39**
	211+88																					0.18	**0.39**

	211+98																				0.17		**0.39**
	213+00																						**0.39**
23	213+25	15	25	28	22	15	17	15	35	36	37	31	35	27	66	71	64	10	12	13			**0.39**
23	WB																						**0.36**
	214+88																						**0.36**
	215+26																					0.15	**0.36**
	215+31																				0.08		**0.36**
	216+42																						**0.36**
	217+10																						**0.36**
	217+50																						**0.60**
24	218+00	29	0	NP	NP		NP	NP	0	13	21	0	12	19		25	40	11	7	8			**0.60**
	218+53																					0.15	**0.60**
	218+58																				0.11		**0.60**
	219+75																						**0.60**
	220+00																						**0.60**
	222+00																						**0.56**
	222+23																				0.12		**0.56**
	222+81																					0.14	**0.56**
	223+75																						**0.56**
25	224+20	7	28	25	0	18	16		34	33	0	34	29	0	68	62		14	12	10			**0.56**
25	WB																						**0.56**
	225+00																						**0.56**
	225+13																				0.13		**0.56**
	225+25																						**0.64**
	226+00																						**0.64**
	226+50																						**0.64**
	226+66																					0.16	**0.64**
	227+25																						**0.64**
26	228+00	23	24	26	21	15	18	15	31	30	31	29	30	25	60	60	56	10	20	12			**0.64**
26	EB																						**0.64**
	228+56																						**0.64**
	229+60																						**0.64**
	230+60																						**0.64**
	231+20																						**0.39**
	231+75																						**0.39**
	232+10																				0.15		**0.39**
	232+40		0	0					0	0		0	0					14	0				**0.39**
27	233+00																	14					**0.39**
27	WB																						**0.39**
	234+48																					0.12	**0.39**
	235+00																						**0.39**
	235+16																				0.14		**0.39**
	235+58																						**0.48**
	235+75																						**0.48**
	237+88																	15					**0.48**
28	238+00		23	0	0	17			25	0	0	26	0	0	51			15	0	0			**0.48**
	238+07																					0.12	**0.48**
	238+44																				0.14		**0.48**
	239+00																						**0.48**
	240+00																						**0.48**
	241+50																					0.12	**0.28**
	241+72																				0.12		**0.28**
	242+00																						**0.28**
	242+25																						**0.28**
29	242+90	10	26	25	30	17	16	20	37	34	33	32	29	35	69	63	68	15	11	15			**0.28**
	244+83																				0.13		**0.28**
	245+00																					0.14	**0.28**
	246+15																						**0.28**
	246+23																						**0.11**
	246+59																						**0.11**
	246+88																						**0.11**
30	EB																						**0.11**
	248+47																					0.13	**0.11**
	249+68																				0.11		**0.11**
	250+00																						**0.11**
	250+75																						**0.20**
	252+06																					0.15	**0.20**
	252+90																				0.12		**0.20**

	253+00																						**0.20**
31	253+15	15	26	27	29	17	17	18	34	34	35	32	33	35	66	67	70	13	14	18			**0.20**
	253+75																						**0.20**
	255+00																						**0.20**
	255+39																					0.12	**0.20**
	256+00																				0.13		**0.20**
	257+00																						**0.20**
	257+20																						**0.32**
	257+75																						**0.32**
32	258+00	26	26	29	23	17	18	16	31	32	36	35	35	27	66	67	63	11	18	11			**0.32**
	258+61																					0.14	**0.32**
	259+08																				0.15		**0.32**
	259+50																						**0.32**
	261+77																					0.13	**0.32**
	262+09																				0.14		**0.32**
	262+18																						**0.21**
33	262+85	12	26	29	31	15	18	20	37	21	18	31	26	25	68	47	43	18	18	18			**0.21**
	263+35																						**0.21**
	264+00																						**0.21**
	264+63																					0.25	**0.21**
	265+42																				0.11		**0.21**
	266+35																						**0.19**
	267+00																						**0.19**
34	268+00	50	24	24	27	27	17	18	31	33	33	33	31	33	33	64	66	11	12	11			**0.19**
34	EB																						**0.19**
	268+30																					0.11	**0.19**
	268+60																				0.10		**0.19**
	269+50																						**0.19**
33A	270+00	21	25	NP	25	17	NP	17	24	13	37	23	9	31	47	22	68	11	16	17			**0.19**
	270+68																						**0.12**
	271+00																						**0.12**
	271+81																				0.10		**0.12**
	271+97																					0.11	**0.12**
35	272+00	24	23	29	23	16	18	16	33	34	35	29	36	29	62	70	64	12	16	9			**0.12**
	273+50																						**0.12**
	274+97																				0.09		**0.29**
	275+03																					0.10	**0.29**
36	278+00	25	27	27	26	17	18	17	34	32	33	36	34	32	70	66	65	15	13	13			**0.29**
	278+14																				0.10		**0.29**
	278+46																					0.13	**0.29**
	279+00																						**0.29**
	280+00																						**0.29**
	281+10																				0.13		**0.29**
	281+50																						**0.29**
	281+84																					0.11	**0.33**
37	283+15	14	25	23	24	16	16	16	33	36	35	32	29	33	65	65	68	13	13	15			**0.33**
	283+22																						**0.33**
	283+32																				0.09		**0.45**
	284+00																						**0.45**
	285+38																					0.11	**0.45**
	286+00																						**0.45**
	286+59																				0.08		**0.45**
	287+50																						**0.45**
38	287+80	23	29	26	23	19	18	17	20	28	27	20	30	21	40	58	48	14	9	11			**0.45**
	288+00																						**0.45**
	288+65																					0.12	**0.53**
	389+81																				0.12		**0.53**
39	289+85	24	32	28	29	19	18	18	32	34	36	38	33	33	70	67	69	17	13	14			**0.53**
	290+28																						**0.53**
	291+68																						**0.53**
	292+08																					0.12	**0.53**
	293+03																				0.13		**0.53**
	295+00																						**0.53**
	295+46																					0.15	**0.54**
	295+88																				0.17		**0.54**
40	297+50	11	32	28	31	19	19	19	30	36	33	42	35	34	72	71	67	20	17	13			**0.54**
	298+00																						**0.54**
	300+00																				0.17		**0.52**

	300+87																						**0.52**
	301+69																					0.26	**0.52**
	302+80																						**0.52**
	303+18																						**0.52**
	304+54																				0.09		**0.52**
	305+18																					0.26	**0.24**
	307+55																				0.16		**0.24**
	308+56																					0.18	**0.24**
	309+64																						**0.24**
	310+20																						**0.52**
	312+57																					0.32	**0.52**
	313+00																						**0.52**
	313+41																				0.19		**0.52**
43	314+10	7	28	0	21	18		16	36	0	37	35	0	23	71		60	25	26	11			**0.52**
	314+84																						**0.52**
	315+05																						**0.52**
	315+47																					0.22	**0.41**
	317+16																				0.16		**0.41**
44	318+00	14	21	30	31	15	19	18	34	35	33	27	40	41	61	75	74	10	12	22			**0.41**
	318+64																					0.24	**0.41**
	320+22																				0.20		**0.41**
	320+93																						**0.41**
	321+81																					0.26	**0.34**
45	322+82	17	0	35	44		23	23	0	43	35	0	41	49		84	84	17	28	30			**0.34**
	323+29																				0.22		**0.34**
	324+92																					0.23	**0.34**
	325+00																						**0.34**
	325+10																						**0.34**
	325+62																				0.15		**0.34**
	327+55																						**0.38**
46	328+10	20	35	29	39	20	15	22	34	36	37	46	36	46	80	72	83	23	21	26			**0.38**
	328+30																					0.22	**0.38**
	329+00																						**0.38**
	329+31																				0.16		**0.38**
	330+24																						**0.38**
	330+40																						**0.38**
	331+00																						**0.39**
	331+84																					0.24	**0.39**
	332+00																						**0.39**
47	332+72	15	33	26	36	19	18	20	35	35	35	44	35	46	79	70	81	18	19	21	0.16		**0.39**
	334+74																				0.22		**0.33**
	335+38																					0.27	**0.33**
	337+00																						**0.33**
48	337+80	18	0	33	28		19	19	0	33	36	0	40	36		73	72	16	17	12			**0.33**
	337+86																				0.17		**0.33**
	338+00																						**0.33**
	338+70																					0.26	**0.33**
	339+00																						**0.33**
	340+83																						**0.41**
	341+19																				0.18		**0.41**
	342+20																					0.26	**0.41**
	342+31																						**0.41**
	342+90																						**0.41**
49	343+22	19	29	32	30	17	20	19	36	39	38	38	41	37	74	80	75	18	23	18			**0.42**
	343+60																						**0.42**
	344+00																						**0.42**
	344+25																				0.21		**0.42**
	345+00																						**0.42**
	345+83																					0.37	**0.42**
	346+70																						**0.42**
	346+99																				0.22		**0.42**
50	348+20	12	39	37	34	23	22	19	40	33	33	46	43	37	86	76	70	26	23	22			**0.42**
	348+54																					0.20	**0.42**
	350+00																						**0.46**
	351+00																						**0.46**
	351+06																				0.17		**0.46**
	351+90																					0.26	**0.46**
	352+16																						**0.46**

51	352+75	10	30	46	52	21	23	24	29	32	30	33	55	57	62	87	87	14	23	35			**0.46**
	354+17																				0.20		**0.46**
	354+38																						**0.46**
	354+82																						**0.76**
	355+18																				0.17		**0.76**
	355+50																					0.36	**0.76**
	356+00																						**0.76**
	357+25																						**0.76**
	357+50																						**0.76**
52	358+10	12	27	34	44	17	20	23	34	42	33	39	47	55	73	89	88	14	20	24			**0.76**
	358+46																				0.16		**0.76**
	358+87																					0.23	**0.76**
	359+10																						**0.76**
	359+71																						**0.76**
	360+50																						**0.47**
	361+57																				0.17		**0.47**
	361+94																					0.27	**0.47**
	362+27																						**0.47**
53	363+00	24	26	44	42	18	23	22	32	34	35	31	53	50	63	87	85	17	25	21			**0.47**
	364+00																						**0.47**
	364+79																				0.14		**0.47**
	364+82																						**0.47**
	365+37																					0.26	**0.47**
	366+00																						**0.33**
	367+00																						**0.33**
	367+50																						**0.33**
54	367+90	19	27	0	0	18			32	0	0	34	0	0	66			13	19	25	0.21		**0.33**
	368+33																					0.30	**0.33**
	370+50																						**0.33**
	371+00																						**0.30**
	371+55																					0.19	**0.30**
	372+15																				0.16		**0.30**
	372+60																						**0.30**
55	373+00	16	NP	32	52	NP	21	25	16	41	33	17	43	56	33	84	89	21	21	26			**0.30**
	373+75																						**0.30**
	374+66																					0.35	**0.30**
	375+24																				0.14		**0.30**
	376+00																						**0.30**
	377+50																						**0.30**
	377.78																					0.30	**0.29**
56	378+00	17	0	42	30		22	22	0	37	31	0	48	53		85	84	8	24	20			**0.29**
	378+25																				0.17		**0.29**
	378+50																						**0.29**
	381+10																					0.29	**0.29**
	381+95																				0.14		**0.19**
57	383+00	11	33	47	0	20	25		34	34	0	41	52	0	75	86		20	24	24			**0.19**
	384+27																					0.33	**0.19**
	385+38																				0.17		**0.19**
	387+33																					0.28	**0.19**
58	388+10	17	26	28	25	18	18	18	24	34	32	29	36	33	53	70	65	22	14	12			**0.19**
	388+49																				0.15		**0.16**
	390+45																					0.29	**0.16**
	391+50																						**0.16**
	391+66																				0.14		**0.16**
	392+95																						**0.16**
59	393+00	18	0	0	0				0	0	0	0	0	0				19	21	0			**0.12**
	393+07																						**0.12**
	393+77																					0.24	**0.12**
	393+90																						**0.12**
	394+08																						**0.12**
	394+25																						**0.12**
	394+95																				0.14		**0.12**
	395+12																						**0.17**
	396+12																						**0.17**
	396+62																						**0.17**
	397+00																					0.24	**0.17**
	397+13																						**0.17**
	398+05																				0.13		**0.17**

60	398+20	17	24	22	33	17	17	24	26	26	40	31	23	40	57	49	80	16	10	31			**0.17**
	398+42																						**0.17**
	398+79																						**0.17**
	400+01																					0.18	**0.06**
	401+01																				0.14		**0.06**
61	403+00	24	25	27	37	18	18	22	13	32	34	13	32	49	26	64	83	13	25	28			**0.06**
	403+23																					0.15	**0.06**
	405+34																				0.15		**0.06**
	406+58																						**0.06**
	406+97																					0.40	**0.06**
	407+10																						**0.08**
62	408+00	27	22	24	26	15	17	17	20	25	33	22	32	33	42	57	66	9	14	15			**0.08**
	408+18																						**0.08**
	408+45																				0.13		**0.08**
	408+56																						**0.08**
	409+83																						**0.08**
	410+41																					0.15	**0.21**
	411+73																				0.19		**0.21**
63	413+00	19	33	NP	NP	20	NP	NP	33	23	16	41	20	16	74	43	32	9	11	14			**0.21**
	413+63																					0.31	**0.21**
	414+50																						**0.21**
	414+63																				0.12		**0.21**
	415+05																						**0.21**
	416+03																						**0.21**
	416+85																					0.26	**0.23**
	418.01																				0.10		**0.23**
64	418+15	51	22	0	0	17			13	0	0	11	0	0	24			6	8	0			**0.23**
	420+23																					0.19	**0.23**
	421+23																				0.09		**0.23**
	421+75																						**0.23**
	422+59																						**0.28**
65	423+00	17	0	0	22			18	0	0	17	0	0	14			31	9	0	10			**0.28**
	423+24																					0.25	**0.28**
	424+35																				0.12		**0.28**
66	426+00	58	NP	NP	27	NP	NP	18	9	10	23	6	9	30	15	19	53	5	7	15			**0.28**
	426+41																					0.25	**0.28**
	426+85																						**0.68**
	427+73																				0.13		**0.68**
	428+50																						**0.68**
	429+28																						**0.68**
	430+52																					0.30	**0.68**
	430+95																				0.10		**0.68**
	432+68																						**0.68**
67	433+00	20	23	26	31	18	17	19	13	27	21	12	29	25	25	56	46	13	9	17			**0.68**
	433+80																					0.20	**0.24**
	434+43																				0.10		**0.24**
	435+00																						**0.24**
	436+08																						**0.24**
	437+49																					0.24	**0.03**
	437+76																				0.10		**0.03**
68	437+90	55	0	0	0				0	0	0	0	0	0				26	0	0			**0.03**
	439+80																						**0.03**
	440+00																						**0.03**
	441+00																						**0.03**
	441+66																					0.22	**0.21**
	441+88																				0.14		**0.21**
69	442+77	28	0	0	28			18	0	0	34	0	0	36			70	13	16	15			**0.21**
	442+81																						**0.21**
	443+18																						**0.21**
	444+64																						**0.21**
	444+83																					0.22	**0.21**
	445+00																				0.10		**0.21**
	445+33																						**0.41**
	445+50																						**0.41**
	446+00																						**0.41**
	447+00																						**0.41**
70	447+90	15	0	38	35		22	21	0	38	34	0	44	44		82	78	21	27	19			**0.41**
70	EB																						**0.41**

	448+61																						**0.41**
	449+10																						**0.41**
	450+96																				0.14		**0.62**
	451+75																					0.20	**0.62**
	452+07																						**0.62**
71	453+00	31	0	30	27		19	19	0	32	32	0	35	28		67	60	16	17	15			**0.62**
	453+53																						**0.62**
	454+02																				0.13		**0.62**
	454+86																					0.22	**0.79**
	455+60																						**0.79**
	457+19																				0.11		**0.79**
	457+50																						**0.79**
	457+57																						**0.79**
	457+50																						**0.79**
72	458+20	18	30	44	24	18	24	17	32	26	33	40	55	33	72	81	66	15	21	14			**0.79**
	460+05																						**0.79**
	460+14																				0.11		**0.33**
	460+38																						**0.33**
	461+30																						**0.33**
	461+89																				0.13		**0.33**
	462+00																						**0.33**
	462+52																						**0.33**
73	463+00	27	0	25	37		21	23	0	34	37	0	38	46		72	83	12	23	25			**0.33**
	464+70																						**0.33**
	464+84																						**0.33**
	465+00																						**0.33**
	465+11																				0.11		**0.16**
	466+36																					0.18	**0.16**
	466+75																						**0.16**
	467+00																						**0.16**
	467+35																						**0.16**
	467+73																						**0.16**
	467+86																						**0.16**
74	468+00	24	26	0	28	18		21	14	0	43	15	0	36	29		79	18	20	19			**0.16**
	469+82																						**0.16**
	470+12																					0.23	**0.16**
	470+27																						**0.13**
	470+64																						**0.13**
	471+29																				0.13		**0.13**
	473+87																					0.19	**0.13**
	474+03																				0.11		**0.13**
	474+50																						**0.13**
	475+00																						**0.13**
	476+05																						**0.13**
	476+93																					0.19	**0.13**
	477+06																						**0.13**
	477+30																				0.13		**0.08**
	477+74																						**0.08**
76	478+00	17	29	2	26	18	-9	12	31	29	19	37	35	26	68	64	45	16	17	25			**0.08**
	480+09																						**0.08**
	480+26																					0.14	**0.08**
	480+37																				0.11		**0.08**
	480+69																						**0.08**
	481+50																						**0.08**
	482+06																						**0.08**
	482+50																						**0.08**
	482+56																						**0.08**
	482+80																						**0.08**
77	483+00	24	26	24	37	18	17	23	34	40	25	35	28	33	69	68	58	12	13	20			**0.08**
	483+17																				0.15		**0.08**
	483+41																						**0.08**
	483+80																					0.12	**0.08**
	484+00																						**0.04**
	485+54																				0.08		**0.04**
	486+14																						**0.04**
	487+27																						**0.04**
78	488+10	17	0	30	36		19	21	0	36	28	0	40	43		76	71	21	16	16			**0.04**
	488+15																						**0.04**

	489+75																						**0.04**
	490+50																						**0.15**
79	493+50																						**0.15**
79	WB																						**0.15**
80	498+00	17	27	28	28	19	18	20	30	26	18	27	29	19	57	55	37	14	14	12			**0.15**
	498+25																						**0.15**
	498+35																						**0.15**
	498+50																						**0.24**
	495+20																						**0.24**
	495+66																						**0.24**
	499+19																						**0.24**
	500+38																						**0.24**
	502+00																						**0.24**
	502+05																						**1.03**
81	503+00	14	30	30	0	17	21		33	41	0	36	39	0	69	80		10	23	19			**1.03**
	503+50																						**1.03**
	504+00																						**1.03**
	504+62																						**1.03**
	505+18																						**1.03**
	505+48																						**1.03**
	505+60																						**0.97**
	505+80																						**0.97**
	506+15																						**0.97**
	506+70																						**0.97**
82	508+16	12	0	0	0				0	0	0	0	0	0				0	0	16			**0.97**
	510+30																						**0.97**
	510+75																						**0.97**
	511+20																						**0.97**
83	513+00	10	24	24	24	16	15	16	33	31	35	34	34	33	67	65	68	14	17	14			**0.33**
	516+61																						**0.33**
	517+30																						**0.33**
84	517+90	14	NP	NP	NP	NP	NP	NP	35	36	38	22	24	25	57	60	63	8	11	10			**0.33**
	518+75																						**0.07**
	520+55																						**0.07**
	521+17																						**0.07**
85	523+00	37	NP	NP	NP	NP	NP	NP	7	10	12	10	7	9	17	17	21	7	8	9			**0.07**
	524+05																						**0.45**
	525+20																						**0.45**
	525+86																						**0.45**
	526+71																						**0.45**
	536+25																						**0.73**
	526+36																						**0.73**
	527+00																						**0.73**
86	527+90	15	NP	22	21	NP	16	17	14	34	34	10	31	28	24	65	62	9	10	13			**0.73**
	528+42																						**0.73**
	529+09																						**0.73**
	529+80																						**0.30**
	530+17																						**0.30**
	531+76																						**0.30**
	531+85																						**0.30**
87	533+00	21	NP	25	23	NP	18	17	12	37	40	7	32	33	19	69	73	8	11	15			**0.30**
	533+75																						**0.30**
	535+69																						**0.30**
	536+16																						**0.30**
	536+25																						**0.71**
	537+00																						**0.71**
	537+06																						**0.71**
	537+32																						**0.71**
88	537+90	13	24	24	23	17	16	16	34	34	36	35	35	34	69	69	70	13	13	12			**0.71**
	540+25																						**0.71**
	540+45																						**0.71**
	540+56																						**0.71**
	540+63																						**0.71**
	540+75																						**0.42**
	541+28																						**0.42**
	542+66																						**0.42**
89	543+00	6	22	24	34	15	16	20	34	35	34	27	32	44	61	67	78	11	12	15			**0.42**
	543+35																						**0.42**

	543+41																						**0.42**
	543+98																						**0.42**
	544+00																						**0.25**
	545+26																						**0.25**
	546+57																						**0.25**
	547+04																						**0.25**
90	548+00	17	0	0	36			20	0	0	36	0	0	44			80	9	11	0			**0.25**
	548+92																						**0.25**
	549+00																						**0.25**
	551+70																						**0.25**
91	553+00	20	36	36	0	20	20		36	32	0	44	46	0	80	78		0	21	21			**0.25**
91	WB																						**0.03**
	554+40																						**0.03**
	557+80																						**0.03**
92	558+10	19	37	28	32	20	17	20	32	35	37	44	36	42	76	71	79	15	17	15			**0.03**
93	563+00	9	32	32	30	20	18	18	31	34	34	43	39	38	74	73	72	20	9	11			**0.09**
94	568+30	14	32	35	0	20	21		36	38	0	45	49	0	81	87		16	18	20			**0.09**
	570+80																						**0.22**
	571+03																						**0.22**
95	573+00	10	31	38	36	21	21	22	43	28	19	44	47	36	87	75	55	26	20	18			**0.22**
	573+31																						**0.50**
	574+00																						**0.50**
	575+00																						**0.50**
	576+00																						**1.36**
	577+15																						**1.36**
	578+30																						**1.36**
	579+00																						**1.36**
96	579+10	12	28	31	27	19	20	20	25	34	22	28	42	21	53	76	43	15	19	19			**1.36**
	579+50																						**1.36**
	579+75																						**1.36**
	580+00																						**0.85**
	581+44																						**0.85**
97	583+00	11	0	0	0				0	0	0	0	0	0				0	0	26			**0.85**
	583+15																						**0.85**
	584+14																						**0.85**
	585+87																						**0.91**
	586+38																						**0.91**
	587+00																						**0.91**
98	588+05	10	NP	NP	NP	NP	NP	NP	26	20	38	17	17	17	43	37	55	29	20	20			**0.91**
	588+22																						**0.91**
	589+12																						**0.91**
	590+50																						**0.38**
	591+14																						**0.38**
	592+16																						**0.38**
99	593+00	28	30	28	37	19	21	21	37	41	31	40	32	49	77	73	80	13	10	19			**0.38**
	594+22																						**0.38**
	594+35																						**0.38**
	594+62																						**0.29**
	594+80																						**0.29**
	596+47																						**0.29**
	596+55																						**0.29**
	597+88																						**0.29**
	598+05																						**0.29**
100	598+20	18	0	35	36		20	21	0	24	30	0	35	36		59	66	19	23	14			**0.29**
	600+05																						**0.29**
	600+12																						**0.29**
	600+16																						**0.33**
	601+20																						**0.33**
	601+26																						**0.33**
	602+50																						**0.33**
101	603+00	37	30	28	29	19	19	19	31	34	35	30	28	29	61	62	64	18	11	19			**0.33**
	605+26																						**0.33**
	606+15																						**0.33**
	606+27																						**0.63**
102	607+90	9	0	34	34		21	21	0	37	41	0	45	45		82	86	14	20	24			**0.63**
	608+55																						**0.63**
	609+38																						**0.63**
	610+20																						**0.52**

	611+10																						**0.52**
	612+52																						**0.52**
103	613+00	15	28	0	0	18			33	0	0	36	0	0	69			14	0	0			**0.52**
	614+10																						**0.31**
	615+50																						**0.31**
	616+15																						**0.31**
	617+58																						**0.31**
104	618+15	21	0	0	28			18	0	0	36	0	0	36			72	22	21	20			**0.31**
	618+66																						**0.31**
	619+92																						**0.40**
	620+18																						**0.40**
	621+13																						**0.40**
	622+24																						**0.40**
105	623+00	26	22	22	22	16	16	14	40	38	39	33	31	30	73	69	69	12	11	9			**0.40**
	623+19																						**0.40**
	624+10																						**0.40**
	626+59																						**0.23**
	627+00																						**0.23**
106	627+90	28	21	22	0	17	16		39	40	0	25	30	0	64	70		8	12	0			**0.23**
	628+38																						**0.23**
	629+05																						**0.23**
	630+00																						**0.23**
107	633+00	38	22	NP	NP	16	NP	NP	34	39	39	26	29	23	60	68	62	12	12	8			**0.35**
	634+00																						**0.35**
	636+78																						**0.35**
	637+15																						**0.35**
108	638+00	8	37	34	27	22	21	19	21	26	33	40	43	32	61	69	65	15	24	16			**0.08**
	638+07																						**0.08**
	639+00																						**0.33**
	640+21																						**0.33**

(1 foot = 0.30 meters)

APPENDIX C. Soil Investigation and Undercut Information for Lucas SR2-21.15

Table C1. Soil Investigation and Undercut Information for Lucas SR2-21.15

Project LUCAS SR2 - 21.15				Standard Penetration				Physical Characteristics						Moisture	Classification	Undercut Depth(ft)	
B #	Boring Location		Depth	n2	n3	N	NL	LL	PL	PI	% Silt	% Clay	Pass 200	M	Class	WB	EB
	1123+00															1	0.10
1	1127+00	44R	2.5	6	7	13								14	3a	1	0.10
1			5	5	12	17					2	2	4	17	3a	1	0.10
1			7.5	3	4	7	13							25	3a	1	0.10
	1129+00															1	0.10
2	1131+00	28L	2.5											4		0.5	0.10
2			5	2	3	5								29	6b	0.5	0.10
2			7.5	3	4	7	5	36	20	16	45	53	98	26	6b	0.5	0.10
3	1134+49	40R	2.5	2	3	5		20	16	4	27	27	54	11	4a	0.5	0.10
3			5	2	8	10								10	4a	0.5	0.10
3			7.5	4	5	9	5							18	6b	0.5	0.10
4	1139+00	55L	2.5	4	4	8								26		0.5	0.10
4			5	3	5	8								28	6b	0.5	0.10
4			7.5	3	5	8	8	38	19	19	39	57	96	24	6b	0.5	0.10
5	1143+00	52R	5	5	3	8		39	19	20	37	57	94	17	6b	0.5	0.10
5			7.5	6	7	13								16	6b	0.5	0.10
5			10	4	6	10	8							20	6b	0.5	0.10
6	1147+00	35L	2.5											5		0.5	0.10
6			5	2	3	5								24	6b	0.5	0.10
6			7.5	2	3	5	5	32	21	11	64	35	99	26	6a	0.5	0.10
7	1151+00	35R	2.5	6	4	10								16		0.5	0.10
7			5	2	3	5		29	18	11	44	42	86	19	6a	0.5	0.10
7			7.5	3	4	7	5							26	6a	0.5	0.10
8	1155+05	40L	2.5	5	6	11								15		0.5	0.10
8			5	6	8	14								15	6a	0.5	0.10
8			7.5	13	13	26	11	28	19	9	63	36	99	18	4b	0.5	0.10
9	1158+80	53R	2.5	5	6	11								12		0.5	0.10
9			5	8	10	18									4a	0.5	0.10
9			7.5	3	4	7	11								4a	0.5	0.10
10	1162+93	40L	2.5	4	3	7								12		0.5	0.10
10			5	10	8	18								22	3	0.5	0.10
10			7.5	6	8	14	7	31	19	12	44	55	99	24	6a	0.5	0.10
11	1167+06	65R	2.5											1		0.5	0.10
11			5	4	5	9		31	20	11	52	41	93	20	6a	0.5	0.10
11			7.5	3	4	7	9							20	6a	0.5	0.10
12	1170+93	42L	2.5	3	5	8								31		0.5	0.10
12			5	4	5	9		44	21	23	33	57	90	20	7-6	0.5	0.10
12			7.5	3	3	6	8							27	6b	0.5	0.10
13			5	3	3	6		35	19	16	47	47	94	14	6b	0.5	0.10
13			7.5	3	3	6	6							15	6a	0.5	0.10
14	1178+98	33L	2.5											9		0.5	0.10
14			5	5	7	12		36	18	18	31	52	83	15	6b	0.5	0.10
14			7.5	4	5	9	9							24	6b	0.5	0.10
15	1182+91	49R	2.5	12	5	17								4		0.5	0.10
15			5											10		0.5	0.10
15			7.5	3	3	6	17							12	6b	0.5	0.10
16	1186+93	30L	2.5	2	6	8								18		0.5	0.10
16			5	3	3	6		41	20	21	37	61	98	25	7-6	0.5	0.10
16			7.5	4	5	9	6							25	6b	0.5	0.10
	1187+80															0.5	0.10
17	1190+96	26R	2.5	3	2	5								14		0.5	0.5
17			5	4	4	8								20	6b	0.5	0.5
17			7.5	3	3	6	5	44	19	25	33	55	88	25	7-6	0.5	0.5
18	1194+98	32L	2.5	4	4	8								13	6b	0.5	0.5
18			5	4	6	10								16	6b	0.5	0.5
18			7.5	3	4	7	8	32	21	11	47	52	99	27	6a	0.5	0.5
19	1198+92	30R	2.5	2	3	5								19	6b	0.5	0.5
19			5	3	2	5								27	6b	0.5	0.5
19			7.5	3	2	5	5	45	22	23	40	58	98	31	7-6	0.5	0.5
20	1202+97	32L	2.5	8	7	15								3		0.5	0.5
20			5	7	4	11								2		0.5	0.5
20			7.5	2	2	4	11	33	18	15	38	35	73	14	6a	0.5	0.5

	1206+50															0.5	0.5
21	1207+00	26R	2.5	5	8	13								16		0.5	0.1
21			5	3	4	7								17		0.5	0.1
21			7.5	3	4	7	7							24	6b	0.5	0.1
22	1210+95	35L	2.5	19	21	40								11		0.5	0.1
22			5	7	9	16		40	19	21	34	57	91	16	6b	0.5	0.1
22			7.5	5	4	9	9							17	6b	0.5	0.1
23	1214+43	19R	2.5	4	6	10								17		0.5	0.1
23			5	3	2	5								13		0.5	0.1
23			7.5	2	3	5	5	32	18	14	24	33	57	21	6a	0.5	0.1
	1216+80															0.5	0.1
24	1219+00	35L	2.5	4	3	7								29		0.5	0.5
24			5	2	3	5								23	6b	0.5	0.5
24			7.5	2	2	4	5	34	21	13	48	50	98	32	6a	0.5	0.5
25	1223+00	66R	2.5	4	5	9		51	21	30	35	81	116	18	7-6	0.5	0.5
25			5	3	5	8								19	6b	0.5	0.5
25			7.5	3	4	7	8							22	6a	0.5	0.5
26	1226+97	33L	2.5	6	7	13								16		0.5	0.5
26			5	5	7	12								18	6b	0.5	0.5
26			7.5	3	2	5	12							25	6a	0.5	0.5
27	1231+00	67R	2.5											14	6b	0.5	0.5
27			5	4	5	9								18	6a	0.5	0.5
27			7.5	3	5	8	9	34	20	14	42	57	99	23	6a	0.5	0.5
28	1235+14	30L	2.5											8		0.5	0.5
28			5	5	6	11								17	6b	0.5	0.5
28			7.5	3	4	7	11	41	21	20	42	56	98	26	7-6	0.5	0.5
	1238+00															0.5	0.5
29	1239+00	90R	2.5	5	6	11								15	7-6	0.5	0.1
29			5	3	3	6		45	21	24	35	63	98	21	7-6	0.5	0.1
29			7.5	3	2	5	6							24	6a	0.5	0.1
30	1243+00	42R	2.5	3	4	7								9		0.5	0.1
30			5	2	3	5								21		0.5	0.1
30			7.5	3	3	6	5	31	14	17	46	41	87	24	6b	0.5	0.1
31	1247+00	70R	2.5	3	3	6								22		0.5	0.1
31			5	4	6	10		56	21	35	38	59	97	23	7-6	0.5	0.1
31			7.5	2	2	4	6							25	7-6	0.5	0.1
32	1251+00	65R	2.5	3	5	8		53	19	34	41	56	97	21	7-6	0.5	0.1
32			5	6	6	12								24	6b	0.5	0.1
32			7.5	3	3	6	8							28	6a	0.5	0.1
33	1254+65	65R	2.5	4	4	8								21		0.5	0.1
33			5	7	7	14								27	6b	0.5	0.1
33			7.5	2	2	4	8							25	6a	0.5	0.1
34	1259+00	16R	2.5	3	3	6								23		0.5	0.1
34			5	4	4	8		51	20	31	41	53	94	27	7-6	0.5	0.1
34			7.5	3	4	7	6							20	7-6	0.5	0.1
35	1263+00	16R	2.5	3	3	6								13		0.5	0.1
35			5	5	5	10		45	20	25	46	50	96	24	7-6	0.5	0.1
35			7.5	2	2	4	6							23		0.5	0.1
36	1267+25	21R	2.5	4	4	8		50	19	31	41	56	97	23	7-6	0.5	0.1
36			5	4	3	7								28		0.5	0.1
36			7.5	2	2	4	7							28		0.5	0.1
37	1271+00	65R	2.5	4	5	9								25	6b	0.5	0.1
37			5	4	5	9								23	6b	0.5	0.1
37			7.5	4	6	10	9	25	14	11	26	38	64	13	6a	0.5	0.1
38	1275+00	20R	2.5	2	4	6								22	6b	0.5	0.1
38			5	4	4	8								22	6a	0.5	0.1
38			7.5	2	2	4	6	45	21	24	40	50	90	28	7-6	0.5	0.1
39	1279+00	30R	2.5	2	2	4		36	19	17	48	45	93	20	6b	0.5	0.1
39			5	3	3	6								20	6b	0.5	0.1
39			7.5	1	2	3	4							15	6b	0.5	0.1
40	1263+00	36R	2.5	4	4	8								23	6b	0.5	0.1
40			5	4	3	7								24	6a	0.5	0.1
40			7.5	1	2	3	7	33	20	13	48	50	98	22	6a	0.5	0.1
41	1287+00	48R	2.5	3	4	7								21	6a	0.5	0.1
41			5	4	4	8								21	6a	0.5	0.1
41			7.5	2	2	4	7	29	16	13	33	41	74	18	6a	0.5	0.1
42	1291+25	8R	2.5	3	4	7								22	6b	0.5	0.1
42			5	7	5	12								26	6b	0.5	0.1

42			7.5	3	3	6	7	38	19	19	48	50	98	26	6b	0.5	0.1
43	1295+03	34R	2.5	3	4	7								29		0.5	0.1
43			5	5	5	10		47	20	27	43	53	96	23	7-6	0.5	0.1
43			7.5	4	4	8	7							24	6a	0.5	0.1
44	1298+97	40L	2.5	5	9	14		57	23	34	30	65	95	18	7-6	0.5	0.1
44			5	7	7	14								17	7-6	0.5	0.1
44			7.5	3	4	7	14							21	6a	0.5	0.1
45	1303+00	36R	2.5	4	5	9								20	7-6	0.5	0.1
45			5	4	5	9		56	23	33	29	58	87	19	7-6	0.5	0.1
45			7.5	3	3	6	9							28	6a	0.5	0.1
46	1307+00	15L	2.5	5	7	12								14		0.5	0.1
46			5	4	6	10								19	6b	0.5	0.1
46			7.5	3	3	6	10	37	21	16	42	56	98	24	6b	0.5	0.1
	1309+00															0.5	0.1
47	1311+26	36R	2.5	5	7	12								19		0.5	0.5
47			5	6	8	14								21	7-6	0.5	0.5
47			7.5	3	2	5	12	48	20	28	30	65	95	27	7-6	0.5	0.5
	1314+00															0.5	0.5
48	1314+94	24L	2.5	8	7	15								9		0.1	0.5
48			5	4	4	8								22	7-6	0.1	0.5
48			7.5	5	5	10	8	44	20	24	37	61	98	22	7-6	0.1	0.5
	1316+00															0.1	0.5
56	1347+00	36L	2.5	6	3	9								7		0.1	0.50
56			5	3	5	8								26	6a	0.1	0.50
56			7.5	5	6	11	8	43	20	23	34	64	98	25	7-6	0.1	0.50
57	1350+97	28R	2.5	5	3	8								8		0.1	0.50
57			5	2	2	4								20	7-6	0.1	0.50
57			7.5	3	4	7	4	34	18	16	32	54	86	21	6b	0.1	0.50
	1353+50															0.1	0.50
58	1354+71	26L	2.5	3	4	7		53	23	30	33	62	95	20	7-6	0.50	0.50
58			5	6	5	11								19	7-6	0.50	0.50
58			7.5	4	6	10	7							20	7-6	0.50	0.50
	1357+65															0.50	0.50
59	1359+00	37R	2.5	4	6	10		55	23	32	30	66	96	15	7-6	0.50	0.1
59			5	7	7	14								15	7-6	0.50	0.1
59			7.5	2	3	5	10							17	7-6	0.50	0.1
60	1362+97	28L	2.5	6	8	14		55	23	32	30	66	96	16	7-6	0.50	0.1
60			5	3	5	8								19	7-6	0.50	0.1
60			7.5	4	5	9	8							24	7-6	0.50	0.1
61	1367+00	23R	2.5	3	3	6								19	6b	0.50	0.1
61			5	4	3	7								22	6a	0.50	0.1
61			7.5	3	3	6	6	30	19	11	39	50	89	21	6a	0.50	0.1
62	1371+03	32L	2.5	10	7	17								15	6b	0.50	0.1
62			5	7	10	17		39	21	18	44	54	98	10	6b	0.50	0.1
62			7.5	4	4	8	17							22	6b	0.50	0.1
63	1375+00	30R	2.5	3	4	7								16	6b	0.50	0.1
63			5	4	5	9		30	18	12	41	41	82	10	6a	0.50	0.1
63			7.5	3	4	7	7							22	6a	0.50	0.1
64	1376+97	28L	2.5	4	9	13								10	6b	0.50	0.1
64			5	3	3	6		37	19	18	54	37	91	22	6b	0.50	0.1
64			7.5	8	20	28	6							14	6b	0.50	0.1
65	1383+00	30R	2.5	6	8	14								14	6b	0.50	0.1
65			5	5	7	12		40	20	20	35	54	89	16	6b	0.50	0.1
65			7.5	5	8	13	12							16	6b	0.50	0.1
66	1386+97	28L	2.5	5	8	13								9	6b	0.50	0.1
66			5	4	6	10								16	6b	0.50	0.1
66			7.5	4	6	10	10	43	21	22	33	62	95	23	7-6	0.50	0.1
67	1390+90	32R	2.5	5	6	11								11	6b	0.50	0.1
67			5	6	6	12								15	6b	0.50	0.1
67			7.5	3	3	6	11	33	19	14	50	49	99	21	6a	0.50	0.1
68	1394+97	28L	2.5	7	8	15								17	7-6	0.50	0.1
68			5	5	5	10		43	20	23	37	60	97	20	7-6	0.50	0.1
68			7.5	4	6	10	10							20	7-6	0.50	0.1
69	1399+11	13R	2.5	5	6	11								16	6b	0.50	0.1
69			5	2	2	4		38	21	17	36	60	96	21	6b	0.50	0.1
69			7.5	3	3	6	4							22	6b	0.50	0.1
70	1402.97	28L	2.5	8	9	17								12	6b	0.50	0.1
70			5	6	7	13								10	6a	0.50	0.1

70			7.5	8	9	17	13	31	18	13	25	57	82	17	6a	0.50	0.1
71	1407+01	23R	2.5	2	3	5								16	6b	0.50	0.1
71			5	3	3	6								16	6b	0.50	0.1
71			7.5	4	7	11	5	32	17	15	33	54	87	25	6a	0.50	0.1
72	1410+97	28L	2.5	7	8	15								10	6b	0.50	0.1
72			5	3	5	8								15	6b	0.50	0.1
72			7.5	7	7	14	8	30	18	12	38	53	91	17	6a	0.50	0.1
73	1415+00	31R	2.5	4	7	11		56	22	34	31	66	97	13	7-6	0.50	0.1
73			5	4	7	11								19	7-6	0.50	0.1
73			7.5	2	2	4	11							28	6b	0.50	0.1
74	1419+00	30L	2.5	4	5	9								14	7-6	0.50	0.1
74			5	4	5	9		42	21	21	31	65	96	15	7-6	0.50	0.1
74			7.5	4	5	9	9							21	6a	0.50	0.1
75	1422+90	23R	2.5	3	4	7								12	6b	0.50	0.1
75			5	2	2	4								22	6b	0.50	0.1
75			7.5	3	4	7	4	33	18	15	28	49	77	20	6a	0.50	0.1
76	1427+05	22L	2.5	5	4	9								15	6b	0.50	0.1
76			5	5	4	9								22	6b	0.50	0.1
76			7.5	4	7	11	9	47	19	28	26	60	86	24	7-6	0.50	0.1
77	1431+00	23R	2.5	5	5	10								13	6b	0.50	0.1
77			5	3	2	5								18	6a	0.50	0.1
77			7.5	3	4	7	5	38	20	18	25	65	90	11	6b	0.50	0.1
78	1435+97	27L	2.5	3	3	6								15	7-6	0.50	0.1
78			5	4	4	8		47	22	25	30	68	98	26	7-6	0.50	0.1
78			7.5	3	2	5	6							32	6a	0.50	0.1
79	1439+00	31R	2.5	4	6	10								14	6b	0.50	0.1
79			5	4	5	9		37	20	17	41	56	97	15	6b	0.50	0.1
79			7.5	3	6	9	9							20	6b	0.50	0.1

(1 foot = 0.30 meters)

APPENDIX D. Soil Investigation and Undercut Information for Lucas I280-4.67

Table D1. Soil Investigation and Undercut Information for Lucas I280-4.67

B #	Boring Location	Depth	Standard Penetration				Physical Characteristics						Moisture	Classification	Undercut Average depth 500 feet
			n2	n3	N	NL	LL	PL	PI	% Silt	% Clay	Pass #200	M	Class	
	237+00														
	297+00														
	298+00														
R1	300+70	2.5	4	6	10		27	16	11	45	36	81	13.4	6a	1.02
R1		5	5	6	11		31	19	12	45	38	83	5.9	6a	
R1		7.5	4	5	9	10							8.3		
R12	301+10	2.5	5	5	10		32	16	16	36	41	77	19.2	6b	
R12	302+00	5	9	11	20		29	16	13	33	46	79	12.4	6a	
R12	304+00	7.5	8	9	17	10							12.5		
	304+12	2.5	4	6	10								16.9		
R5		5	4	7	11		28	17	11	36	37	73	12.0	6a	
R5		7.5	7	8	15	10	27	16	11	35	41	76	12.2	6a	
R5															
															1.67
R4	309+30	2.5	11	6	17								8.5		
R4		5	13	12	25		32	19	13	50	45	95	15.5	6a	
R4		7.5	13	15	28	17	35	17	18	30	56	86	17.5	6b	1.58
R6	311+75	2.5	9	8	17		16	13	3	20	13	33	19.3	3a	
R6		5	5	6	11		29	18	11	41	44	85	14.3	6a	
R6		7.5	7	7	14	11							11.5		
	314+00														
R11	314+83	2.5	7	4	11								8.0		
R11		5	3	5	8		31	18	13	40	48	88	18.0	6a	
R11		7.5	7	9	16	8	29	16	13	39	44	83	14.7	6a	1.72
	315+00														
	317+00														
R7	317+85	2.5	6	6	12		29	18	11	63	35	98	18.0	6a	
R7		5	3	4	7		32	18	14	54	42	96	25.4	6a	
R7		7.5	4	6	10	7							17.8		
	318+00														
	319+00														
															1.70
R10	321+50	2.5	3	4	7		29	17	12	43	55	98	16.5	6a	
	322+00														
	323+00														
M5	323+50	2.5	6	8	14								20.5	6a	
M5		5	5	6	11								9.0		

M5		7.5	6	5	11	11							16.5	6a	
R9	324+75	2.5	1	3	4		29	18	11	37	52	89	17.6	6a	
R9		5	1	1	2		41	19	22	26	66	92	34.0	7-6	
R9		7.5	2	2	4	2							29.0		1.63
	325+00														
	327+00														
R8	327+60	2.5	4	5	9								14.3		
R8		5	3	3	6		33	17	16	50	48	98	29.4	6b	
R8		7.5	1	2	3	6	26	15	11	36	41	77	20.6	6a	
	328+00														
R3	328+08	2.5	3	3	6		31	18	13	38	54	92	20.6	6a	
R3		5	1	1	2		NP	NP	####	24	20	44	15.7	4a	
M4	329+28	2.5	6	5	11								21.2	6a	1.40
M4		5	1	1	2		26	15	11	22	56	78	21.6	6a	
M4		7.5	2	2	4	2							18.9	6a	
M7	330+75	2.5	3	2	5								17.0	3a	
M7		5	1	2	3		26	15	11	26	50	76	21.0	6a	
M7		7.5	2	2	4	3							21.0	6a	
	333+00														
M1	333+85	2.5	8	10	18								9.3	6a	
M1		5	2	1	3		27	16	11	25	37	62	14.9	6a	
M1		7.5	2	2	4	3							17.4	6a	
M2	336+10	2.5	6	7	13								15.5		0.15
M2		5	3	4	7		29	17	12	30	43	73	18.7	6a	
M2		7.5	3	4	7	7							15.5	6a	
M3	338+08	2.5	6	10	16								13.9		
M3		5	6	7	13		27	16	11	35	38	73	19.0	6a	
M3		7.5	6	7	13	13							18.9	6a	
	339+00														
	339+60														

(1 foot = 0.30 meters)

APPENDIX E. Soil Investigation and Undercut Information for Medina I71-5.78

Table E1. Soil Investigation and Undercut Information for Medina I71-5.78

Coordinate	Bor #		n	NL	LL	PL	PI	% Silt	% Clay	P200	M		W5		average undercut depth 500 feet	average undercut depth 2500 feet
839.00													**Value**	**Value**		
840.00	1	1.0	16								15					
841.00		3.5	11		25	17	8	28	49	77	16	4a				
842.00		6.0	12	11							15					
843.00																
844.00	2	1.0	22		26	17	9	37	39	76	13	4a		**0.22**		
845.00		3.5	11								15				**0.968**	
846.00		6.0	11	11							16		**0.16**			
847.00														**0.13**		
848.00	3	1.0	24								12					
849.00		3.5	10								17					
850.00		6.0	10	10	38	23	15		72	72	19	6a			**0.968**	
851.00													**0.15**	**0.1**		
852.00	4	1.0	13								13					
853.00		3.5	14		29	17	12		71	71	14	6a				
854.00		6.0	14	13							14		**0.1**	**0.11**		
855.00															**0.968**	**0.97**
856.00	5	1.0	36		29	19	10		43	43	11	4a				
857.00		3.5	50								7		**0.11**	**0.11**		
858.00		6.0	50	30							5					
859.00																
860.00	6	1.0	22		25	17	8		36	36	13	4a			**0.968**	
861.00		3.5	50								13		**0.11**	**0.12**		
862.00		6.0	50	22							6					
863.00																
864.00	7	1.0	8								14		**0.19**			
865.00		3.5	50								7				**0.956**	
866.00		6.0	50	8							6					
867.00													**0.15**			
868.00	8	1.0	19								11					
869.00		3.5	15								18					
870.00		6.0	9	9							17				**1.036**	
871.00																
872.00	9	1.0	19								13			**0.18**		
873.00		3.5	26		30	19	11		70	70	16	6a				
874.00		6.0	23	19							19					
875.00														**0.17**	**1.036**	
876.00	10	1.0	19		33	20	13		78	78	15	6a				
877.00		3.5	25								16					
878.00		6.0	22	19							14					
879.00	11	1.0	12		31	20	11		81	81	19	6a	**0.18**			
880.00		3.5	13								28				**0.933**	**0.86**
881.00		6.0	10	10							22			**0.19**		

882.00													**0.22**			
883.00																
884.00	12	1.0	18								15			**0.37**		
885.00		3.5	21								17				**0.903**	
886.00		6.0	26	18							15					
887.00																
888.00	13	1.0	16		31	19	12		70	70	15	6a		**0.31**		
889.00		3.5	21								12		**0.28**			
890.00		6.0	15	15							17				**0.550**	
891.00														**0.34**		
892.00	14	1.0	11		30	19	11		73	73	15	6a				
893.00		3.5	11								16		**0.3**			
894.00		6.0	13	11							17			**0.24**		
895.00															**0.841**	
896.00	15	1.0	7		29	20	9		34	34	17	4a	**0.26**			
897.00		3.5	17								14			**0.36**		
898.00		6.0	20	7							14					
899.00													**0.2**			
900.00	16	1.0	14								16				**1.262**	
901.00		3.5	20								13					
902.00		6.0	27	14							11					
903.00																
904.00	17	1.0	13								16		**0.23**			
905.00		3.5	12		32	19	13		74	74	16	6a			**1.109**	**1.10**
906.00		6.0	26	12							15					
907.00																
908.00	18	1.0	14								14					
909.00		3.5	15								13					
910.00		6.0	17	14	30	19	11		75	75	17	6a			**1.058**	
911.00																
912.00	19	1.0	19								13		**0.19**	**0.2**		
913.00		3.5	19								15					
914.00		6.0	11	11							21					
915.00														**0.24**	**1.058**	
916.00	20	1.0	21								14		**0.16**			
917.00		3.5	23		34	21	13		85	85	20	6a				
918.00		6.0	22	21							18					
919.00													**0.21**	**0.15**		
920.00	21	1.0	10		34	21	13		72	72	16	6a			**1.158**	
921.00		3.5	25								16					
922.00		6.0	24	10							15					
923.00													**0.23**	**0.19**		
924.00	22	1.0	18								15					
925.00		3.5	26		32	20	12		81	81	18	6a			**1.183**	
926.00		6.0	22	18							18		**0.24**	**0.22**		
927.00																
928.00	23	1.0	17								12					
929.00		3.5	5								15		**0.33**	**0.2**		
930.00		6.0	9	5							15				**1.183**	**1.18**

931.00																
932.00	24	1.0	20		32	20	12		80	80	12	6a	**0.23**			
933.00		3.5	21								15			**0.32**		
934.00		6.0	14	14							19					
935.00														**0.3**	**1.183**	
936.00	25	1.0	22		32	20	12		77	77	15	6a	**0.25**			
937.00		3.5	22								17					
938.00		6.0	22	22							13			**0.26**		
939.00													**0.21**			
940.00	26	1.0	18		30	20	10	38	34	72	18	6a			**1.158**	
941.00		3.5	15								15			**0.27**		
942.00		6.0	16	15							16					
943.00													**0.3**			
944.00	27	1.0	18								13					
945.00		3.5	13		31	21	10	36	37	73	17	6a		**0.28**	**1.228**	
946.00		6.0	9	9							18		**0.22**			
947.00																
948.00	28	1.0	22								12			**0.32**		
949.00		3.5	8		31	19	12		72	72	18	6a				
950.00		6.0	4	4							24		**0.29**		**1.228**	
951.00														**0.22**		
952.00	29	1.0	14								13					
953.00		3.5	28		26	18	8	38	34	72	14	4a	**0.21**			
954.00		6.0	12	12							17			**0.34**		
955.00															**1.158**	**1.13**
956.00	30	1.0	13								15		**0.3**			
957.00		3.5	23		32	20	12		80	80	16	6a				
958.00		6.0	24	13							17					
959.00													**0.25**			
960.00	31	1.0	11		24	14	10		38	38	11	4a			**1.066**	
961.00		3.5	17								17					
962.00		6.0	17	11							17					
963.00													**0.3**			
964.00	32	1.0	12		26	16	10	38	34	72	14	4a				
965.00		3.5	7								15				**1.054**	
966.00		6.0	10	7							16					
967.00																
968.00	33	1.0	15								15					
969.00		3.5	17		25	17	8	39	34	73	17	4a		**0.27**		
970.00		6.0	12	12							12				**1.049**	
971.00														**0.28**		
972.00	34	1.0	40								14					
973.00		3.5	26		30	19	11		76	76	14	6a				
974.00		6.0	23	23							16					
975.00														**0.32**	**1.003**	
976.00	35	1.0	37		30	19	11		76	76	16	6a				
977.00		3.5	29								14					
978.00		6.0	38	29							15					

979.00														**0.29**		
980.00	36	1.0	17								15				**0.971**	**0.84**
981.00		3.5	13								16					
982.00		6.0	30	13							23		**0.3**	**0.25**		
983.00																
984.00	37	1.0	39								14		**0.33**			
985.00		3.5	32		28	17	11		76	76	12	6a		**0.32**	**0.911**	
986.00		6.0	41	30							13					
987.00																
988.00													**0.26**			
989.00														**0.23**		
990.00															**0.426**	
991.00																
992.00	38	1.0	39		31	19	12		79	79	15		**0.34**	**0.26**		
993.00		3.5	32								14					
994.00		6.0	37	30							15					
995.00													**0.33**	**0.24**	**0.677**	
996.00	39	1.0	24								17					
997.00		3.5	22								16					
998.00		6.0	25	22							16		**0.28**	**0.23**		
999.00																
1000.00	40	1.0	13								15				**0.694**	
1001.00		3.5	14		31	19	12		74	74	13	6a		**0.25**		
1002.00		6.0	15	13							14		**0.25**			
1003.00																
1004.00	41	1.0	19								15			**0.32**		
1005.00		3.5	30								13		**0.27**		**0.694**	**0.73**
1006.00		6.0	27	19							14					
1007.00														**0.27**		
1008.00	42	1.0	17		30	19	11		75	75	17	6a	**0.23**			
1009.00		3.5	9								13					
1010.00		6.0	9	9							18			**0.24**	**0.690**	
1011.00																
1012.00														**0.19**		
1013.00													**0.14**			
1014.00																
1015.00														**0.17**	**0.797**	
1016.00													**0.32**			
1017.00																
1018.00														**0.21**		
1019.00																
1020.00	43	1.0	18								17		**0.17**		**0.971**	
1021.00		3.5	30								9			**0.13**		
1022.00		6.0	35	18							9					
1023.00													**0.25**			
1024.00	44	1.0	22		30	20	10	39	42	81	22	4a		**0.22**		
1025.00		3.5	22								15				**1.056**	
1026.00		6.0	11	11							16		**0.23**			
1027.00																

1028.00	45	1.0	5								12			**0.26**		
1029.00		3.5	29		24	17	7	34	37	71	11	4a	**0.25**			
1030.00		6.0	18	5							14				**1.085**	**1.07**
1031.00														**0.46**		
1032.00	46	1.0	15								13					
1033.00		3.5	15		21	15	6	42	29	71	10	4a	**0.27**			
1034.00		6.0	9	9							19			**0.24**		
1035.00															**1.129**	
1036.00	47	1.0	29								14		**0.33**	**0.32**		
1037.00		3.5	12		32	21	11		72	72	20	6a				
1038.00		6.0	13	12							13					
1039.00													**0.27**			
1040.00	48	1.0	25		28	19	9	36	38	74	14	4a		**0.26**	**1.105**	
1041.00		3.5	27								11					
1042.00		6.0	20	20							12		**0.27**			
1043.00														**0.32**		
1044.00	49	1.0	12								12					
1045.00		3.5	10								10				**0.977**	
1046.00		6.0	13	10							13		**0.23**	**0.24**		
1047.00																
1048.00																
1049.00													**0.25**	**0.24**		
1050.00															**0.748**	
1051.00																
1052.00																
1053.00													**0.26**			
1054.00																
1055.00														**0.25**	**0.521**	**0.79**
1056.00																
1057.00													**0.25**			
1058.00														**0.28**		
1059.00																
1060.00	50	1.0	12		28	18	10	26	42	68	13	4a			**0.879**	
1061.00		3.5	15								19		**0.31**			
1062.00		6.0	19	12							19			**0.2**		
1063.00																
1064.00	51	1.0	15								13		**0.35**			
1065.00		3.5	11		26	17	9	29	43	72	15	4a		**0.21**	**0.879**	
1066.00		6.0	12	11							15					
1067.00													**0.18**			
1068.00	52	1.0	15								13			**0.25**		
1069.00		3.5	17		26	16	10	32	44	76	15	4a				
1070.00		6.0	9	9							17		**0.22**		**0.879**	
1071.00																
1072.00	53	1.0	4								18			**0.29**		
1073.00		3.5	11		37	22	15		88	88	21	6a				
1074.00		6.0	16	4							15		**0.26**			
1075.00														**0.21**	**0.879**	
1076.00	54	1.0	7								14					

1077.00		3.5	19		33	20	13		64	64	16	6a	**0.24**			
1078.00		6.0	11	7							17					
1079.00														**0.3**		
1080.00	55	1.0	7								13				**0.879**	**0.93**
1081.00		3.5	34		33	19	14		76	76	14	6a	**0.35**			
1082.00		6.0	20	7							16					
1083.00																
1084.00	56	1.0	4		35	21	14		75	75	21	6a	**0.29**			
1085.00		3.5	27								14				**0.911**	
1086.00		6.0	21	4							14					
1087.00														**0.19**		
1088.00	57	1.0	10								15					
1089.00		3.5	15		30	20	10	39	41	80	17	4a				
1090.00		6.0	12	10							14			**0.3**	**1.095**	
1091.00																
1092.00	58	1.0	9								15		**0.22**			
1093.00		3.5			35	20	15		93	93	23	6a		**0.19**		
1094.00		6.0		9							22					
1095.00															**0.817**	
1096.00	59	1.0	11								15		**0.32**			
1097.00		3.5	27		32	20	12		78	78	17	6a		**0.23**		
1098.00		6.0	28	11							14					
1099.00																
1100.00													**0.24**		**0.667**	
1101.00														**0.27**		
1102.00																
1103.00													**0.3**			
1104.00														**0.33**		
1105.00															**0.306**	**0.87**
1106.00																
1107.00													**0.31**	**0.31**		
1108.00																
1109.00																
1110.00														**0.31**	**1.268**	
1111.00													**0.27**			
1112.00	60	1.0	12		31	19	12		71	71	16	6a				
1113.00		3.5	13								16					
1114.00		6.0	13	12							15		**0.28**	**0.27**		
1115.00															**1.379**	
1245.00		3.5	28								15					
1246.00		6.0	34	28							15					
1247.00																
1248.00	94	1.0	14								20		**0.2**			
1249.00		3.5	30		35	20	15		82	82	18	6a		**0.2**	**0.720**	
1250.00		6.0	23	14							18					
1251.00																
1252.00	95	1.0	12								12			**0.22**		
1253.00		3.5	24		29	18	11		74	74	14	6a				
1254.00		6.0	28	12							13				**0.773**	

1255.00													**0.16**			
1256.00	96	1.0	11								13			**0.23**		
1257.00		3.5	39		26	17	9	31	28	59	11	4a				
1258.00		6.0	22	11							17		**0.27**			
1259.00														**0.25**	**0.930**	**0.89**
1260.00	97	1.0	8								15					
1261.00		3.5	12		33	21	12		71	71	17	6a				
1262.00		6.0	27	8							15		**0.32**			
1263.00														**0.28**		
1264.00															**0.802**	
1265.00													**0.27**			
1266.00																
1267.00														**0.31**		
1268.00																
1269.00															**0.761**	
1270.00													**0.24**	**0.32**		
1271.00																
1272.00																
1273.00																
1274.00														**0.24**	**1.864**	
1275.00																
1276.00	98	1.0	9		34	20	14		77	77	17	6a				
1277.00		3.5	15								16			**0.25**		
1278.00		6.0	15	9							16					
1279.00															**1.482**	
1280.00	99	1.0	7		33	21	12		78	78	17	6a				
1281.00		3.5	33								14					
1282.00		6.0	25	7							16					
1283.00																
1284.00	100	1.0	6		42	23	19		84	84	22	7-6			**1.068**	**1.25**
1285.00		3.5	15								18					
1286.00		6.0	16	6							17					
1287.00													**0.25**			
1288.00	101	1.0	11								15			**0.26**		
1289.00		3.5	27		32	20	12		75	75	15	6a			**1.019**	
1290.00		6.0	37	11							14		**0.27**			
1291.00																
1292.00	102	1.0	5								16			**0.27**		
1293.00		3.5	10		44	22	22		88	88	22	7-6	**0.25**			
1294.00		6.0	13	5							21				**1.095**	
1295.00														**0.36**		
1296.00	103	1.0	6								15					
1297.00		3.5	20		31	21	10	39	34	73	18	4a	**0.21**			
1298.00		6.0	11	6							28			**0.28**		
1299.00															**1.129**	
1300.00	104	1.0	8						1	1	21	1a				
1301.00		3.5	10		31	18	13		75	75	18	4a	**0.26**			
1302.00		6.0	24	8							19			**0.28**		
1303.00																

1304.00	105	1.0	5								17		**0.3**		**1.129**	
1305.00		3.5	23		30	20	10	33	42	75	14	4a		**0.37**		
1306.00		6.0	13	5							18					
1307.00																
1308.00	106	1.0	10		29	19	10	32	39	71	13	4a	**0.38**			
1309.00		3.5	5								19			**0.31**	**1.129**	**1.06**
1310.00		6.0	16	5							15					
1311.00													**0.28**			
1312.00	107	1.0	15								15					
1313.00		3.5	23		31	19	12		74	74	14	6a		**0.27**		
1314.00		6.0	32	15							15		**0.26**		**1.085**	
1315.00																
1316.00	108	1.0	9								16			**0.23**		
1317.00		3.5	25								16		**0.23**			
1318.00		6.0	12	9							15					
1319.00														**0.25**	**0.909**	
1320.00	109	1.0	8		25	16	9	35	40	75	13	4a				
1321.00		3.5	11								15		**0.22**			
1322.00		6.0	12	8							19					
1323.00														**0.22**		
1324.00	110	1.0	9		30	18	12		74	74	16	6a	**0.22**		**0.909**	
1325.00		3.5	16								14					
1326.00		6.0	13	9							18			**0.24**		
1327.00																
1328.00	111	1.0	11		28	17	11		71	71	13	6a	**0.23**			
1329.00		3.5	27								14			**0.22**	**0.909**	
1330.00		6.0	15	11							16					
1331.00													**0.19**			
1332.00	112	1.0	6								17					
1333.00		3.5	28		33	19	14		76	76	17	6a		**0.31**		
1334.00		6.0	21	6							15		**0.2**		**0.909**	**0.99**
1335.00																
1336.00	113	1.0	10								18			**0.19**		
1337.00		3.5	29		36	21	15		76	76	17	6a				
1338.00		6.0	22	10							16		**0.22**			
1339.00															**0.994**	
1340.00	114	1.0	6								15			**0.24**		
1341.00		3.5	25		34	22	12		76	76	17	6a	**0.21**			
1342.00		6.0	25	6							17					
1343.00																
1344.00	115	1.0	8		35	20	15		77	77	16	6a	**0.17**	**0.25**	**1.121**	
1345.00		3.5	16								27					
1346.00		6.0	41	8							15					
1347.00														**0.23**		
1348.00	116	1.0	11								16		**0.21**			
1349.00		3.5	34								16				**1.121**	
1350.00		6.0	32	11							16			**0.27**		
1351.00																
1352.00	117	1.0	9								16		**0.25**			

1353.00		3.5	13		42	24	18		89	89	23	7-6		**0.33**		
1354.00		6.0	22	9							18		**0.28**		**1.121**	
1355.00																
1356.00	118	1.0	6								18			**0.25**		
1357.00		3.5	17		38	22	16		76	76	23	6b				
1358.00		6.0	13	6							21		**0.25**			
1359.00														**0.39**	**1.121**	**1.03**
1360.00	119	1.0	8								16					
1361.00		3.5	16		34	18	16		81	81	16	6b	**0.31**			
1362.00		6.0	14	8							18					
1363.00														**0.33**		
1364.00	120	1.0	9								23		**0.29**		**0.952**	
1365.00		3.5	31		31	18	13		76	76	15	6a				
1366.00		6.0	22	9							16					
1367.00														**0.3**		
1368.00	121	1.0	15		30	18	12		77	77	16	6a	**0.32**			
1369.00		3.5	17								17				**0.909**	
1370.00		6.0	21	15							21			**0.33**		
1371.00													**0.24**			
1372.00	122	1.0	6		35	19	16		76	76	17	6b				
1373.00		3.5	27								14					
1374.00		6.0	13	6							23			**0.25**	**0.909**	
1375.00													**0.21**			
1376.00	123	1.0	10								16					
1377.00		3.5	23		29	19	10	36	36	72	12	4a		**0.26**		
1378.00		6.0	20	10							14		**0.26**			
1379.00															**0.909**	
1380.00	124	1.0	16								16					
1381.00		3.5	14		28	18	10	32	44	76	14	4a	**0.29**	**0.38**		
1382.00		6.0	17	14							17					
1383.00																
1384.00	125	1.0	14								14		**0.36**		**0.909**	**0.98**
1385.00		3.5	20		46	22	24		89	89	20	7-6		**0.4**		
1386.00		6.0	16	14							16					
1387.00																
1388.00	126	1.0	16								16		**0.23**	**0.2**		
1389.00		3.5	15		29	18	11		73	73	15	6a			**0.956**	
1390.00		6.0	14	14							14					
1391.00													**0.24**	**0.26**		
1392.00	127	1.0	16		32	20	12		83	83	15	6a				
1393.00		3.5	15								15					
1394.00		6.0	15	15							15		**0.24**			
1395.00																
1396.00	128	1.0	17		30	19	11		71	71	12	6a				
1397.00		3.5	16								13					
1398.00		6.0	13	13							14					
1399.00																
1400.00	129	1.0	15								15	6a				
1401.00		3.5	23		34	21	13		76	76	13					

1402.00		6.0	25	15							13					
1403.00																
1404.00	130	1.0	7								23					
1405.00		3.5	13		36	23	13		84	84	25	6a				
1406.00		6.0	7	7							29					
1407.00																
1408.00	131	1.0	12								21					

(1 foot = 0.30 meters)

APPENDIX F. Soil Investigation and Undercut Information for ROS US35

Table F1. Soil Investigation and Undercut Information for ROS US35

Boring		Standard Penetration				Physical Characteristics								Undercut Depth (ft)
B #	Depth	n2	n3	N	NL	LL	PL	PI	% Silt	% Clay	P 200	M	Class	
B1	1	6	10	16					17	16	33	10		
	2.5	10	14	24					17	16	33	3	3a	
	5.5	7	7	14	14				17	16	33	10		1
PB1	2.3	4	7	11		NP	NP	NP	13	13	26	20		
	3.8	5	5	10		NP	NP	NP	13	13	26	18	3a	
	5.3	5	7	12	10							14		1
B5	2.1	6	8	14								7		
	3.6	10	13	23		40	24	16	11	27	38	13	6b	
	5.1	6	7	13	13							11		1
B6	0	5	6	11								10	6a	
	1.5	8	13	21		36	21	15	13	21	34	8	2-6	
	3	9	13	22	11	36	21	15	13	21	34	8	2-6	1.86
B7	2.1	8	11	19		26	13	13	19	25	44	10	6a	
	3.6	5	4	9					5	5	10	6	1b	
	5.1	6	7	13	9				5	5	10	6	1b	1.2
B8	0	7	11	18					35	24	59	8		
	1.5	8	8	16					35	24	59	8		
	3	3	4	7	7				35	24	59	14		2.12
B11	4	31	29	60					8	9	17	5	1b	
					30									0
B13	0	9	13	22								8		
	4	9	10	19		38	18	20	48	33	81	14	6b	
					19									0
B14	0	0	0									11		
	3	8	10	18								12		
	5	12	17	29	18							11		2
PB5	1	5	6	11					55	32	87	15		
	3	4	6	10										
					10									0
B15	0	6	5	11		29	18	11	62	24	86	12	6b	
	1.5	6	10	16								14		
	4.5	8	15	23	11							7		0
B16	0	7	13	20		35	17	18	41	33	74	8	6a	
	1.5	8	26	34		35	17	18	41	33	74	15	6b	
	4.5	8	8	16	16							7		0
PB6	2	4	4	8								18		
	3.5	5	7	12					6	7	13	5	1b	
	5	8	9	17	8				6	7	13	5	1b	2.3
PB9	2	9	12	21		26	16	10	46	21	67	15	4a	
	4	7	7	14		26	16	10	46	21	67	14		
	6	9	11	20	14							8		2
B30	0	5	5	10		21	9	12	21	16	37	5		
	2	2	2	4		21	9	12	21	16	37	9		
	4	3	4	7	4	21	9	12	21	16	37	13		2
B38	2.1	3	9	12		34	22	12	20	27	47	11	6b	

	3.6	6	10	16		34	22	12	20	27	47	12		
	5.1	4	5	9	9							8		2
B40	1	7	9	16								10		
	3	7	7	14		34	17	17	38	33	71	10	6b	
	5	4	4	8	8							14		3
B42	0	8	9	17								7		
	1.5	8	11	19								10		
	4.5	5	9	14	14	NP	NP	NP	63	23	86	13	4b	3
B44A	2	50	50	100								2		
	4	50	50	100								4		
	6	50	50	100	30							7		1.5
B49	3	20	19	39					65	32	97	11		
	5	50	50	100					65	32	97	13		
					30									1.5
B50	2	5	10	15								2		
	5	7	11	18								5		
					15									2
PB16	2	2	2	4		31	14	17	15	30	45	23		
	4	2	2	4		31	14	17	15	30	45	20		
	6	2	2	4	4	31	14	17	15	30	45	20	6b	2
B53	0	8	11	19								6	6a	
	4	11	13	24		NP	NP	NP	60	24	84	8	4b	
	6	11	13	24	19							20		2
B60	3	16	19	35		32	15	17	38	40	78	13		
					30									3
B61	4	6	8	14								9		
					14									3
PB18	2	12	12	24		24	16	8	48	27	75	16		
	4	9	11	20		24	16	8	48	27	75	18	4a	
	6	9	11	20	20	24	16	8	48	27	75	18		3
B66	2	50	50	100					47	38	85	11		
												14	6a	
					30							14	4a	1.5
B67	2	50	50	100					42	44	86	10		
	4	50	50	100					42	44	86	11		
	6	50	50	100	30				42	44	86	10		1.5
B82	2	50	50	100					31	49	80	11		
	4	50	50	100					31	49	80	12	6a	
	6	50	50	100	30				31	49	80		6a	1.8
B89	2	50	50	100					31	46	77	13		
	4	50	50	100								12		
	6	50	50	100	30							10		1.8
PB20	2	50	50	100								13		
	4	50	50	100										
	6	50	50	100	30									1.8
B99	2	50	50	100					46	21	67	11		
	4	37	50	87								9		
	6	37	50	87	30							8		1.8
PB21	2	50	50	100										

	4	50	50	100								21		
	6	50	50	100	30							16		1.8
B104	2	34	44	78		34	19	15	48	28	76	11	4b	
	4	34	44	78		25	15	10	21	15	36	12	4a	
	6	38	50	88	30							12		1.8
PB21	2	50	50	100										
	4	50	50	100										
	6	50	50	100	30									1
B125	0	6	9	15								24		
	2.5	5	7	12								21		
					12									1
B126	0	10	11	6								10		
	5	3	5	8								9		
					6									0
B128	0	3	4	7		26	16	10	15	21	36	18		
	3	8	8	16		26	16	10	15	21	36	16	4a	
	5	3	3	6	6	26	16	10	15	21	36	13		3
B135	2					22	17	5	42	24	66	11	4a	
	4					22	17	5	42	24	66	18		
	6					22	17	5	42	24	66	20		0
B136	4								18	17	35	14	3a	
	6													
														0
PB27	2	5	19	24		24	19	5	63	18	81	18	4b	
	3.5	4	7	11		24	19	5	63	18	81	21		
	5	4	6	10	10	24	19	5	63	18	81	21		3
B137	2					25	15	10	43	25	68	16	4a	
	4					25	15	10	43	25	68	16	1a	
	6					25	15	10	43	25	68	19	6a	0
B138	4											14		
	6													
														0
B139	3					35	19	16	44	34	78	16	6b	
	6					35	19	16	44	34	78	20		
	8.5											12		0
PB28	3	4	6	10		25	14	11	35	20	55	13		
	6	8	8	16		25	14	11	35	20	55	14	4b	
	8.5	5	7	12	10				10	9	19	5	3a	0
B140	2					32	17	15	52	33	85	15	6a	
	4					32	17	15	52	33	85	17		
	6					32	17	15	52	33	85	18		0
B141	2					37	21	16	41	37	78	18	6b	
	4											9		
	6											21		0
B142	4											12		
	6											12		
														0
B143	2					33	17	16	44	43	87	18	6b	
	4					33	17	16	44	43	87	16		
	6					33	17	16	44	43	87	16		0
OC1	2								6	7	13	10	1a	

	4								26	22	48	14		
	6								26	22	48	13		0
OC4	2					33	14	19	13	17	30	13	2-6	
	4					33	14	19	13	17	30	13		
	6					33	14	19	13	17	30	15		0
OC5	2					35	15	20	20	20	40	12	6b	
	4					35	15	20	20	20	40	16		
	6					35	15	20	20	20	40	20		0
RA2	4	2	2	4		31	16	15	21	31	52	14	6a	
	6	5	6	11					4	5	9	10		
		2	2	4	4				4	5	9	6	1b	0
LR7	2	20	14	34		28	16	12	34	25	59	16	6a	
	3.5	8	12	20		28	16	12	34	25	59	12	6a	
	5	7	5	12	12	28	16	12	34	25	59	12	6a	0
VA1	2								35	17	52	16		
	4											3		
	6											3		0
WR1	0	7	9	16		42	20	22	47	44	91	21		
	1.5	10	8	18		42	20	22	47	44	91	21	7-6	
	5	13	13	26	16	42	20	22	47	44	91	19		0
WR2	2	6	7	13					27	13	40	10		
	3.5	6	9	15					27	13	40	15		
	5	9	9	18	13				27	13	40	15		0
CR1	2	19	30	49		30	16	14	24	22	46	11	6a	
	4	13	18	31					10	9	19	10	1b	
	6	50	50	100	30				10	9	19	10		0
CR5	2.5	5	5	10		34	19	15	47	27	74	21	4b	
	4	5	5	10		34	19	15	47	27	74	23	3a	
					10									0
LR4	2	6	4	10		43	18	25	10	22	32	13		
	4.5	4	2	6		43	18	25	10	22	32	15	2-7	
					6									0
VR7	2	6	9	15					6	5	11	7	3a	
	4	3	4	7					6	5	11	7		
	6	5	6	11	7				6	5	11	11		2
PB3	0	10	14	24										
	5	20	21	41		40	16	24	16	15	31	10		
					24									2.8
PB10	4	10	14	24										
	6	9	12	21										
					21									2
														2
														2

(1 foot = 0.30 meters)

APPENDIX G. Soil Investigation and Undercut Information for JAC US32

Table G1. Soil Investigation and Undercut Information for JAC US32

Boring		Standard Penetration				Physical Characteristics							Classification	
B #	Depth	n2	n3	N	NL	LL	PL	PI	% Silt	% Clay	P 200	M	Class	Undercut Depth (ft)
B15	1	4	4	8		70	31	39	7	93	100	34	7-6	2
	3.5	4	4	8			0							
	6				8		0							
B16	1	3	3	6		33	18	15	26	26	52	14	7-6	2
	3.5	3	3	6			0							
	6				6		0							

APPENDIX H

Overview of Technologies Other than Boring for Assessing Subsurface Conditions

The purpose of this appendix is to summarize the current technology to identify soft spots in subgrade during a new construction or reconstruction project. This summary has been compiled based on conversations with State DOTs and experts in pavement materials, design, evaluation, and construction, and that have worked extensively in the area of subgrade treatments. Pavement engineering experts consulted include Dr. Marshall R. Thompson, Richard N. Stubstad, Harold L. VonQuintus, and Michael I. Darter.

Current technology does not provide a definite means to reliably identify subgrade type, strength or moisture contents in a non-destructive and speedy manner using onboard devices. Reviews of guidelines from other States, and personal communication with DOT personnel, have not pointed to particular agency-specified test methods that are being used in routine practice for the purpose of identifying subgrade soft spots. However, on a project-specific basis, (typically at a district level), sound engineering judgments are made to identify soft spots and remediate the problem.

RECOMMENDATIONS FOR EVALUTING SUBGRADES AND SUITABLE TREATMENT OPTIONS

In developing a plan for subgrade evaluation, it is to be recognized that subgrade evaluation needs to be performed in two distinct phases:

a. Prior to construction or reconstruction, i.e. subsurface evaluation on the existing pavement
b. During construction, i.e. when the subgrade is compacted and the base layer is being placed over it.

Subgrade materials are known to change on an average every 700 feet. Subgrade variability can be as high as 30-50% and the modulus values are not normally distributed. The very fact that this length is qualified as an "average," and pavement engineers have to work with such high levels of variability suggests that there can be no set guideline that can be used to accurately monitor changes in subgrade properties over a project length using point specific test methods. For acquiring the required information to accurately determine soft spots and the extent of stabilization to be undertaken during reconstruction, it is essential to collect information on a continuous basis along the horizontal plane of the pavement sections. Current technology does not offer this testing capability.

The level of detail and the accuracy of the prediction increase from preconstruction testing to during-construction testing. It is generally recommended that substantial preconstruction testing be performed to obtain a fairly good understanding of the underlying soils. These tests should ideally involve a preliminary test with random sampling to assess the variability existing in the sections, followed by more extensive or localized tests to acquire more detailed information so as to make appropriate design and construction decisions. However, the most accurate information can only be gathered at the time of construction, during which time certain key decisions have to be made with regard to subgrade treatment options.

The following three technologies are recommended for consideration by ODOT to enable subsurface evaluation at a higher sampling rate than the currently used boring logs data:

1. Falling Weight Deflectometer – Backcalculation and Forward calculation
2. Ground Penetrating Radar
3. Dynamic Cone Penetrometer

The falling weight deflectometer (FWD) and the Dynamic Cone Penetrometer (DCP) are localized testing devices that can be used in the preconstruction evaluation. The Ground Penetrating Radar (GPR), a technology to survey subsurface features and defects is fast becoming a preferred onboard tool for measuring layer thicknesses and identifying moisture under pavements. GPR data is "continuous" along the test section and can be collected at highway speeds. The DCP can also be used as a testing tool during the construction phase to make "on-spot decisions".

Falling Weight Deflectometer – Backcalculation and Forward calculation

The falling weight deflectometer (FWD) is perhaps the most suitable evaluation method to get a variety of information, both qualitative and quantitative, from an existing pavement. In particular, FWD is ideal for evaluating subgrade strength and variability therein. This is the most widely used deflection-based test method adopted by agencies in the United States and worldwide.

The outer sensor readings are good indicators of the subgrade strength. The backcalculated subgrade modulus and the observed variability therein are key parameters in evaluating the strength of the subgrade and treatment options. A simple means of evaluating the variability in subgrade strength is to scan through the FWD deflection data and determine the variability in the outer sensor readings. However, this is only applicable if the layer properties and the layer thicknesses are uniform along the project. The frequency of testing can range from 100 foot intervals or can be modified based on the observed variability.

Principle of Operation, Equipment and Software

The FWD device consists of an impact loading mechanism and a set of sensors to measure vertical surface displacements at the load location and at specified offsets from the load. The loading component delivers a transient load to the pavement surface and the sensors measure the surface deflection at the specified locations. The entire system is typically trailer mounted as shown in Figure H1. The loading device consists of a load plate that can apply an impulse load of different magnitudes ranging from1500 to 27000 lb. (6.7 t 120 kN). The load can be applied from three standard drop heights resulting in a load pulse of 0.025 to 0.03 seconds. The load plate is circular and has a standard diameter of 8 inches. Figure H2 shows an FWD loading plate in contact with the pavement surface.

The vertical deflection response is measured at the surface of the pavement at different sensor locations, as shown in Figure H3. The sensor locations are typically chosen to adequately characterize the pavement structure being tested. These deflection measurements are used to characterize the deflection basin of the pavement, an example for which is shown in Figure H4. A back-calculation algorithm is used to estimate the modulus of all pavement layers based on the measured deflections and the layer thicknesses determined from cores or by referring to design documents.

Figure H1. Trailer Mounted Falling Weight Deflectometer Device

Figure H2. FWD Loading Plate in Contact with Pavement Surface

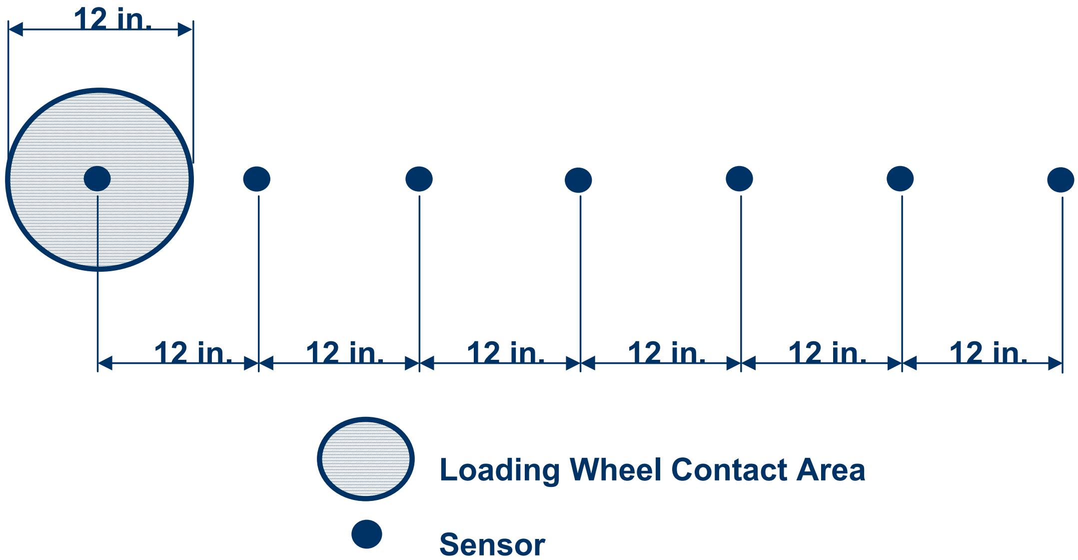


Figure H3. Typical Location of Loading Plates and Deflection Sensors for FWD

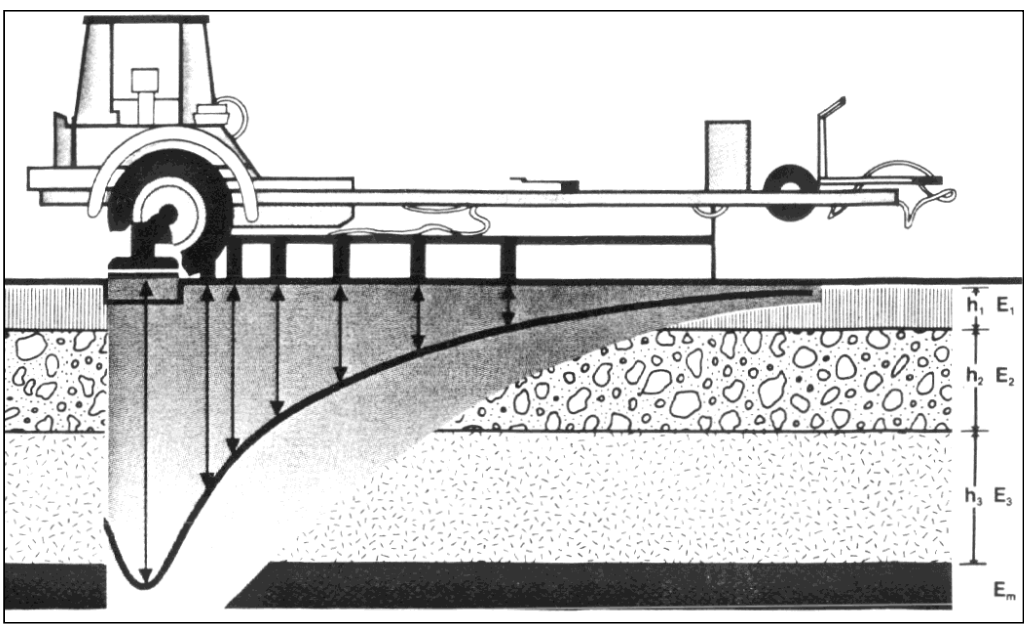


Figure H4. Typical Deflection Basin Measured from FWD

Test Procedure

The FWD has been implemented in the United States since 1978. The test method has been standardized as ASTM D4694-03, *Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Devices*. ASTM Standard D4695-03, *Standard Guide for General Pavement Deflection Measurements*, provides the guidance and procedural information for measuring pavement surface deflections, directly under, or at locations radially outward (offset) from the load.

Data Analysis Procedure

FWD data analysis uses the back calculation procedure where in the modulus values of the different pavement layers are backcalculated based on the measured deflection values at each sensor location. MODULUS, EVERCALC, BISDEWF, are some of the most commonly used backcalculation programs used today.

Forward Calculation Using the Hogg Model

Closed-form solutions for determining select layered-elastic properties of pavement systems have been used extensively in the past. Already in 1884, a Frenchman named Boussinesq developed a set of closed-form equations for a semi-infinite, linear elastic median half-space, including the modulus of elasticity of the median, based on a point load. Subsequently, it has been shown (Ref. *Pavement Analysis.* The Technical University of Denmark, Elsevier (1987)] that the apparent or composite subgrade modulus derived from any FWD sensor at offset "r" can be calculated from Equation (1):

$$E_{o,r} = (0.84 \cdot a^2 \cdot \sigma_o) / (d_r \cdot r) \qquad \textbf{Equation H1}$$

where: $E_{o,r}$ = "surface" or composite modulus of the subgrade beneath the sensor used;

a = radius of FWD loading plate;

σ_o = (peak) pressure of FWD impact load under loading plate;

d_r = (peak) FWD deflection reading at offset distance “r”;

and r = distance of deflection reading d_r from center of loading plate.

The suggested constant of 0.84 assumes that Poisson’s ratio is 0.4 (from the calculation $1 - \mu^2$). If d_r is a reasonably large distance from the edge of the loading plate, the load can be assumed a point load, so the plate pressure distribution does not matter. Furthermore, small changes in Poisson’s ratio have only a minimal impact on Equation (H1).

Subsequent developments by Burmeister, Odemark, Westergaard, and Hogg (among others) have allowed the use of the shape of the deflection basin to estimate various layered-elastic (or plate on dense liquid) moduli from FWD deflection readings.

Centerline Subgrade Modulus Based on the Hogg Model

One method to ascertain the approximate subgrade stiffness, or elastic modulus, directly under an imposed surface load is the "Hogg" model.

The Hogg model is based on a hypothetical two layer system consisting of a thin plate on an elastic foundation. The method in effect simplifies the typical multilayered elastic system with an equivalent two-layer "stiff layer on elastic foundation" model. Depending on the choice of values along the deflection basin used to calculate subgrade stiffness, there can be a tendency to either over- or under-estimate the subgrade modulus. The Hogg model utilizes the deflection at the center of the load and one of the offset deflections. The offset distance where the deflection is approximately one-half of that under the center of the load plate was shown by Hogg to be where the biases inherent to the simplified two-layer system model compensate. Variations in pavement thickness and the ratio of pavement stiffness to subgrade stiffness are taken into account, since the distance to where the deflection is one half of the deflection under the load plate is controlled by these factors.

The underlying model development for a finite subgrade was first published in 1944 [Ref: Hogg, A. H. A., "Equilibrium of a Thin Plate on an Elastic Foundation of Finite Depth", Philosophical Magazine, Volume 35 (243), pp 265-276, 1944]. The implementation of the model used in this study was published in 1983 [Ref: Wiseman, G., and Greenstein, J., "Comparison of Methods of Determining Pavement Parameters from Deflection Bowl Measurements", Proceedings of the 7th Asian Regional Conference on Soil Mechanics and Foundation Engineering, pp 158-165, 1983].

The equations used are as follows:

$$E_0 = I \frac{(1+\mu_0)(3-4\mu_0)}{2(1-\mu_0)} \left(\frac{S_0}{S}\right)\left(\frac{p}{\Delta_0 l}\right) \text{ .... Equation H2}$$

Curve Fitting:

$$r_{50} = r\frac{(1/\alpha)^{1/\beta} - B}{\left[\frac{1}{\alpha}\left(\frac{\Delta_0}{\Delta_r} - 1\right)\right]^{1/\beta} - B} \text{ .... Equation H3}$$

$$l = y_0\frac{r_{50}}{2} + \left[(y_0 r_{50})^2 - 4mar_{50}\right]^{\frac{1}{2}}$$

if $\frac{a}{l} < 0.2$, then $l = (y_0 - 0.2m)r_{50}$ .... Equation H4

$$\left(\frac{S_0}{S}\right) = 1 - \overline{m}\left(\frac{a}{l} - 0.2\right)$$

if $\frac{a}{l} < 0.2$, then $\left(\frac{S_0}{S}\right) = 1.0$ .... Equation H5

where:

E_0	=	Subgrade Moduli, psi
μ_0	=	Poisson's Ratio for Subgrade
S_0	=	Theoretical point load stiffness
S	=	Pavement Stiffness = p/Δ_0 (area loading)
p	=	Applied load, pounds
Δ_0	=	Deflection at center of load plate, inches
Δ_r	=	Deflection at offset distance r, inches
r	=	Distance from center of load plate, inches
r_{50}	=	Offset distance there $\Delta_r/\Delta_0 = 0.5$
l	=	Characteristic length, inches
h	=	Thickness of subgrade, inches
I	=	Influence Factor – see table below
α, β, B	=	Curve fitting coefficients – see table below
y_0 m	=	Characteristic length coefficients – see table below
$\overline{m}$	=	Stiffness ratio coefficient – see table below

The implementation of the Hogg model described by Wiseman included three cases, one for an infinite elastic foundation, and the other two cases are for a finite elastic layer with a thickness that is assumed to be approximately 10 times the characteristic length, *l*. The two finite thickness cases are for Poisson's ratios of 0.4 and 0.5, respectively. The various constants used for the Hogg models are shown in the table above. Case *II* was used to calculate the subgrade moduli for purposes of this pilot study.

Agency Use

Many States surveyed use FWD testing in their routine engineering practice or for forensic evaluation and reconstruction design. Texas, Illinois, Washington, Minnesota are some of the States that use the FWD data in their reconstruction projects. The Mechanistic Empirical Design Guide developed from the NCHRP 1-37A project strongly recommends the use of FWD testing to evaluate existing pavements to aid in reconstruction strategy selections. Note that The Mississippi DOT and Florida DOT have done studies to correlated subgrade moduli calculated from FWD data collected directly on the subgrade – but this is not applicable to the current study for the DOT.

Ground Penetrating Radar

Ground penetrating radar (GPR) is a geophysical nondestructive technique that uses electromagnetic pulses to test, characterize, or detect subsurface materials based on changes in electrical and magnetic properties of the subsurface layers. GPR has been extensively used for measuring pavement layer thickness, and more recently has been applied to the measurement of pavement density, air content and detection of moisture in subgrade.

Principle of Operation

GPR works using short electromagnetic pulses radiated by an antenna which transmits these pulses and receives reflected returns from the pavement layers, as shown in Figure.H5a below. The reflected pulses are received by the antenna and recorded as a waveform, as shown in Figure H5b. As the equipment travels along the pavement, it generates a sequence of waveforms as shown in Figure H6c. The layer boundary between the asphalt and base is clearly visible in this sequence of waveforms. These waveforms are digitized and interpreted by computing the amplitude and arrival times from each main reflection. The pavement thickness and dielectric permittivity can be computed from these amplitudes and arrival times according to the following equations (Maser and Scullion, 1992):

$$Thickness(mm) = \frac{Velocity * t}{2} = \frac{150 * t}{\sqrt{\varepsilon_a}}$$

(H6)

Where:

$$\varepsilon_a = \left[\frac{Apl + A}{Apl + A} \right]^2 \qquad \text{(H7)}$$

Where *velocity* is calculated from $\square_a$,the dielectric constant of the asphalt; *t* is the time delay between the reflections from the top and bottom of the asphalt, computed automatically from each waveform; *A* is the amplitude of the reflection from the top of the asphalt, computed from each waveform; and *Apl* is the amplitude of the reflection from a metal plate, obtained during calibration.

Equipment and Software

The current ground penetrating radar (GPR) technology used in highway and transportation applications emerged over 30 years ago through two separate efforts: (a) the development of ground-coupled antenna systems for geological and geotechnical applications; and (b) the development of air-coupled horn antennas for mine detection.

The ground-coupled equipment has traditionally been used for maximum depth penetration and where information is more qualitative rather than quantitative. The ground-coupled technology has been widely used for a variety of subsurface applications, including mapping of groundwater, bedrock, and soil layers, detecting pipes, buried drums, and subsurface contamination, and locating reinforcement. Antennas are available with center frequencies ranging from 80 MHz to 1.5 GHz, providing a wide range of penetration depths and resolutions.

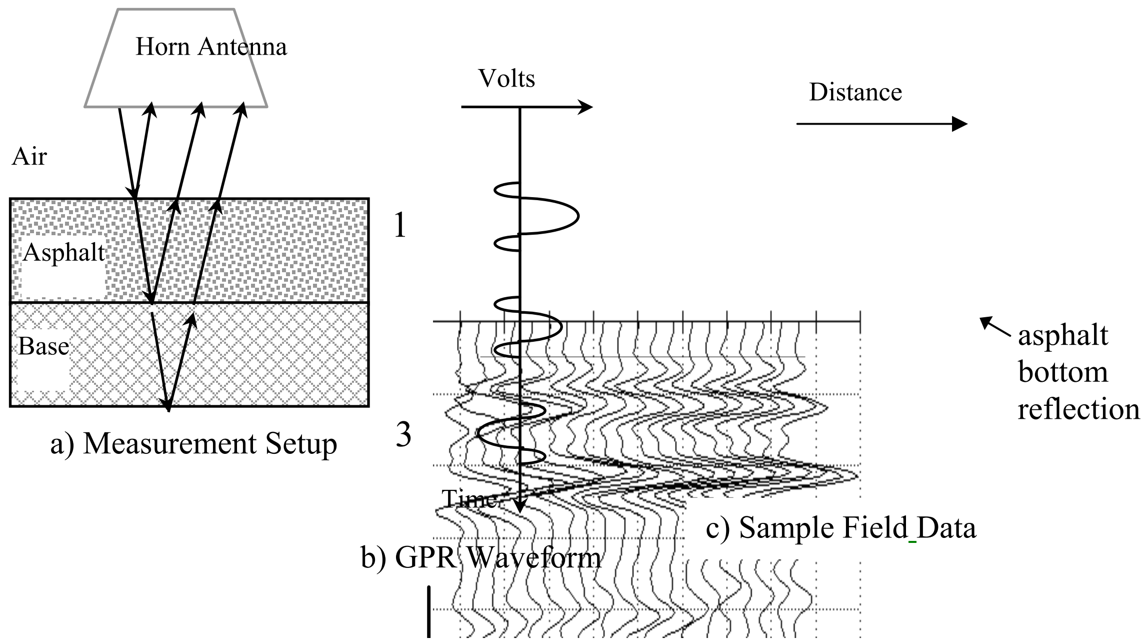


Figure H5. Principle of GPR for Pavement Layer Thickness Evaluation

Data from ground-coupled equipment is generally analyzed from a graphical display on a computer screens. The analysis seeks to relate arrival patterns from different reflectors to depths, horizontal locations, and qualitative descriptions of subsurface conditions (Morey, 1984; Ulricksen, 1983).

GPR has shown a high potential for detecting saturated subgrade areas and depth of water table. The presence of moisture in the subgrade is reflected by the subgrade dielectric permittivity. Areas where this value is high are likely to have high moisture content, assuming that there are no other changes in material properties. Results from such studies have either not been verified against field data or have shown some variability. Therefore, it is suggested that the use of GPR technology can be used to find "potential" soft spots for further investigation with cores or boring logs or DCP.

Agency Use

In a study done at North Dakota , for one of the sections evaluated in the study the mean base dielectric was calculated as 9.15, and therefore a threshold of 11 (20% above the mean) was established. The areas where the base dielectric exceeded this threshold were considered the most likely to have saturated base. However, these results were not confirmed with physical observation at these locations.

Minnesota has recently conducted studies to evaluate the depth of water table and the depth of frost line underneath existing pavements to place spring time load restrictions. Results show promise for further development at this stage.

One of the limitations of GPR has been the cost and complexity of the equipment, the need for interpretive expertise, and the requirement for office data processing. Recent developments with GPR hardware have yielded systems which are less expensive and easier to operate, and could overcome the equipment complication. On the data processing side, prototype software for automated on-site processing has been developed (e.g., *Maser, 2002*) and may overcome some of the processing issues.

However, as the technology improves, the high speed antennas are getting sophisticated to measure near-depth features with higher precision and thereby compromising on features at greater depths in the pavement. The GPR technology to evaluate subgrade conditions should use low speed antennas.

Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer, commonly referred to as the DCP, is a testing device to quickly estimate the in-situ strength and deformation characteristics of unbound pavement layers. The test can be performed on insitu soils that can either be unfinished (undisturbed) or compacted materials. The test essentially involves driving a cone shaped probe into the soil using a dynamic load and measuring the advancement of the device for each applied blow. Under constant load, load height, and cone size and shape has a direct impact on the depth of penetration achieved with each blow.

The strength of the material being tested has a direct impact on the depth of penetration achieved with each blow. In other words, the resistance to penetration is dependent on the strength of the material. This resistance to deformation, in turn, is dependent on density, moisture, degree of compaction, and material type, all of which are to be evaluated for the specific needs being addressed by this project.

For the purpose of subgrade evaluation, the DCP test can be performed during both phases of testing, i.e. prior to reconstruction as well as during construction. For use during the pre-construction stage, the DCP test can be performed in locations where a pavement core has been removed to be able to reach the unbound layers. For example, in locations identifies as those potential for soft spots in subgrade from FWD and GPR tests, the DCP test can be performed to gain a better understanding of the actual condition of the sample. However, during construction, the DCP test can be performed along the project at regular intervals.

The use of DCP in quality control and quality assurance tests in construction activities has gained increased popularity for the simple reason that the equipment is simple and easy to handle. It is amenable to many types of evaluations and several material types. It is also an economical device with little or no operator training needs. The information gathered with regard to base/subbase relative thickness and strength is invaluable compared to the resources and time consumed to perform the test.

Principle of Operation and Equipment

The DCP is defined by ASTM 6951-03 as a device used to assess the in situ strength of undisturbed soils or compacted materials. The DCP device consists of a 15.8 mm - diameter steel rod with a standard cone shaped tip, an 8-kg (17.6 lb) hammer that is dropped by a fixed height of 575mm, a coupler assembly and a handle. The cone tip has a diameter of 20 mm (0.79in) with an included angle of 60 degrees to reduce side friction. This is accompanied with a sliding rod, 15.8mm in diameter, but shorter in length, and attached parallel to main rod to measure the penetration of the device. Figures F and G show the DCP device. The entire device is made of stainless steel to protect it from corrosion. However, the cone tip is made of hardened tool steel or a similar material to resist wear and tear.

The test is conducted by dropping the weight from the height of 575 mm and measuring the penetration of the cone. The data recorded include the number of blows and the depth. The rate of penetration is defined as the depth of penetration per blow, and is often referred to as the penetration index or the DCP ratio. The units used is mm/blow or in/blow. The penetration rate is determined as the slope of the curve relating the number of blows to the depth of penetration. The device can be operated manually or can be automated by installing it on a trailer as shown in Figures H8 and H9. The automated DCP (ADCP) has a fully developed software tool to determine the soil support values being sought.

Figure H6. Photo showing the Dynamic Cone Penetrometer in Operation (Courtesy of, Minnesota DOT).

Figure H7. Penetration of DCP into the Pavement Layer Being Evaluated (Courtesy of Minnesota DOT).

Figure H8. Automated DCP Attached to a Trailer (Courtesy of Minnesota DOT).

Figure H9. Photo Showing the ADCP in Operation (Courtesy of Minnesota DOT).

Data Analysis

The penetration rate, PR, in in/blow, measured by the DCP has been correlated to several engineering properties of the material. It was initially correlated to the California Bearing Ratio (CBR) of the pavement subgrade (Kleyn,1975; Livneh, 1987). These models defined a relationship between the log of CBR and the log of PR. Further studies extended a different relationship for fine and coarse-grained soils (Harrison, 1989). More recently, the US Army Corps of Engineers (Webster et al., 1992) developed a relationship based on a wide range of tests on granular and cohesive materials. This relationship expressed below, which is the most widely used relationship today.

$$\text{Log CBR} = 2.465 - 1.12\ (\log \text{PR}) \qquad \text{(H8)}$$

Correlations of the penetration rate (*PR*) to other engineering properties are accomplished based on the relationship these properties have with the CBR. For example, the resilient modulus (M_R), was correlated to the CBR (Heukelom, W.; Klomp, AJ, 1962), as shown below.

$$\text{Mr} = 1500 * \text{CBR} \qquad \text{(H9)}$$

Equations 1 and 2 can be used to relate the *PR* to M_R values for subgrade soils. This was validated by studies that verified the computed modulus to the backcalculate modulus from FWD data (Chen, 2001). Furthermore, several studies have also correlated the *PR* to the elastic modulus of the subgrade (Chua, 1988, Pen 1990). In addition some agencies have plans to develop correlations between resilient modulus and the penetration rate or index. One such correlation is included in the 2002 Design Guide for all unbound materials and soils, which is shown below.

$$CBR = \frac{292}{PR^{1.12}} \qquad \text{(H10)}$$

The resilient modulus of the unbound layer is then determined by the following regression equation.

$$M_R = 2555(CBR)^{0.64} \qquad \text{(H11)}$$

The CBR is measured in accordance with AASHTO T193.

Data Interpretation

The PR from the DCP test is typically used to estimate the CBR of the soil sample. It is however to be noted that the CBR does not necessarily provide a true reflection of the moisture or density of the sample. Given the variation of density and CBR with change in moisture content, it is know that for a given value of CBR, the soil can have different moisture and density values. In other words, several combinations of moisture and density (and unconfined pressure) can give the same CBR value or PR from a DCP test. Moreover, the .moisture condition in the pavement changes constantly. Therefore, it is highly recommended that insitu moisture content be tested at the time of construction along with DCP test.

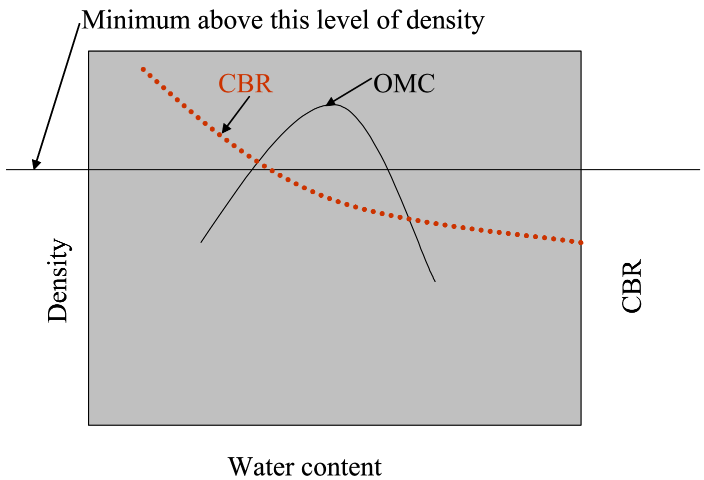


Figure H10. Density and CBR versus Moisture Content

Agency Use or Adoption

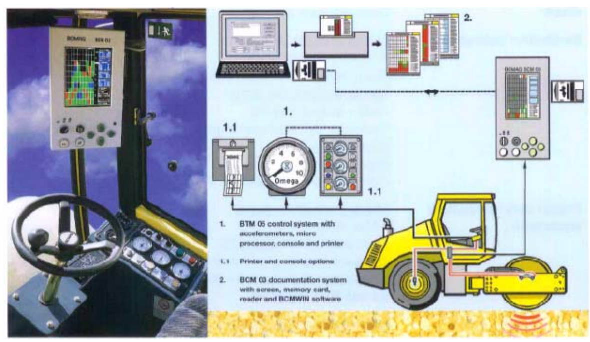
The DCP is used extensively by various agencies for evaluating unbound layers prior for reconstruction designs. Those agencies with extensive experience include Illinois, Indiana, Louisiana, Minnesota, Mississippi, Oklahoma, Texas, Pennsylvania Turnpike, and the Corp of Engineers. Many other agencies have the DCP but use it on more of limited basis. Other agencies are in the process of evaluating the DCP for use in reconstruction design and new pavement design through existing and on-going research studies (for example, Montana DOT). These agencies have realized the benefit from using the DCP to provide input data to the new 2002 Design Guide, as well as other mechanistic-empirical (M-E) design procedures. Minnesota, Mississippi, Oklahoma and other agencies have test protocols and data collection guidelines for using the DCP for reconstruction design and forensic studies. ASTM has been recently standardized a procedure for general use of the equipment. That procedure is ASTM D6951.

Appendix I

Intelligent Compaction for Soils—Principle and Operation

The intelligent compaction device manufactured by BOMAG is called the BOMAG VarioControl (BVC). This device has the ability to adjust its compactive energy relative to the stiffness of the grading materials encountered during the grading process, thereby optimizing resources and achieving adequate compaction. In other words the chances of over compaction in soft spots are greatly reduced. Figure 1 below shows the intelligent compaction equipment and a schematic of the automated process.

a) The device



b) Automated vibration control process

Figure I1. Intelligent Compaction for Unbound Materials (Figure Courtesy BOMAG)

The device uses a single drum roller and imparts real time adjustment to the vibration process and compactive energy to produce a uniform grading. The system generates linear vibration of the roller drum and uses a combination of vertical and horizontal vibration during the compaction process. The vertical direction contributes to maximum energy and can attain compaction at greater depths and achieve higher acceleration in the compactive process. On the other hand, the horizontal direction provides minimum compactive energy and stiffens the top layers of the soils strata.

In the automated process, the device adopts an adjustment to the combination of the directional vibrations imparted so as to transmit appropriate compactive energy for a uniformly finished pavement layer. The device contains two acceleration sensors that continuously monitor the soil deformations of the roller drum in real time, and in turn trigger the system to adjust the vibration process of the roller drum. In other words, the soil condition, the thickness of the layer, and the resulting stiffness dictate the intensity of compaction provided by the device.

The system also allows a convenient means of recording and presenting data at a project level. The device is integrated with a Global Positioning System (GPS) system that can be used for both specifying and recording the compaction process along a given project.