CONTEXT SENSITIVE ROCK SLOPE DESIGN SOLUTIONS

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U.S. Department of Transportation
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CTIP

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
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FOREWORD

Context sensitive designs in transportation are key to developing facilities that fit within the engineered setting, preserving scenic, aesthetic, historic, and environmental resources while maintaining motorist safety and mobility. Many Federal Land Management Agency partners of the Federal Highway Administration (FHWA) Federal Lands Highway Division (FLHD) manage roads in complex geologic settings, with steep mountainous terrain and various environmental concerns. Projects constructed in these areas often require rock excavation, slope stabilization, and rockfall mitigation to achieve the desired roadway template. Projects constructed in these areas often require rock excavation, slope stabilization, and rockfall mitigation to achieve the desired roadway template. In many cases, traditional methods of excavation are not suitable for these projects. For example, in national parks and forests, presplitting during rock blasting has been prohibited for aesthetic reasons. Even along state-owned roads, these blasting methods are becoming less common. In areas where rockfall is a danger, devices such as rock bolts, rock fences, catchment ditches, or wire mesh nets must be installed.

Recently, new technologies have emerged for use on transportation projects that can provide natural-looking cuts while maintaining the stability of the slope. But while many stabilization and rockfall mitigation methods are available, context sensitive solutions are not widely used within the FLHD regions. Thus, guidelines are needed to help engineers design various context sensitive stabilization and mitigation systems that meet all safety, environmental, and aesthetic requirements.

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16. Abstract

The Federal Highway Administration (FHWA) Federal Lands Highway Division (FLHD) evaluated the application of context sensitive solutions (CSS) for rock slope design. The application of context sensitive design in transportation is a method of developing facilities that fit within the engineered setting and preserve scenic, aesthetic, historic, and environmental resources while maintaining safety and mobility.

Proper development of context sensitive solutions starts before the scoping stage and incorporates a number of factors, including community concerns, the effects of roadway development on the physical character of the surrounding area, and a visual prioritization of design considerations. Before starting construction, the contractor and land management agency should agree on a defined standard of performance and communication protocols to ensure that all project goals are attained.

The aesthetics of common rock slope construction and mitigation practices can be enhanced with some modifications. Advantages, limitations, design guidelines, aesthetic value, construction materials, case examples, relative costs, and maintenance procedures are included for each method. Discussions are intended to guide the reader in CSS rock slope development.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric tons)	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric tons")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF SYMBOLS AND ABBREVIATIONS

~	Approximately equal to
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials/ASTM International
AWG	American Wire Gage
BS	British Standard
CALTRANS	California Department of Transportation
CDOT	Colorado Department of Transportation
CFLHD	Central Federal Lands Highway Division
CSS	Context Sensitive Solutions
DOT	Department of Transportation
EFLHD	Eastern Federal Lands Highway Division
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
FLHD	Federal Lands Highway Division
FS	Factor of Safety
ft	Foot (feet)
ft^2	Square foot (feet)
ft-tons	Foot-Tons
in	Inch(es)
kJ	KiloJoules
kPa	Kilopascal
m	Meter(s)
m^2	Square meter(s)
MPa	Megapascal
MSE	Mechanically Stabilized Earth
PTI	Post-Tensioning Institute
PVC	Polyvinyl Chloride
U.S.	United States
WFLHD	Western Federal Lands Highway Division

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CHAPTER 1 – INTRODUCTION

To meet a Vital Few Goal on Environmental Stewardship and Streamlining, the Federal Highway Administration (FHWA) has implemented context sensitive solutions (CSS), a set of principles designed to improve the quality and lessen the environmental impact of transportation projects. In CSS, the word "context" refers to a project's surroundings—its natural environment as well as its historical setting and role in the community (i.e., its use as a public space or thoroughfare). Thus, under the rules of CSS, every project will be planned, designed, and constructed with each of these considerations in mind. In support of this program, the FHWA promotes the development of principles and processes that can be used in all states and within federal lands to improve the quality of transportation decision-making. This includes opportunities to enhance environmental protection and encourage partnerships that promote ecosystem conservation or encourage broader mitigation strategies.

One way to achieve this objective is to incorporate CSS principles in designing rock slopes for transportation facilities—in other words, to design facilities that fit within the project setting and preserve scenic, aesthetic, historic, and environmental resources while maintaining safety and mobility. Many federal agencies served by the Federal Lands Highway Division (FLHD) manage roadways in complex geologic settings, often in steep mountainous terrain, with numerous environmentally sensitive features. Projects constructed in these regions often require rock excavation, slope stabilization, and rockfall mitigation to achieve the desired roadway template and provide a safe public facility.

Rock excavation through mountainous terrain for the construction of travel corridors has been in continuous development for many years. Many of the existing excavation methods use blasting techniques that were originally developed for use by the mining industry and were mainly focused on maximum rock excavation and rapid production with little attention to environmental protection or the aesthetic impacts of the final cut. State DOTs often struggle in designing a safe rock slope that does not appear overly engineered and seems to fit within the project setting.

Over the past several years, rock slope design technologies have been developed for transportation application, but there is no comprehensive document that compares existing and developing technologies or offers selection and implementation guidelines related to context sensitive areas. This document will discuss existing and developing technologies for contact sensitive designs and provide a reference for the selection, evaluation, design, and construction of rock slopes.

Moreover, there is very little published information focusing specifically on the aesthetic concerns of rock slope construction, slope stabilization, and rockfall protection measures. Many of the techniques reviewed in this document are derived from personal experiences, conversations with state DOT construction design personnel, and case histories. Beginning in the early 1990's, engineers Kerry Cook and Craig Dewey have been applying these techniques to several FLHD projects. Examples of some of these projects were presented in the FHWA Special Roadway Aesthetic Treatments Photo Album Workbook. The workbook is intended as a "living document" where examples of innovative aesthetic treatments that have been applied nationwide on U.S. transportation projects are highlighted. Robert Cummings published one of the first papers that specifically addressed blasting and rock slope alterations that address both safety and aesthetics (Cummings 2002). Cummings' paper discusses aesthetically appealing rock slope design for new construction of travel corridors, but does not consider slope stabilization, rockfall protection, or slope maintenance issues. This paper addresses the most common stabilization, protection, and maintenance techniques used in areas that experience high rockfall hazards, as well as the aesthetic impacts of each.

This paper also addresses the costs associated with various CSS practices. For example, although engineers have developed new mitigation techniques that can control small or discrete rockfall events, we know that large or frequent failures cannot be easily or economically mitigated. The designer must always assess mitigation construction costs versus the impacts and losses caused by rockfall and design the roadway layout and/or mitigation alternatives accordingly.

The objective of this report is to provide design, construction, and maintenance solutions for rock slope excavation, stabilization, and mitigation in context sensitive regions. It addresses state-of-the-art and state-of-practice technologies for the evaluation, design, and construction of context sensitive rock slopes. Key features of the report include the following:

- Advantages and limitations of existing and developing technologies and their acceptability for use on context sensitive projects.
- Relative cost comparisons of design, construction, and maintenance options.
- Design methods and examples for each application.

CHAPTER 2 – CONTEXT SENSITIVE CONSIDERATIONS FOR ROCK SLOPES

UNDERSTANDING CONTEXT

To design and construct natural-looking rock slopes, the designer/engineer and contractor must first consider the following questions (Maher et al. 2005):

- How will the proposed transportation improvement affect the general physical character of the area surrounding the project?
- Does the area to be affected have unique historic or scenic characteristics?
- What are the safety, capacity, and cost concerns of the community?

Answering the above questions will help the engineer/designer address the basic issues of CSS in the early stages of roadway layout or mitigation method.

The critical first step of CSS is assessing the surrounding area—the context of the project—and then designing the rock slope to follow the area's natural characteristics. Rock slope context can include such factors as weathering patterns, fracture planes, vegetation, rock/slope color, and roadway layout. For example, the context of Zion National Park in southern Utah features steep-walled, light- to reddish-brown canyons with sparse vegetation and numerous rock outcroppings. Thus, an engineer following CSS would design cut slopes that were steeply sloped, colored to match the natural staining, and re-vegetated with a native seed mix. In contrast, the context in Washington's Olympic National Park and other areas of the Pacific Northwest includes heavily vegetated, moderately sloping landscape. Cut slopes designed to follow CSS principles in this area would be laid back, with rounded transitions between the cut area and the natural slope; the designer might also use revegetation and rock coloring to help blend the cut face into the natural terrain.

THE DESIGN PROCESS

The design process can be broken into five distinct steps: assessing slope stability, selecting the most appropriate excavation technique(s), designing safe and aesthetically pleasing rock cuts, determining visual prioritization, and developing any necessary stabilization and/or rockfall protection methods. Designers must also establish consensus among stakeholders throughout the design process.

Slope Stability Analysis

Engineers analyze slope stability for rock (or predominantly rock) slopes by using the scan-line survey and stereographic analysis technique, often referred to as a kinematic analysis. A scan-line survey evaluates the dip, orientation, spacing, and surface condition of the discontinuities in a section of rock. A kinematic analysis considers the potential for movement in a slope—any motion that's geometrically possible—and determines the possibility that a rock mass might move or slide.

If a proposed slope angle presents a kinematically possible mode of failure, it should be analyzed using a stability analysis method (i.e., limit equilibrium analysis), which compares the forces that will be resisting failure to those that could be causing it. The ratio between these two sets of forces is the slope factor of safety, or FS.

Geologic Features and Their Effects on Slope Character and Stability

Geology is the main consideration in determining the best excavation technique(s), slope design, stabilization, and protection measures for a rock slope. For engineers and other rock slope designers, some of the key components of a slope's geology are its orientation and angle and the type and structure of rock it comprises.

Slope Orientation and Angle:

To determine the inclination and orientation, or "attitude," of a slope or any other type of plane, geologists typically measure two angles: strike and dip. The *strike* is defined as the line of intersection between the slope and the horizontal plane. Identifying the strike tells the engineer the precise direction that the slope is facing. Strike is measured in degrees and bearing (compass direction) relative to north; for example, a slope with a strike of N45°E is oriented—45° east of due north. The d*ip* is the maximum angle, measured from a horizontal plane, of the surface that is perpendicular to the strike. An apparent dip is any other dip in the slope that's not perpendicular to the strike line (and therefore not as steep).

Discontinuity orientation is most conveniently expressed as dip and dip direction for rock slope engineering purposes. The dip direction is the direction of the horizontal trace of the strike line measured clockwise from north. The orientation of the plane can be completely defined by five digits. Dip is expressed in 2 digits and dip direction in 3 digits. By always writing dip direction as three digits, there can be no confusion as to which set of figures refers to dip direction. For example, a discontinuity with a dip of 55 degrees and an azimuth orientation of 90 degrees would be expressed as 55/090. A discontinuity with a dip of 5 degrees and an azimuth orientation of 310 degrees would be expressed as 05/310. This is illustrated in Figure 1.

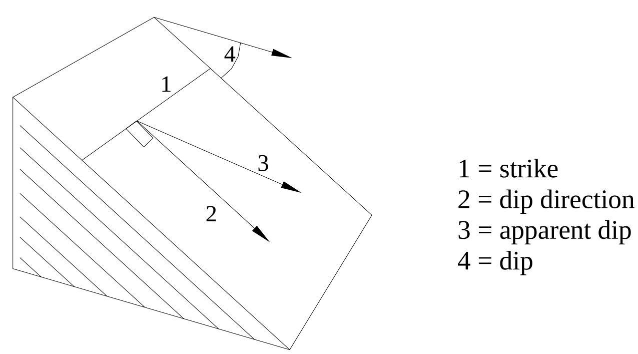


Figure 1. Illustration. Rock discontinuity orientation parameters.

Rock Type and Structure:

Slope stability also depends heavily on the type and condition of the rock and soil that comprise the slope. In slopes consisting primarily (or entirely) of rock, the biggest concern is the geologic structure of the rock: its discontinuities—bedding surfaces, joints, foliation, faults, and other natural defects—and the location and orientation of those discontinuities. It's the geometric interrelationship of the rock mass and its discontinuities that determines, to a large part, the stability of a slope.

In all but the rare case of a completely unfractured rock unit, the rock mass can be considered a three-dimensional assemblage of rock blocks delineated by sets of discontinuities. These discontinuities can occur as unique, randomly oriented features or repeating members of a discontinuity set. This system is sometimes referred to as the structural fabric or characteristic of the rock mass. In most cases, engineering properties of the fractured rock mass—strength, permeability, and deformability—depend more on the discontinuities than on the properties of the intact rock.

For example, geologic structure can influence many short-range aesthetic features, such as slope texture and roughness, as rock with multiple fractures (less than 1/3 to 1 meter or 1 to 3 feet apart) is likely to show blasting/machine scars and other unacceptable levels of surface damage.

For extremely weak rock, engineers use classic soil mechanics principles for defining the FS of the rock mass. Methods that use soil mechanics principles are limit equilibrium approaches such as the method of slices (e.g., Bishop Method, Spencer-Wright Method, and Morgenstern-Price Method). There are several different computer programs for analyzing slope stability, excavation design, and geotechnical applications.

Methods of Excavation

CSS principles require engineers to determine the best excavation technique(s) for the project, considering the type of rock to be removed, the end use of the material, and the cost and context of the roadway. Different rock types require different types of excavation. In many cases, the excavation method will influence the dimensions and stability of the final slope and the rockfall mitigation strategy. Different types of excavation will also produce varying levels of superficial damage, such as drill-hole traces and machine scars. Thus, excavation method(s) must be agreed to by all project stakeholders. These excavation methods are addressed in Chapter 3.

Safe and Natural-Looking Rock Cuts

To ensure safety, the angle (or angles) of the rock cut should be developed in accordance with the results of a kinematic analysis. All relevant modes of failure that may occur with an improperly cut slope angle must be considered. If a slope is cut at an angle that allows for one or more of the possible modes of failure, it may require expensive mitigation and maintenance for many years after the initial construction. Designing a slope in a manner that takes into account all relevant failure modes will reduce the stabilization and/or protective measures required, which will minimize costs, and, if context is properly considered, will improve the aesthetics of the slope.

Designing a natural-looking rock cut can be challenging if the designer is not familiar with current design practices and proper techniques for stabilization and protection. Construction drawings and specifications should include examples of the proposed layout of the rock cut in the form of pictures, sketches, and acceptable/unacceptable cut slope configurations and excavation techniques. Flexibility is essential in context sensitive design because the heterogeneity of geological formations and the changing topography along the length of a rock cut often require on-site design decisions. Communication between the contractor and the contracting agency, before and during construction, is paramount in creating rock cuts that are safe and aesthetically acceptable to all stakeholders.

Visual Prioritization

Visual prioritization is the process of determining which aesthetic enhancements will truly enhance the visible aspects of the roadway and those that will result in needless expense. In many cases, visual prioritization is performed by a landscape specialist working as part of a multidisciplinary highway design team and in close coordination with the land management agency. Visual impacts should be considered according to their location as well as the duration and distance of motorist and non-motorist view (i.e., how long a person will see the feature and from how far away). In general, the most significant visual impacts to the highway user are those that will be apparent for longer than approximately 10 seconds when driving at the posted speed limit.

When prioritizing visual impacts, the designer must consider both the *short-* and *long-range viewsheds* (Cummings 2002).

Short-Range Viewshed

The short-range viewshed includes slope features that are visible within short distances, normally in the motorist's final approach or while they are passing the slope. Short-range features include slope texture, roughness, revegetation, stabilization methods, blasting/machine scars, and certain rockfall protection structures (e.g., rockfall draperies). While these features all contribute to the overall aesthetics of the slope, they typically require careful evaluation against duration of motorist view to avoid needless expense. The posted speed along a roadway and the location of the slope with respect to the roadway are main factors when evaluating the duration of view. Motorists are less likely to notice intricate slope texture or rock bolts while traveling at high speeds past a slope. Short-range features located on the inside of a curve, near the slope crest, parallel to the roadway, or on the slope-end opposite of traffic direction are less likely to be noticed than features located on the outside of curves, at eye level, on the slope-end facing traffic direction, or in straight roadway sections that offer extended view times.

Long-Range Viewshed

The long-range viewshed includes features that are visible to motorists at some distance from the slope, even while traveling at high speeds. Long-range features include slope variations, cut slope angles, and rockfall protection structures such as rockfall barriers and fences. Probably the most effective method of increasing rock cut aesthetics is fitting long-range features into the landscape by mimicking natural landform processes and by creating proper transitions between cut slopes and the natural terrain. Areas with long monotonous cuts, slopes with an extended view, highly variable topography, and geologically significant areas are good candidates for long-range features.

Stabilization, Protection, and Avoidance Measures

If a slope cannot be stabilized by proper slope angle selection, *slope stabilization measures* normally provide the most cost-effective and aesthetically pleasing means of rockfall mitigation. Stabilization measures work to reduce or inhibit rockfall by either removing the unstable section(s) of rock or providing internal or external support to the rock mass (either increasing the resisting forces in the rock mass or decreasing the driving forces).

Engineers must review potentially unstable slopes or areas of rockfall and consider all applicable stabilization methods in terms of cost, feasibility, stability improvement, and aesthetic impacts, then perform limit equilibrium stability analyses with the proposed stabilization measures until the slope is at the AASHTO-recommended factor of safety (FS).

In areas of high rockfall risk or where stabilization is not feasible, engineers must evaluate the effects of *rockfall protection methods* on potential impact energies, bounce height of rockfall, maintenance requirements, cost, and aesthetics. The use of rockfall protection methods accepts the reality that rockfall will occur and strives to protect structures by stopping, diverting, or controlling it.

Protection structures are normally placed at the toe of the slope and act to either stop the rockfall or deflect it from the roadway. A common feature of all protective structures is their energy-absorbing characteristics. Properly designed protective structures are able to absorb repeated high-energy rockfall impacts.

Avoidance measures may be a valid option if the cost of stabilization, protection, and maintenance is greater than the avoidance cost. Avoidance should always be considered in very hazardous areas, although it can be an expensive option. Avoidance options include elevating the roadway, tunneling, or relocating the roadway. An in-depth discussion of avoidance structures and design parameters is outside the scope of this report.

Building Consensus among Stakeholders

Effective CSS designs also require consideration of stakeholder concerns, particularly those involving safety and cost. One of the challenges in any type of rock slope design—particularly a natural-looking rock slope—is developing a cut slope that meets long-term stability objectives.

For example, rock slopes that are cut near vertical typically look more natural, but they are less stable than cuts that are laid back at a specific slope ratio that is not as steep as the surrounding terrain. Thus, it's imperative that the designer/engineer establish an understanding with the stakeholders that addresses all of the aesthetic, safety, and cost considerations of the improvements. A successful context sensitive project involves gathering all stakeholders early in the scoping and design process to prevent confusion, disagreements, and delays that may develop later.

Preparing a Bid

Once established, the desired slope parameters should be included in the bid document as a set of measurable guidelines that will provide acceptable aesthetics and safety while allowing the contractor flexibility in construction. Designers should avoid detailed design specifications to allow the contractor some freedom during construction, as slope layout is highly dependent on local geologic features.

Project bid documents should include the following (modified from Cummings 2002):

- A standard of performance that is defined through measurable physical characteristics. These characteristics can be in the form of acceptable vs. unacceptable excavation techniques, which will produce a certain level of slope roughness, texture, and drill hole traces/machine scars as shown in Figure 2.

- Photos, cross sections, and plan views reflecting the anticipated cut slope configuration and sculpting, see Figures 3 through 5, plus description or illustrations of the intended aesthetic enhancements, such as revegetation and rock staining.

- A list of acceptable/unacceptable stabilization and protective mitigation methods.

In addition, the contractor must agree to the level of aesthetic attainment described in the bid documents, and the contracting agency must commit to inspecting, measuring, and enforcing the aesthetic criteria as strictly as it does any other elements of a construction or mitigation project.

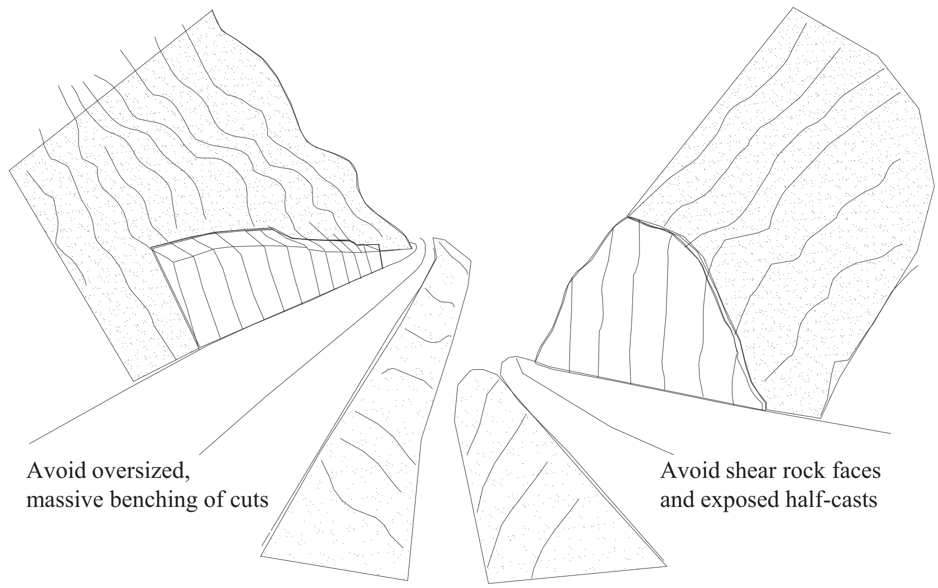


Figure 2. Illustration. Details of typical slope cuts to be avoided.

(b)

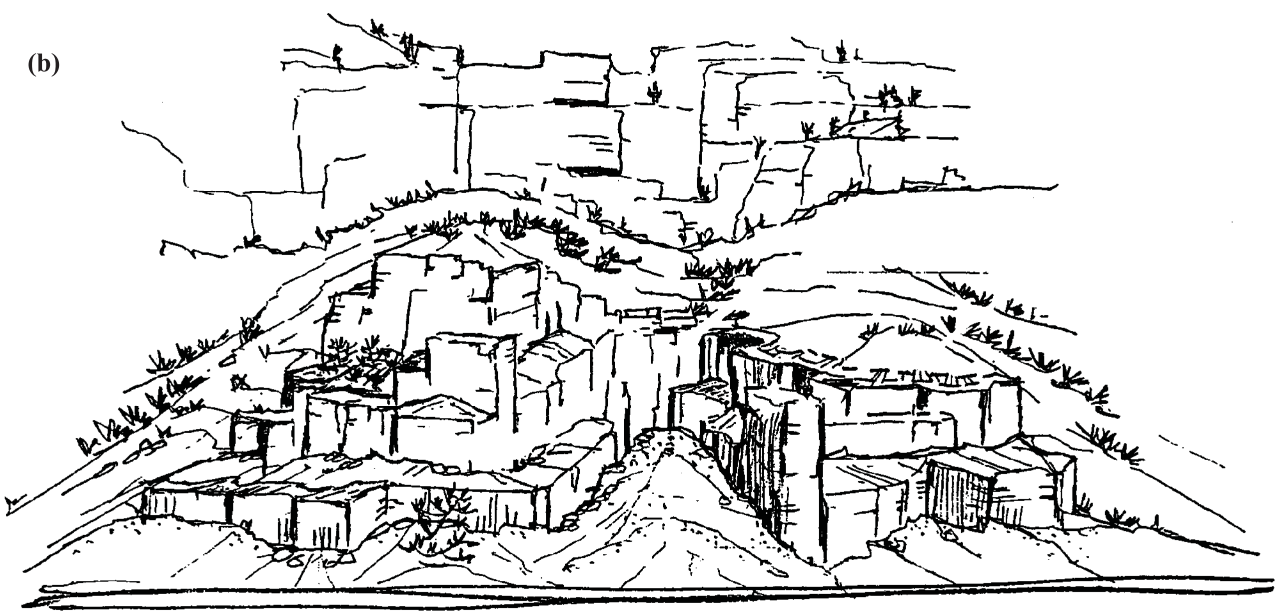
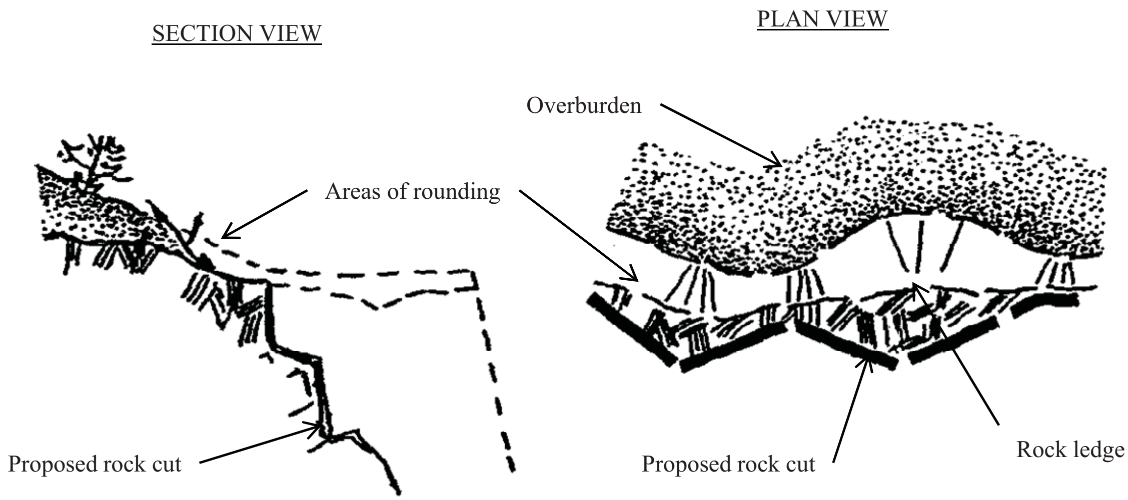


Figure 3. Illustration. Perspective view of the desired slope configuration and key design elements for different geographic settings. (a) Alpine environment with slope rounding and talus deposits (b) Arid/desert environment with blocky slope transitions and sparse vegetation.



Note: Round overburden on top of cut following contours into draws and onto ridges

Figure 4. Illustration. Example of typical details for a sculpted rock cut.

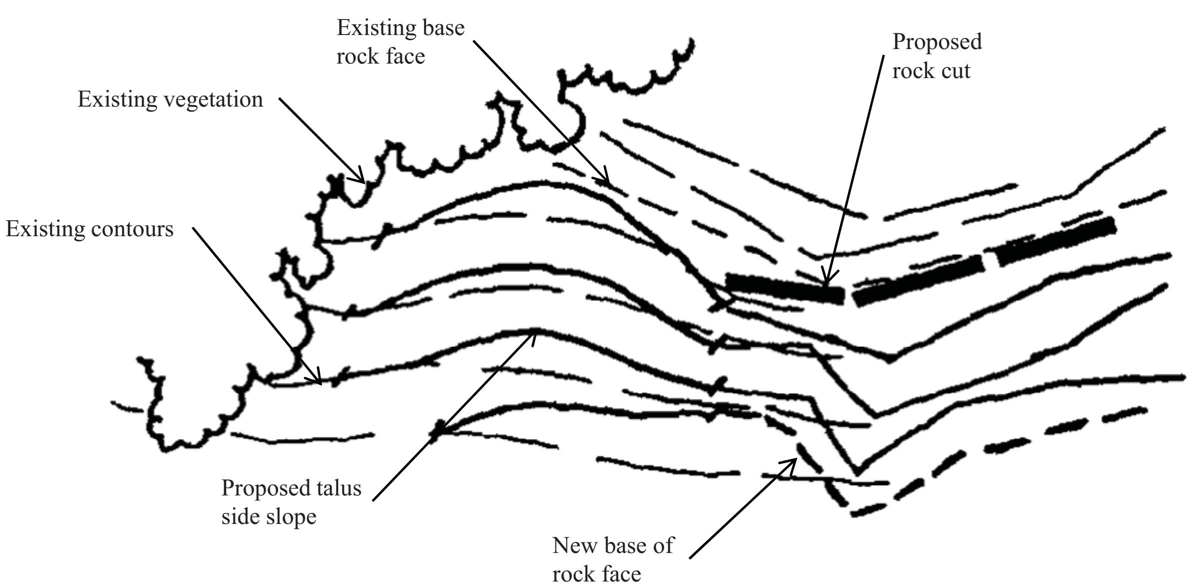


Figure 5. Illustration. Slope variation details used to enhance aesthetics.

CHAPTER 3 – ROCK EXCAVATION METHODS

This section reviews standard excavation practices used to construct and modify rock slopes and provides current design and construction guidelines for their use in context sensitive areas. Several of these practices have been used for many years, while others are new techniques or recent modifications of established methods. The most common are blasting (which includes drilling the holes to be filled with explosives), ripping, and breaking. Table 1 provides a brief description of these procedures, along with the advantages and limitations of each. Each procedure is discussed in detail below.

BLASTING

Blasting—the controlled use of explosives to excavate rock—has been part of construction engineering for hundreds of years.

In any blasting situation, the geologic structure of the rock mass will be the most important consideration. Other considerations include the degree of scarring that would be acceptable (some areas can tolerate more blasting scars than others), cost, and safety (blasting cannot be performed in close proximity to populated areas).

Effect of Geologic Structure on Blasting Procedure

The first consideration when designing a blasting operation should be the local geologic conditions. Rock competency and fracture patterns can have a significant impact on the success of a blasting operation.

Discontinuity Sets

When discussing blasting, the single most important geologic factor is fracture: the spacing and orientation of any breaks, or *discontinuity sets,* in the rock. In particular, the orientation of the discontinuity sets with respect to the cut slope angle will influence any slope failures that may occur along the slope face. The modes of failure can be grouped into four primary mechanisms, shown left to right in Figure 6.

- planar failure (a),
- wedge failure (b),
- circular failure (c), and
- toppling failure (d).

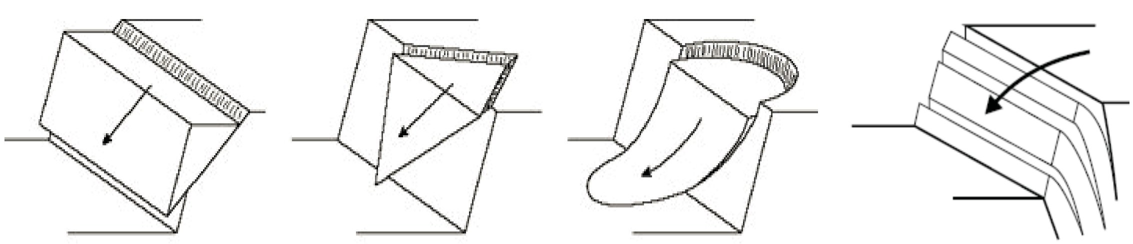


Figure 6. Illustration. The four primary mechanisms of slope failure.

Table 1. Description, advantages, and limitations of common excavation practices.

PROCEDURE	DESCRIPTION	ADVANTAGES	LIMITATIONS
Presplit Blasting	Presplit holes are blasted before production blasts. Procedure uses small diameter holes at close spacing and lightly loaded with distributed charges.	Protects the final cut by producing a fracture plane along the final slope face that fractures from production blasts cannot pass. Can produce steeper cuts with less maintenance issues. Performs well in hard competent rock.	The small diameter borings limit the blasting depth to 15 m (50 ft). Borehole traces are present for entire length of boring. Does not perform well in highly fractured, weak rock.
Smooth Blasting	Smooth blast holes are blasted after production blasts. Procedure uses small diameter holes at close spacing and lightly loaded with distributed charges.	Produces a cosmetically appealing, stable perimeter. Can be done on slopes years after initial construction. Drill hole traces are less apparent than presplitting. Performs best is hard, competent rock.	The small boring diameter limits blasting depth to 15 m (50 ft). Borehole traces are present for much of the boring length. Does not protect the slope from damage caused by production blasting. Does not perform well in highly fractured, weak rock.
Cushion Blasting	Cushion blasting is done after production blasts. Larger drill holes are used with small diameter, lightly loaded distributed loads. Space around the explosive is filled with crushed rock to cushion the explosive force.	Reduces the amount of radial fracturing around the borehole and also reduces borehole traces. The large diameter holes allow blasting depths up to 30 m (100 ft). Produces a ragged final slope face. Performs well in all rock types.	Radial fractures are more abundant than presplit and smooth blasting. Slope face is more prone to raveling. A catchment area is recommended at slope base. More demanding on the driller. Borehole traces still apparent in hard, competent rock.
Step Drilling	Larger diameter drill holes, drilled vertically and used as production blasting (although spaced closer and loaded lighter to minimize radial fractures). Slope face is formed along base of blast holes.	If properly designed the final slope face shows minimal signs of blasting. Can be used when sloped controlled blasting cannot. Best used in moderately to highly fractured rock.	Can produce extensive damage to slope or inadequate base fracturing if not designed properly. Should only be used with experienced driller and blasting engineer. Only applicable for slopes between 0.7:1 and 1:1 (H:V). Does not perform well in hard competent rock.
Horizontal Drilling	Larger diameter, closely spaced, lightly loaded horizontal borings are used for production style blasting. Used in massive rock to eliminate drill holes or in areas of poor access.	Eliminates bore hole traces when drilled perpendicular to the slope face. Good in massive rock where traces are not acceptable.	Demanding on the driller and explosives engineer. Can produce extensive radial fractures or inadequate base fracturing if not loaded properly. Requires complicated loading and timing procedures, and special stemming procedures.
Ripping	Uses a tractor with an attached tooth or teeth that is lowered into the rock and dragged to break up material for excavation.	Much cheaper and safer than blasting. Can be done in close proximity to development without disturbance. Is effective on a variety of angled cuts and an excavator can be used after ripping to slope sculpting.	The tooth of the ripper can leave scars on the rock surface. The tractor cannot be used on steep slopes because of risk of overturning. Ripping is limited to relatively low density rocks.

In order to avoid long-term slope instability and increased maintenance costs, designers should measure and evaluate prominent discontinuities on the rock face using a scan line survey and computer-based kinematic analysis, also known as a equal area net (or stereonet) analysis. Regardless of the number of joints in a slope, one set will usually be the dominant (or weakest) and therefore will dictate the rock slope design. Generally speaking, the direction of this dominant joint will have the greatest influence on blasting results and potential failure modes. For example, if this joint set is parallel to the final slope face as illustrated in Figure 7, the borehole can prematurely link to the joint, which will create coarse or blocky burden fragmentation and severe end break (breakage at the end of the row of blastholes). In this case, increasing the borehole spacing will reduce fragmentation size (if the end result of the blast will be rip-rap, the explosive load can also be reduced).

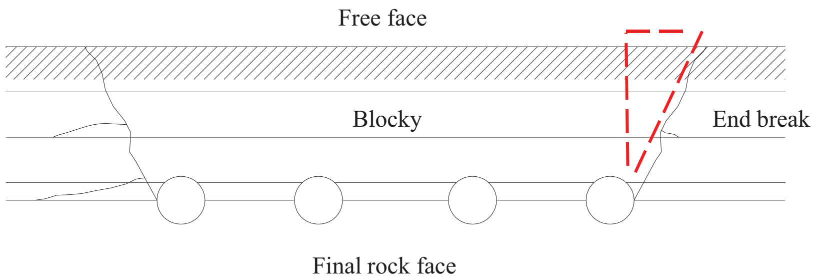


Figure 7. Illustration. Excessive end break caused by blasting parallel to jointing (modified from Konya and Walter 2003).

However, there can be problems blasting perpendicular to the final slope face, as well illustrated in Figure 8. While end break is not typically a problem in this case, backbreak (or overbreak)—fractures that extend from the blastholes back into the final slope face—can be significant (backbreak can cause slope instability and possible raveling of large blocks during excavation and thereafter). In addition, creating blastholes in an area with a significant number of joints can create blocky breakage. Reducing the spacing between blastholes can prevent this, but it might make backbreak worse. In this case, using smaller blastholes with a better distribution of powder may be the best solution (Konya and Walter 2003).

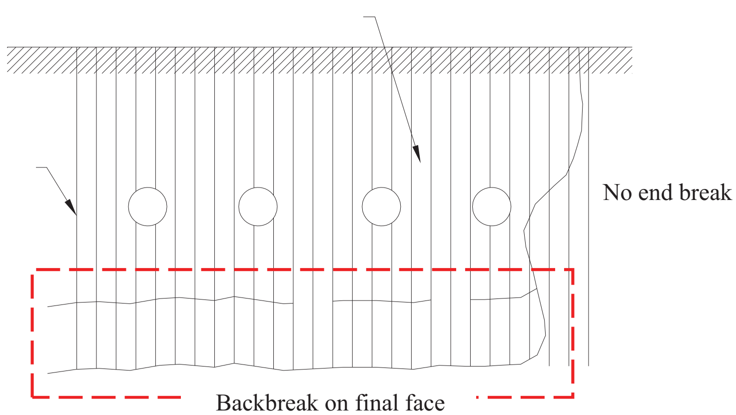


Figure 8. Illustration. Excessive backbreak caused by blasting perpendicular to jointing (modified from Konya and Walter 2003).

When blasting perpendicular to the final slope face, discontinuities occurring at sharp angles from the excavation plane tend to have the biggest effect. For example, discontinuities between 30° and 80° don't have much impact, but discontinuities from 20° to 25° can create some backbreak. Discontinuity angles less than 15° can allow the blast energy to travel into the discontinuity plane, which can cause it to form the final slope face as shown in Figure 9.

However, if these discontinuity planes are favorably orientated with respect to the road (orientations that parallel the road alignment or road bed), they can be used for the final face of the cut slope, resulting in a more natural-looking rock cut. The use of favorable joint orientation and/or bedding planes for controlling the blast is the most common and accepted method for developing rock slopes that fit within the geologic context of the surrounding area.

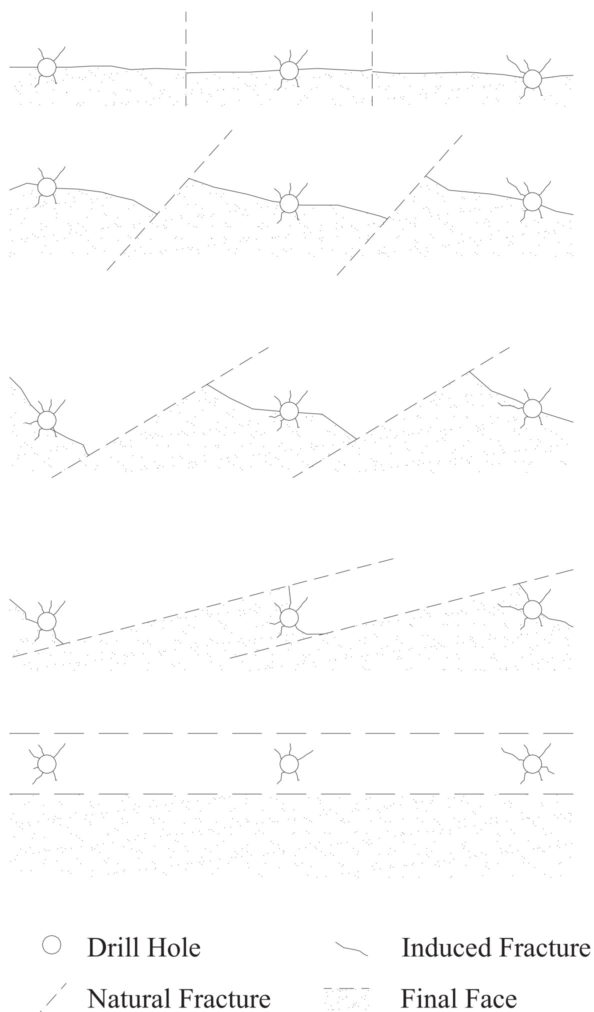


Figure 9. Illustration. The effect of joint orientation on the quality of the final wall face (modified from Matheson 1986).

Slope Dip

A slope's dip—its fall, illustrated as an imaginary line running down the steepest part of the slope—is another important factor to be considered in blasting. Blasting with the dip carries a greater risk of backbreak than blasting against the dip because the discontinuities (joints, bedding, etc.) channel the energy along the planes. However, this type of blasting allows engineers to use smaller explosive charges (or blast larger burdens) because the blasted rock moves more readily down the slope than it would if the blast were oriented against the dip. Blasting with the dip also creates a better-looking slope toe.

On the other hand, blasting against the dip typically creates less backbreak but can create more overhangs. It also can leave more material at the slope toe, resulting in a rough surface. Blasting against the dip also removes a smaller burden, meaning it will require more explosives.

Figure 10 illustrates the effect of dip on blasting. In this cut, blasting on the left side was performed against the dip, while blasting on the right side was done with the dip.

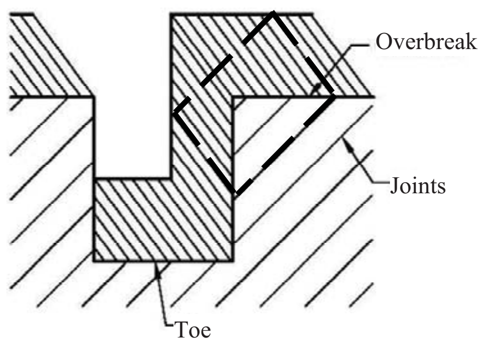


Figure 10. Illustration. Example of an excavation that blasts against the dip on the left side and with the dip on the right side (modified from Konya and Walter 2003).

Slope Strike

The strike of a slope—the direction the crest of the slope travels (i.e., the "across slope" direction), also plays a role in blasting design. Blasting parallel to strike in bedded rock can produce unpredictable results. The blast pattern intersects many different rock layers, and each layer will respond differently, as fragmented block size, toe conditions, and degree of backbreak all may vary slightly among them as shown in Figure 11.

Mud and Soft Seams

In addition to strike and dip, the presence of mud or soft seams in a slope also requires special consideration in the blast design. They can occur in any rock type, and are often unseen. Clay seams often respond like a liquid in that during initiation of a blast they provide an almost instantaneous attenuation of explosive energy. Therefore, it is essential to stem across soft seams to obtain good blasting results.

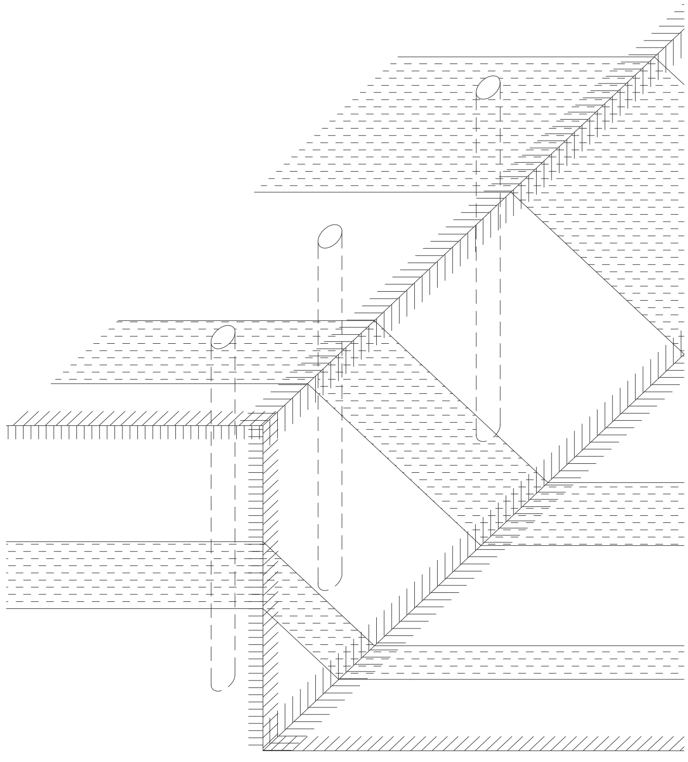


Figure 11. Illustration. Example of a blasting pattern that runs parallel to strike (modified from Konya and Walter 2003).

Blasting Methods

Blasting is used for rock excavation on both small- and large-scale projects. There are two general types: *production blasting* and *controlled blasting*.

Production Blasting

Production blasting uses large explosive charges, widely spaced, that are designed to fragment a large amount of *burden* (the rock that lies between the existing slope face and the blasthole). Production blasting is the most efficient way to remove large rock burdens, but it typically creates radial fractures around the blasthole and backbreak (fractures that extend into the final slope face), which reduce the strength of the remaining rock mass and increase its susceptibility to slope raveling and rockfall.

Controlled Blasting

Controlled blasting is used for removing material along the final slope face. In some cases, it’s also used before production blasting to create an artificial fracture along the final cut slope, which will prevent the radial cracks caused by production blasting from penetrating back into the finished face.

Controlled blasting can also be used alone, without production blasting. Controlled blasting creates less backbreak than production blasting because it removes less burden and uses more tightly spaced drill holes with lighter charges.

There are several types of controlled blasting; they vary most importantly in the amount of burden they remove and the type of powder they use. The discussion below will focus on controlled blasting techniques that best minimize the visual impacts of the blasting process, thus meeting the objectives of CSS design. These techniques are *presplit blasting*, *smooth blasting*, and *cushion blasting*.

Presplit Blasting:

Presplit blasting, or presplitting, is used before production blasting to protect the final rock face from damage caused by the production blasting. Presplitting creates a fracture plane along the final slope face, which prevents the radial cracks created by production blasting from penetrating into the finished face; without presplitting, production blasting damage can extend up to 15 m (50 ft) into the final slope face. Presplitting also allows for steeper and more stable cuts than any other blasting procedure. In massively bedded, competent rock, a properly charged presplit blast will contain drill hole half cast (the hole trace is split in half, axially) for almost the entire length of the blast line and will have no backbreak because the energy from the blast will travel uniformly, thus creating a continuous fracture between holes.

However, presplitting creates abundant visible drill traces, which makes it unsuitable in some areas (such as national parks). In some cases, these half casts can be chipped away with a pneumatic hammer, but it's very difficult to eliminate them without completely removing the outer layer of rock. In areas where such scars are not acceptable, presplit blasting will not be a suitable option. Figure 12 shows an example of a cut slope that used presplit basting methods which left visible half casts in the slope face.

Presplit blasting requires relatively small drill holes, between 5 to 10 cm (2 to 4 in) in diameter because its goal is to create discrete fractures, not massive breaking. However, because the small hole diameters allow the drill bit to deviate from the anticipated line more readily than larger drill diameters; the maximum depth of presplitting is usually about 15 m (50 ft). For this reason presplitting is used only for relatively small blasting operations.

Because of these limitations, presplitting is most often used on slopes steeper than 1H:1V (45°), which helps the drillers to maintain adequate hole alignment at depth. Presplitting performs best in competent, hard to extremely hard rock; it is the best method for minimizing backbreak, as the induced fracture plane prevents the shockwave from the main blast from being effectively propagated behind the final face of the rock mass. Presplitting is most difficult in highly fractured, weathered, and/or soft rock, where it requires the use of closely spaced drill holes and/or uncharged guide holes (see below).

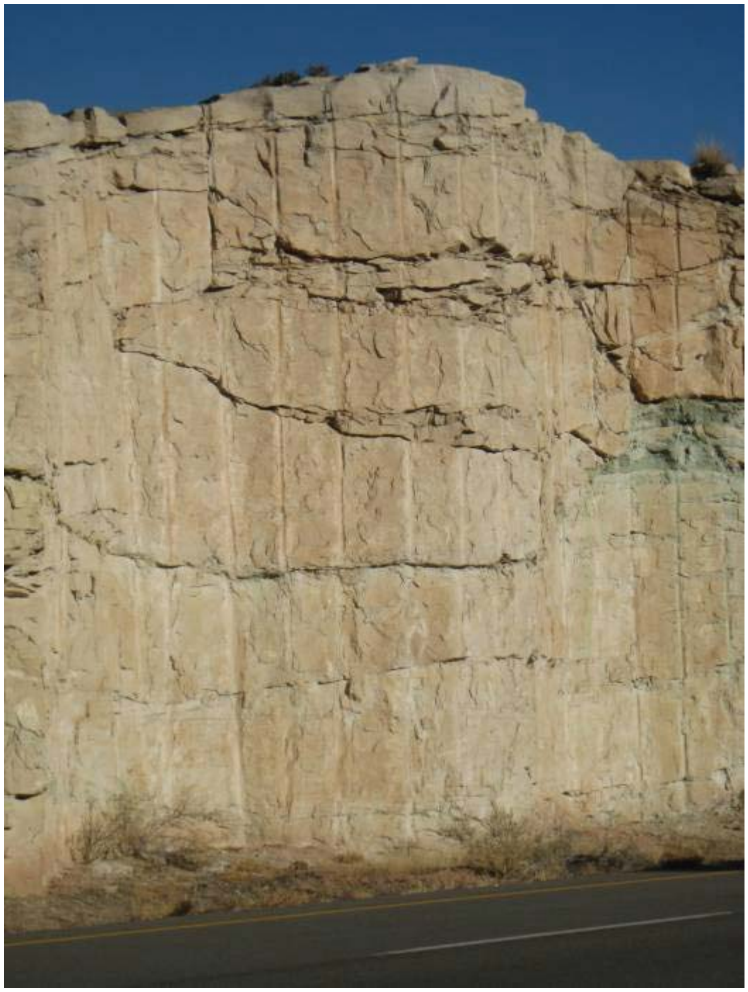


Figure 12. Photo. Example of a presplit slope in massive sandstone. Note the abundant drill hole traces (half casts).

Smooth Blasting:

Smooth blasting, also called contour blasting or perimeter blasting, can be used before production blasting as an alternative to presplitting. It's also used after production blasting, either as an entirely different event or as the last delay of the production blast. Smooth blasting uses drill holes with roughly the same diameter and depth as those used in presplitting, spaced slightly further apart and loaded with a slightly larger charge density. If the burden is adequately reduced, smooth blasting produces a more ragged slope face with minimal backbreak.

Smooth-blasted slopes may require more maintenance than presplit slopes due to increased radial fractures from the controlled blasting and overall fracturing from production blasting. Although smooth blasting creates abundant drill hole traces, they're generally less noticeable than the half casts left by presplitting. If drill hole traces are not acceptable, smooth blasting may be suitable only if the cut slope height is small and the drill traces can be easily removed with a pneumatic hammer or other device (see below).

Smooth blasting is best preformed in hard, competent rock, although it can be used in soft or highly fractured rock by increasing the spacing of the drill holes and/or adding uncharged guide holes to the pattern. Smooth slope blasting can be used on a variety of cut slope angles and is effective in developing contoured slopes with benches or other slope variations.

Cushion Blasting:

Cushion blasting, sometimes referred to as trim blasting, uses a row of lightly loaded “buffer” holes filled with crushed stone over the entire depth of the hole, which reduce the impact on the blasting holes and protect the surrounding rock mass from the shock caused by the blast, thus minimizing the stress and fractures in the finished slope face as shown in Figure 13.

Figure 13 also illustrates other blast hole drilling techniques (breaker, production, and looker drill holes), which can be used in conjunction with cushion blasting to fragment and mobilize the rock mass in the production zone. The application of these drilling methods is contingent on the structural characteristics of the rock, the existing and final slope geometry, and access via pioneering to the production zone.

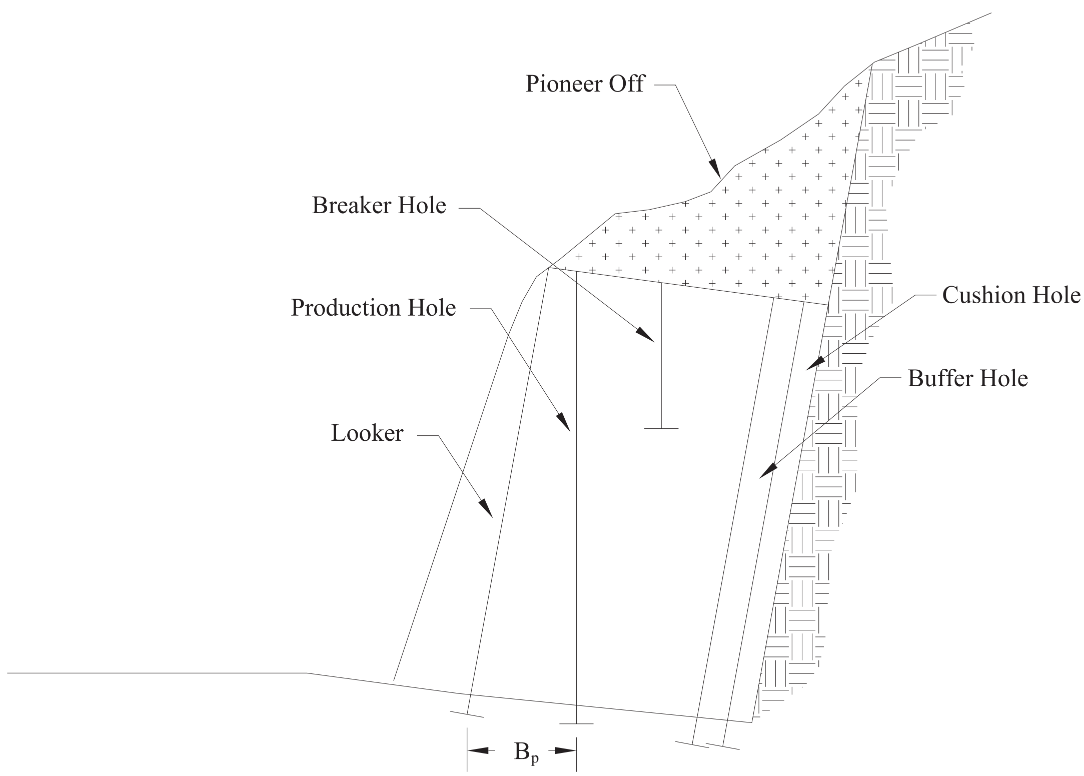


Figure 13. Illustration. Cross section of a cushion blasting design using buffer holes to control the burden on the cushion holes (modified from Cummings 2002).

The maximum diameter for cushion holes used in transportation is typically 75 mm (3 in). The drill steel used to advance these smaller holes tends to drift at depth, meaning the maximum depth is usually held to 12 m (40 ft). Cushion blasting creates some backbreak, which can make a slope more prone to raveling. Because cushion blasting can increase the danger of rockfall, the catchment area may need to be enlarged.

Figure 14 shows a recently constructed slope created using cushion blasting in fractured granitic rock. Note the wider ditch width in relation to the cut height.

Cushion blasting is more demanding than presplit or smooth blasting for the explosives engineer because hole spacing, burden, and charge density must be carefully chosen and continually reassessed in order to minimize backbreak. It also can be more time consuming because more drilling is required and charges take more time to load.

In poorly lithified, moderately to highly fractured and weathered formations, cushion blasting produces better results than smooth or presplit slope blasting. However, even cushion blasting may can leave drill hole traces in massive, homogeneous formations with few fractures.

Figure 14. Photo. Final configuration of a cushion-blasted slope in granitic rock.

Explosives

The type of explosive used in any project depends on the hardness and structural characteristics of the rock and the overall geometry of the cut (burden, depth, and width). There are numerous types of explosives, and for each type there are several different concentrations and mixtures. Properties to be considered when selecting an explosive include its sensitivity, density, strength, water resistance, fumes, price, and availability. Table 2 provides a general overview of explosives commonly used in the transportation industry.

Dynamite

Dynamite is the best known and most widely used explosive. It is classified according to its percentage by weight of nitroglycerin (percentages range from 15 to 60%). Strength does not increase linearly with proportion, however. For example, 60% dynamite is about 1.5 times stronger than 20% dynamite.

There are several variations in dynamite composition:

- Straight dynamite consists of nitroglycerine, sodium nitrate, and a combustible absorbent (such as wood pulp) wrapped in strong paper to make a cylindrical cartridge.

- Gelatin dynamite consists of a nitrocellulose-nitroglycerine gel. It is available in very high strengths (up to 90% nitroglycerin), making it useful for excavating extremely hard rock.

- Ammonia dynamite has similar composition to straight dynamite, but a portion of the nitroglycerine content is replaced with ammonium nitrate to create more stable and less costly dynamite. It has a strength of approximately 85% of straight dynamite.

Ammonium Nitrate and Fuel Oil (ANFO)

This combination of a nitrogen fertilizer and fuel oil has largely replaced dynamite in medium and large borehole blasting. The explosiveness of ANFO greatly increases with the concentration of fuel oil (the maximum is 6%). Mixing can be done on-site or in the factory, although premixed compounds present concerns regarding handling and storage (premixed ANFO has been known to spontaneously combust when kept in storage for long periods of time). Straight ammonium nitrate can be shipped and stored the same way as any other blasting agent. ANFO does not combust well in water, but it can be sealed in bags to prevent water seepage.

Slurry (Water Gel)

Also known as a dense blasting agent (DBS), slurry is a mixture of a sensitizer, an oxidizer, water, and a thickener. The sensitizer can be any number of reducing chemicals, but is usually TNT (trinitrotoluene). The oxidizer is ammonium nitrate. The thickener is guar gum or starch. High-density slurry can remove a greater burden than ANFO, which allows for the use of smaller diameter boreholes (or wider borehole spacing) to obtain the same explosive power and fragmentation. However, the higher price of the slurry may offset the cost savings of drilling fewer holes. Slurries are reasonably insensitive, but temperature and density have large effects

Table 2. Explosives commonly used in transportation projects.

TYPE OF EXPLOSIVE	DYNAMITE	AMMONIUM NITRATE AND FUEL OIL (ANFO)	SLURRY (WATER GEL)	EMULSION EXPLOSIVES
Most Common Application(S)	Most often used in smaller boreholes. Gelatin dynamites are useful for blasting extremely hard rock.	Medium and large borehole blasting and cushion blasting. The most common general-purpose explosive in use today.	Often used in place of dynamite because of safety and convenience.	Has begun to replace dynamite, particularly in wet or submerged conditions.
Composition	Straight dynamite contains nitroglycerine, sodium nitrate, and a combustible absorbent (e.g., wood pulp). Ammonia dynamites contain ammonium nitrate. Gelatin dynamites contain nitrocellulose to create the gelatinous consistency.	Ammonium nitrate (a nitrogen fertilizer) mixed with up to 6% fuel oil.	A sensitizer (typically TNT), an oxidizer (ammonium nitrate), water, and a thickener (such as guar gum or starch).	An oxidizer solution (typically ammonium nitrate) and oil.
Strength	Straight dynamite is the benchmark for explosive weight/strength comparisons. It is generally available in 15% to 60% concentrations of nitroglycerin (gelatin dynamite contains up to 90% nitroglycerin).	Similar strength to straight dynamite.	Stronger than ANFO, less strong than gelatin dynamite.	Similar in strength to slurry explosives.
Impact Sensitivity	Ammonia and gelatin dynamites are less volatile and sensitive to shock and friction than straight dynamite.	Premixed compounds can be sensitive. If not pre-mixed, they are quite stable and insensitive.	A lot less sensitive than dynamite but more sensitive than emulsion. More sensitive at higher temperatures.	Emulsions are the least sensitive type of explosives. Cartridges are fairly resistant to rupturing during normal handling.
Water Resistance	Straight dynamite has good water resistance. Gelatin dynamite is nearly waterproof. Ammonia dynamite has poor water resistance.	Poor water resistance	Good to excellent water resistance.	Excellent water resistance.
Fumes	Straight dynamite has some toxic fumes. Ammonia and gelatin dynamite fumes are less toxic.	ANFO produces less toxic fumes than dynamite but more than slurry or emulsion explosives.	Slurries and emulsions have a similar fume class.	Slurries and emulsions have a similar fume class.
Price/ Availability	Dynamite is easy to obtain and relatively inexpensive.	The least expensive and most available explosive.	Widely available. Less expensive than dynamite, more expensive than ANFO.	Similar in both cost and availability to slurries.

on this (i.e., slurries become less sensitive and less fluid as temperature decreases). Sensitivity can be increased by adding sensitizers to the composition. Slurries load about three times faster than conventional dynamite, making them more convenient and faster to use.

Emulsion Explosives

Emulsions are a water-in-oil type of explosive consisting of microdroplets of super-saturated oxidizer solution within an oil matrix. The oxidizer is usually ammonium nitrate. Packaged in a thin, tough plastic film, emulsion cartridges have a good degree of rigidity and resistance to rupturing during normal handling but maintain the ability to rupture and spread when tamped.

Drilling Methods

Blast holes are drilled at various orientations, from vertical through horizontal. To create vertical holes, which are used almost exclusively in production blasting, rock slope excavation uses two types of drilling: *downhole* and *step drilling*. *Horizontal drilling* is used for both production and controlled blasting because of limited drill rig access or geometry requirements. Angled drilling can be performed as determined by slope face angle requirements.

Downhole Drilling

Also known as vertical or production drilling, this technique is used in production blasting using a conventional rotary tri-cone blast hole rig or a rotary percussion rig if smaller blast holes are adequate.

Step Drilling

Step drilling is another type of vertical drilling that’s also used in production blasting, most often to produce relatively flat and benched slopes (usually shallower than 1:1 H:V). It’s similar to downhole drilling, but creates holes that gradually increase or decrease in depth to allow for a stepped slope "break" line shown earlier in Figure 14. (This method is technically not part of a controlled blasting operation because it relies on backbreak to form the slope face.) If done properly, step drilling can produce a slope face that shows minimal signs of blasting—just drill holes entering the slope face, which are noticeable only by someone looking directly at the face. On projects involving step drilling, drillers have been awarded a pay item for tightening the drill hole pattern and using lighter, distributed loading to avoid performing excessive blasting charges along the slope later.

Step drilling is limited to ideal geologic conditions, such as blocky volcanic rock, where breakage at the bottom of each blasthole is reasonably well controlled, but it can provide good results with minimal backbreak. It has proven popular with contractors who favor the vertical drilling setup.

In step drilling, the blast holes are loaded with more explosives (about 25% greater charge density) at the bottom of the hole, which helps to ensure proper fracturing along the base of the excavation. However, this heavier loading will also increase the amount of radial fracturing and backbreak along the final slope face and create the need for a widened catchment area. Step drilling should be used only when the driller and blast designer are experienced in the practice because of the potential for excessive backbreak and a ragged slope face. In most instances, the vertical drill holes are extended beyond the final cut line (a practice known as sub-drilling) to ensure proper fragmentation and achieve a more natural final cut face as illustrated in Figure 15.

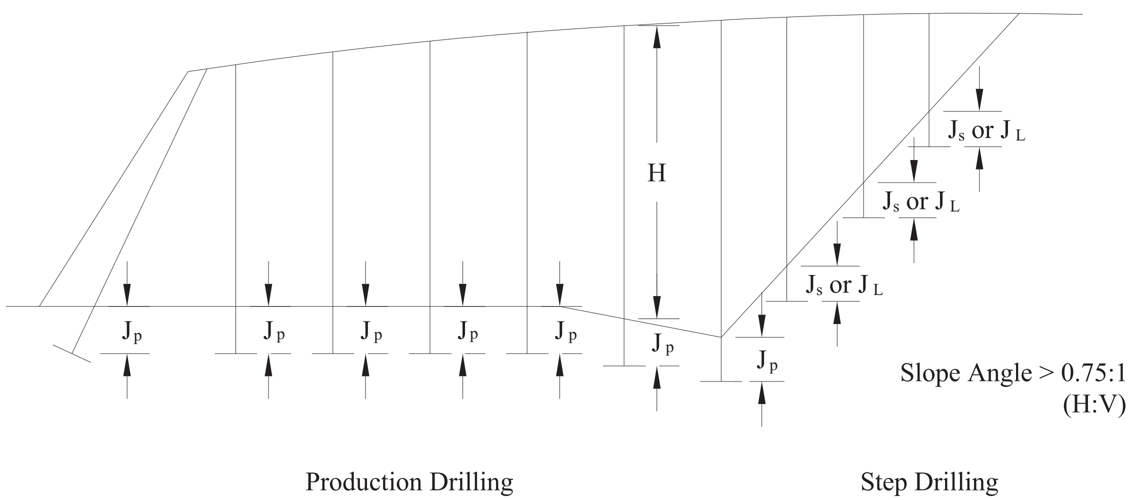


Figure 15. Illustration. Cross section of downhole and step drilling with sub-drilling techniques (modified from Cummings 2002).

Horizontal Drilling

Horizontal drilling is an effective technique for starting new excavations and for small excavations with poor access at the top of the slope. There are two basic techniques used for horizontal drilling. The first uses blastholes drilled perpendicular to the final rock face as shown in Figure 16, while the second uses holes drilled parallel to the rock face. When drilling perpendicular to the face, angled holes are typically required to mobilize and fragment the rock at the toe (these holes are called toe lifters) and the ditch (ditch lifters) to achieve the proper final slope configuration.

The second method sometimes uses a fan configuration, which can leave a distinctive pattern is shown in Figure 17.

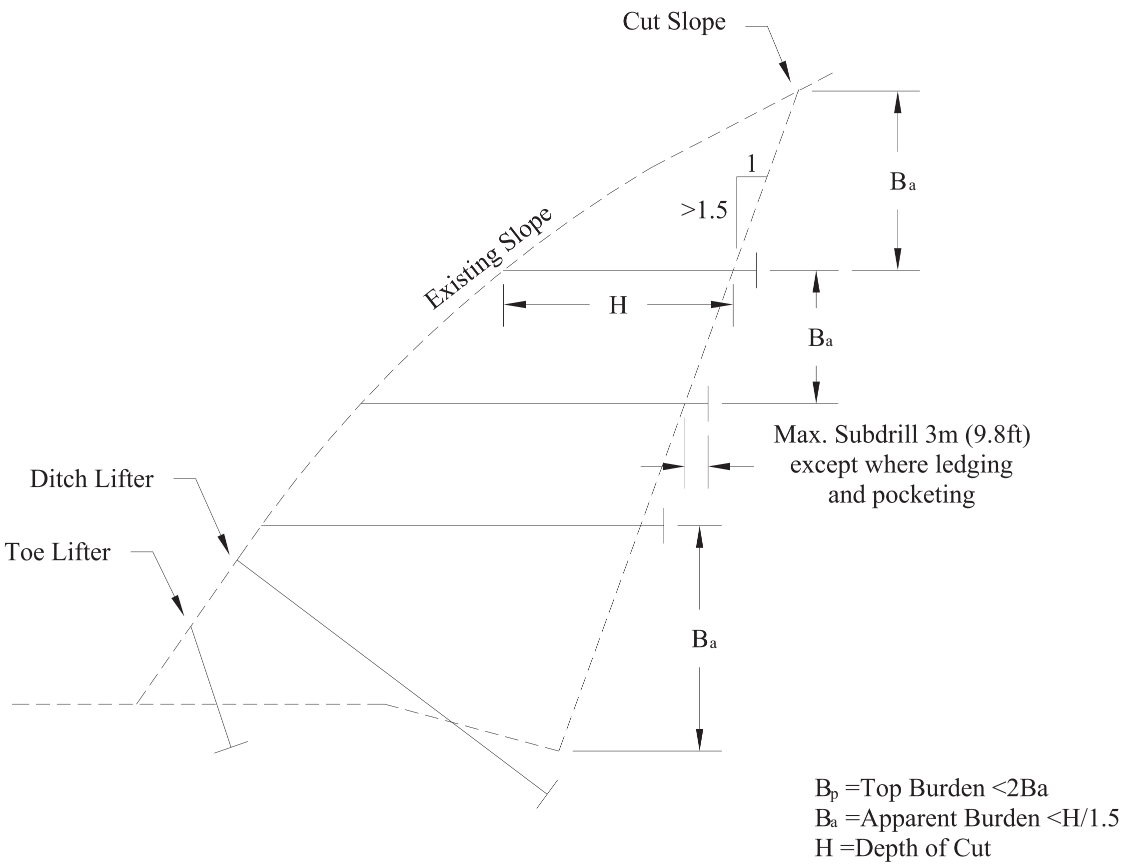


Figure 16. Illustration. Horizontal drilling design concept (modified from Cummings 2002).

In horizontal drilling, it can be difficult to maintain drill hole orientation, location, and depth. However, this is critical to avoid excessive fracturing in the final cut slope. In some cases, special drilling equipment (such as drills suspended from a crane) may be required to access the upper portions of the rock face. Special loading and timing allowances also may be required, and the drilling pattern must be adjusted to keep the drill steel from drifting downward.

The loading of explosives is also more complicated in horizontal drilling. It typically requires either packaged product or pneumatically loaded bulk product and stemming (filling, such as drilling cuttings, that's used to fill the blast hole above or between charges to "stem," or retain the explosive force within the hole).

Figure 17. Photo. Drill hole traces left by horizontal drilling parallel to the rock face (fan drilling).

In addition, horizontal drilling and blasting can produce badly fractured slope faces, as the production blastholes typically extend all the way to the final rock face. For this reason, a widened catchment area is recommended for slopes excavated this way.

Figure 18 depicts blast damage to a rock face that was excavated using horizontal blasting methods. Note the draped wire mesh in the upper portion of the photo, which was installed to control rockfall that was caused, in part, by blast damage.

Figure 18. Photo. Blast damage caused by horizontal drilling perpendicular to the rock face.

Drilling Equipment

Drilling horizontal holes is accomplished using a rig with a boom-mounted drill guide (generally a track rig) that has the ability to rotate the drill guide into a horizontal position and drill. Vertical and angled holes are bored using a downhole drilling rig or a track drilling rig as compared in Table 3.

Downhole Drilling Rig

Drilling with a downhole rig is best suited for vertical or near-vertical boreholes, deep drilling, and hard rock. Bit diameters range from 75 to 230 mm (3 to 9 in), allowing for precise borings at significant depths (although downhole drilling is engineered for a maximum depth of about 60 m or 200 ft, greater depths have routinely been achieved). Most of these drills are mounted on trucks or large tracks and therefore require wider, moderately graded benches to access the site.

Track Drilling Rig (Percussion Drill Head)

Track drills, also known as drifter drills, are the most commonly used drills in civil applications and can be used to advance vertical, angled or horizontal boreholes up to 12 m (40 ft) in depth. Bit size ranges between 40 and 150 mm (1.7 and 6.0 in.). The holes are advanced through percussion, either through a drill at the head or with tooling such as a downhole pneumatic hammer. They feature a boom that allows for borings along a slope face at a height determined by the boom length as seen in Figure 19. Track drilling rigs are generally smaller than downhole rigs and have better maneuverability, and consequently can access more difficult terrain.

Table 3. Comparison of vertical drilling rigs (modified from Konya and Walter 2003).

	DOWNHOLE DRILLING RIG	PERCUSSION/TRACK DRILLING RIG
Most Common Application(s)	Hard rock drilling of relatively deep holes. Can drill straighter holes and holes of different sizes with same rig.	Rock drilling of relatively shallow holes (vertical, angled and horizontal).
Depth and Penetration	Maintains a virtually constant penetration rate at all depths. Has higher average drilling speed for deep holes.	Higher initial penetration rates, but drilling speed falls off with each steel added.
Air Requirements	Can require less air because drill exhaust helps clean holes. Can use high-pressure air to increase drilling speeds.	Requires air for both hole cleaning and drilling. High-pressure air can cause drift and shorten steel life.
Noise Impacts	Comparatively low impact makes downhole drilling quieter, as exhaust noise is muffled in the hole.	Requires drill exhaust muffler to reduce noise. Impact noise difficult to control.
Shanks and Coupling	No shank pieces or coupling required. Uses standard API rod threads.	Shank piece and coupling threads subject to higher wear rates and more frequent replacement.
Impact and Vibration	Fewer moving parts. Almost all energy goes into rock instead of into mounting, meaning less wear on rig.	Rig must withstand much of the drilling impact and vibration.

Figure 19. Photo. Common track drill used to advance vertical blastholes.

Portable Crane-Mounted or Hand-Held Drills

Drilling on slopes with limited access will require *horizontal* drilling (see above) and/or the use of portable crane-mounted or hand-held drills, which can drill both vertical and angled borings. When drilling blastholes deeper than 5 m (15 ft), the drill will be mounted to a rigid frame or platform, typically suspended from a crane, to ensure proper alignment. Maximum drilling depth for portable rigs is around 12 m (40 ft) and bit sizes range from 40 to 100 mm (1.7 to 4 in). For borings less than 5 m (10 ft) deep, a hand-held sinker drill or jackleg-mounted drill (a drill supported on a single leg) can be used. However, drilling with a hand-held drill is slow because its downward pressure is limited by the weight of the drill and the physical strength of the operator.

Blasting Design

Blasting projects must be designed with several factors in mind, including the type of explosives used, borehole diameter, and loading levels. Each type of blasting—presplit, smooth, and cushion blasting—has its own formula.

Presplit Blasting

As discussed above, presplit blasting (or presplitting) is most often done before production blasting to create a secondary fracture plane that will protect the final slope face from damage in the main production blast. Table 4 lists recommended borehole diameters, burden, spacing, and explosive charges for presplit blasting.

Table 4. Parameters for drilling in a presplit blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Explosive Charge	
(mm)	(in)	(m)	(ft)	(kg/m)	(lb/ft)
38-44	1.50-1.75	0.3-0.46	1.00-1.50	0.03-0.1	0.08-0.25
50-64	2.00-2.50	0.46-0.6	1.50-2.00	0.03-0.1	0.08-0.25
75-90	3.00-3.50	0.6-1.0	1.50-3.00	0.05-0.23	0.13-0.50
100	4.00	0.6-1.2	2.00-4.00	0.23-0.34	0.25-0.75

In order to reduce fracturing, presplit blasting holes are drilled with smaller diameters than production holes. Presplit-hole diameter will also be influenced by many other factors, as well. For example, large-diameter holes can hold more explosives and can be spaced further apart than small-diameter holes, but can cause more backbreak if the burden-to-spacing ratios are not properly designed. Large-diameter holes yield lower drilling and blasting costs because they are less expensive per unit volume to drill. Large-diameter holes are better suited for relatively homogeneous, easily fractured rock with few planes of weakness (discontinuities) and for deep rock cuts. Small-diameter holes use less explosives and require smaller spacing between holes, which allow for better distribution of explosives, more uniform rock breakage, less backbreak, and reduced ground vibrations. Although more holes must be drilled, small-diameter holes can be drilled quickly, resulting in a relatively low unit cost. However, this may be offset by higher explosives costs, as more explosives are required to fill the extra holes. In addition, drilling depths on small-diameter holes are limited because the small-diameter drill bits are more likely to wander at depth than larger bits.

Theoretically, the burden for presplit blasting is unlimited. But in reality, variations in geology that are not visible on the outer face of the slope can limit that burden. Thus, the engineer must core the interior of the slope to identify the condition of the rock before determining the blasting design. In any case, a minimum of 10 m (30 ft) of burden is recommended for any presplit blasting procedure.

Hole spacing in presplit blasting is typically 10 to 12 times the borehole diameter. In very favorable geologic conditions, spacing can be increased to 14 times the borehole diameter. Wider spacing is used for hard, competent material with relatively few discontinuities; in very soft and/or weathered materials, spacing is decreased. In weak and soft formations or where corners are blasted, unloaded guide holes are recommended to direct the cracking. These guide holes are drilled between the normally spaced presplit holes (thus, using guide holes prevents the contractor from spacing the presplit holes any further apart).

Holes used for presplit blasting are lightly loaded and range from 22.5 to 25 mm (7/8 to 1 in) in diameter. A heavier charge (2 to 3 times the normal load) is used at the bottom of the borehole to ensure shearing at the floor. A common charge density is approximately 0.45 kg per square meter (0.1 lbs per square foot) of face area in the main section of the hole and 0.9 to 1.3 kg per square meter (0.2 to 0.3 lbs per square foot) at the bottom. The loads may have an air annulus (ring) surrounding them to cushion the explosive blast and reduce the radial cracking around the borehole. Figure 20 indicates three configurations.

The authors of the *DuPont Blaster's Handbook* (1978) show that slurry or water gel (in the form of "Tovex T-1") can provide excellent presplitting results while permitting increased loading rates and reduced labor costs. Konya and Walter (2003) recommend ammonium nitrate for all controlled blasting. For small-scale blasting (such as sliver cuts) in presplitting operations, 50-grain detonation cord has proven effective.

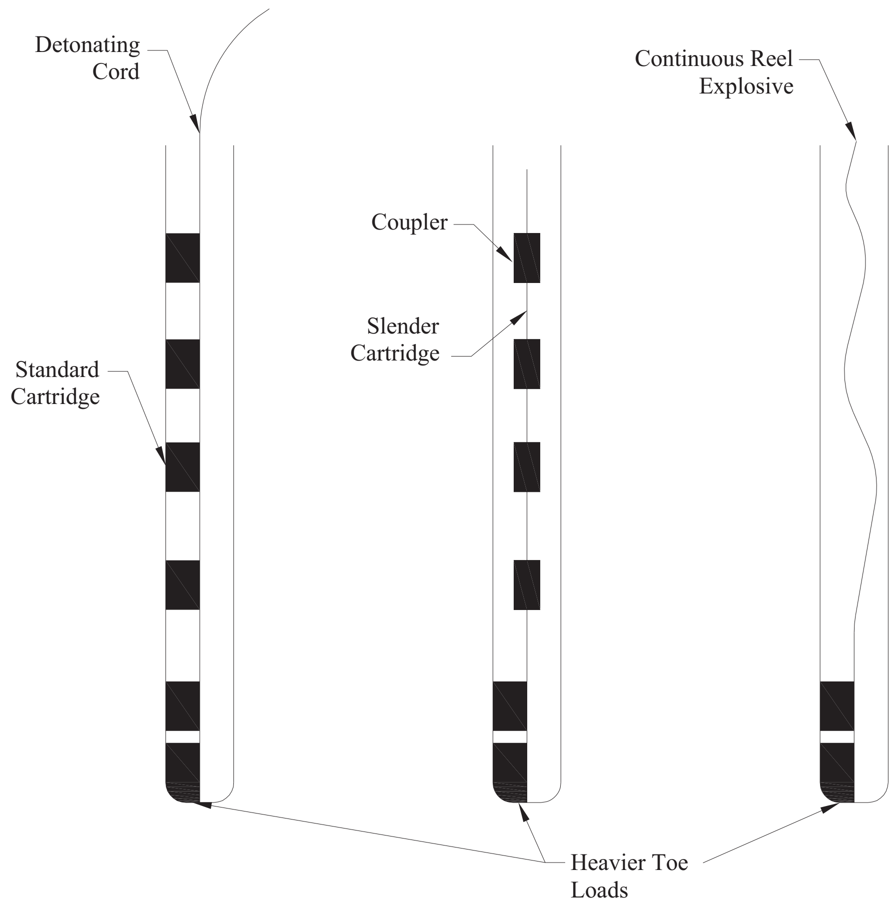


Figure 20. Illustration. Three options using lightly loaded, distributed charges in presplit blasting (modified from U.S. Department of the Interior 2001).

Smooth Blasting

Smooth blasting is a type of controlled blasting that's done either before production blasting, as an alternative to presplitting, or afterwards, either as an entirely different event or as the last delay of the production blast. Table 5 shows recommended borehole diameters, burden, spacing, and explosive charges for smooth blasting.

Table 5. Parameters for drilling in a smooth blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Burden		Explosive Charge	
(mm)	(in)	(m)	(ft)	(m)	(ft)	(kg/m)	(lb/ft)
38-44	1.50-1.75	0.6	2.00	1	3.00	0.05-0.55	0.12-0.25
50	2.0	0.75	2.50	1.06	3.50	0.05-0.55	0.12-0.25

As with presplit holes, smooth blasting holes are smaller than production holes in order to limit fracturing around the drill hole. The diameter of the hole is a function of geology, as discussed above.

The burden-to-spacing ratio for smooth blasting is approximately 1.5 to 1. Hole spacing for smooth blasting is slightly greater than presplit blasting, about 14 to 20 times the hole diameter, which means that holes are approximately 0.7 to 1.5 m (2.3 to 5 ft) apart. Wider spacing is used for hard rock and closer spacing is used for weak rock. Unloaded guide holes (drilled between the normally spaced blastholes) are recommended for weak and soft formations or for blasting corners.

The charge density, diameter, distribution, and explosive type used in smooth blasting are essentially the same as with presplit blasting. In smooth blasting, the borehole should be sealed with a tamping plug, clay plug, or other type of stemming to prevent the charge from being extruded from the hole by charges on earlier delays. Stemming also prevents excessive rifting (splitting) of the rock and permits the use of lighter charges because blast energy is better contained and therefore better distributed.

Cushion Blasting

Cushion blasting, another type of controlled blasting that's typically done after production blasting, uses a row of lightly loaded "buffer" holes filled with crushed stone (stemming), which reduces the impact on the surrounding rock as well as the finished slope face. Cushion blasting can be used with both vertical and angled holes, and good alignment is essential in both cases. The cushion holes are drilled along the final slope line and loaded with light, well-distributed charges and fired after the main production blast.

The required burden is established *either* by the last row of production boreholes *or* by a separate set of buffer holes (these buffer holes determine the burden so that the cushion blast holes produce enough backbreak to avoid borehole traces).

Table 6 shows the recommended borehole diameters, burden, spacing, and explosive charges for cushion blasting.

Table 6. Parameters for drilling in a cushion blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Burden		Explosive Charge	
(mm)	(in)	(m)	(ft)	(m)	(ft)	(kg/m)	(lb/ft)
50-64	2.00-2.50	1.0	3.00	1.2	4.00	0.03-0.1	0.08-0.25
75-90	3.00-3.50	1.2	4.00	1.5	5.00	0.05-0.2	0.13-0.5
100-115	4.00-4.50	1.5	5.00	1.8	6.00	0.1-0.3	0.25-0.75
127-140	5.00-5.50	1.8	6.00	2.1	7.00	0.3-0.45	0.75-1.00
152-165	6.00-6.50	2.1	7.00	2.7	9.00	0.45-0.7	1.00-1.50

Diameters of buffer and cushion boreholes are smaller than those of production holes, and buffer boreholes have a slightly larger diameter than cushion boreholes. The diameter of a cushion hole depends on many factors, as discussed above.

The burden for cushion holes varies according to the rock characteristics. For example, the burden of hard, competent rock will be smaller than the burden of soft, easily fractured rock. It is important to conduct one or more test blasts and continually analyze and back-calculate results from production blasting to determine the proper burden, spacing, and charge density.

The spacing on cushion and buffer blastholes varies depending on the bedrock type and structural characteristics, but generally ranges from 15 to 24 times the borehole diameter. The burden-to-spacing relationship varies, but spacing on cushion holes should always be less than the width of the burden being removed (U.S. Department of the Interior 2005). When removing weak, heavily fractured material or when blasting corners, uncharged guide holes can be drilled between the normally spaced cushion holes to guide the blast-induced fracture.

Charge loading in cushion blasting is similar to that in smooth blasting in that lightly loaded, well-distributed charges are fired after the main production blast. Charges are typically 25 mm (1 in) in diameter and charge densities are 0.45 to 0.7 kg per square meter (0.1 to 0.15 lb per square foot) of face area for the main borehole and two to three times that for the bottom of the borehole. Historically, cushion holes are surrounded by some type of stemming (crushed rock or other loose inert material that helps cushion the blast) for the entire length of the borehole. According to the *DuPont Blaster's Handbook* (1978), an air annulus surrounding the charge produces similar results and reduces loading time.

Removing Drill Hole Traces and Blasting Scars

In weak rock, drill hole traces can be removed by chipping away at the corners of the traces or removing the outer layer of rock using a hoe ram, excavator bucket, or pneumatic hammer. For strong rock, it is nearly impossible to completely remove these traces.

In some cases, blasting is followed by other methods of excavation, which are used to get rid of remaining rock and soil to create a more aesthetically appealing final face. In cases where there is less rock to remove in the first place, these methods can be used on their own.

Ripping

Ripping is a process of breaking up rock and soil with a large tooth or teeth attached to the back of a bulldozer.

Where feasible, ripping is generally preferred over blasting because it is considerably less expensive; ripping costs are typically 50 to 65% less than blasting. Ripping is also significantly less dangerous than blasting and requires fewer permits and special precautions. Ripping can be done in close proximity to populated areas or other places where blasting noise and vibrations are restricted. However, ripping is limited to soft to moderately firm, fractured rock and construction of low-angle cut slopes and shallow, near vertical cuts. In dense rock formations, light blasting is sometimes performed before ripping.

Once the material is loosened by ripping, an excavator can be used to remove it and perform slope sculpting (see below). Ripping gives the contractor a lot of freedom to aesthetically enhance a slope by adding additional contour and allowing for revegetation in certain areas.

The teeth on rippers can leave scar marks on the rock after excavation. In most cases, these can removed using the same procedure used to remove drill hole traces. In soft and/or massive rock, the contractor may use a jet of high-pressure water or a vibratory compactor, known as a plate bucket, which is attached to an excavator or loader to remove the scars.

Ripping is usually done in one direction, but in very tough materials ripping in a grid pattern will increase excavation efficiency. The pass spacing is determined by the end use of the material (fill, aggregate, waste, etc.) and the capacity of the excavating equipment. In most cases, it is best to maximize ripping depth, but in stratified formations it may be best to rip along the natural layers.

Ripping is generally done in the same direction that loading will take place (i.e., parallel to the plane). However, when the material exhibits a foliation or bedding plane, ripping perpendicular to the plane produces much better fracturing.

Ripping Equipment

There are basically two types of rippers: the pull- (or tow-) type ripper and the integral bulldozer-mounted ripper. In rock excavation, a bulldozer-mounted ripper as shown in Figure 21 works better than a pull-type ripper because it can exert greater downward pressure.

Rippers also come in single- and multi-toothed configurations. Single-toothed rippers are used for difficult ripping work, where maximum ripping depth is required and/or the material is dense. Multi-toothed rippers, which can use up to five teeth, are used for softer ground or for secondary purposes such as breaking up already ripped ground.

Figure 21. Photo. Bulldozer with an integral ripping attachment.

Choosing the proper bulldozer-mounted ripper depends of four factors: downward pressure on tip, horsepower of the bulldozer, weight of the bulldozer, and angle of tooth penetration (Kelly 1970). The first three factors will influence the size and type of the bulldozer used, and the last is a function of the style of ripper (see below). Bulldozer style and size is not discussed in this document. Most ripper manufacturers' websites includes information on the bulldozers that are compatible with their products; ripper mounting brackets and hydraulic control mechanisms vary widely.)

Here three main styles of rippers:

Hinge-Style Ripper:

The hinge-style ripper, also known as the radial-type ripper shown in Figure 22, is fixed to the bulldozer with a pin, around which the ripper arm rotates. Because of its maneuverability, this type of ripper is best at creating sculpted and natural-appearing rock cuts.

Parallelogram-Style Ripper:

The parallelogram-style ripper features two hinged arms, which keep the shank (the tang of the tooth) vertical and hold the tooth at a constant angle as it is lowered into the material. This provides excellent penetration in many types of rock. The parallelogram-style ripper works best in easy to moderately rippable materials. In more difficult conditions, contractors prefer to have the option of selecting different tooth angles, which provides better penetration, and so would use an adjustable parallelogram-style ripper.

Figure 22. Photo. Typical hinge- or radial-style ripper (Nichols and Day 2005).

Breaking

Breaking is done with a *hydraulic hammer* (also known as a *breaker* or *hoe ram)*, a percussion hammer fitted to an excavator that is typically used for demolishing concrete structures and is shown in Figure 23. It is used to break up rock in areas where blasting is prohibited due to environmental or other constraints. Like a ripper, a hydraulic hammer can be used in most rock types, although when sculpting a slope face, it works best in soft or moderately to highly fractured rock; existing discontinuities in the rock act as presplit lines, minimizing hammer-induced scars and fractures while creating a slope face that appears to be naturally weathered.

Figure 23. Photo. Application of a hydraulic hammer attached to an excavator.

To allow for maximum downward pressure, the hammer is positioned perpendicular to the ground surface as shown in Figure 24. Hammering locations are spaced evenly in a grid-like fashion so that the end rock product is fractured into pieces that can be loaded and hauled. For slope excavations, the hammering angle should be not be parallel to the major discontinuity orientation, as this may cause fractures into the final slope face as Figure 25 shows.

Figure 24. Photo. A hydraulic hammer sculpting a rock face (the material to be removed has been outlined with common marking paint).

Figure 25. Photo. A hydraulic hammer expanding a sculpted area, creating planting areas and more natural-looking slope variation.

After breaking, the excavated slope can be configured to look like a part of the natural landscape, with the addition of boulders and topsoil and reseeding with native vegetation as Figure 26 shows.

Figure 26. Photo. Completed rock slope prior to placement of topsoil and a native seed mix.

CHAPTER 4 – ROCK SLOPE/LANDSCAPE INTEGRATION

A major component of context sensitive design is the final appearance of an engineered slope: how it looks on its own as well as how it fits into the surrounding landscape. To create the best and most natural-looking results, engineers and designers typically use a combination of excavation, as discussed earlier in Chapter 3, and rock slope/landscape integration, which uses physical and cosmetic alterations to modify the shape of a slope and give it a more natural appearance by mimicking the surrounding topography.

In some cases, safety or cost concerns make it impossible to achieve a completely natural look. However, in any case, the engineer and the contractor should strive to develop a slope that is safe, looks natural, and satisfies the interests of all project stakeholders.

Table 7 provides an overview of the most common rock slope/landscape integration techniques, along with the advantages and limitations of each. Each procedure is discussed in detail below.

PHYSICAL ALTERATIONS

Physical alterations, which remove or reposition sections of rock and/or soil, are an effective way to improve the appearance and stability of a slope.

Major Slope Warping

Major slope warping is the process of rounding (or sculpting) the lateral ends of a cut slope to smooth its transition to the surrounding terrain as shown in Figure 27. It can be accomplished through blasting/ripping, scaling, and other excavation techniques, which were discussed in greater detail in Chapter 3.

Although this technique can be used on any rock type, it generally produces the best results in hard rock. Creating a lower angled slope on the ends of a cut increases the exposed surface area of the rock there, resulting in faster weathering rates compared to rock in steeper sections of slope.

Major slope warping has become a common practice on highway projects, industrial parks, golf courses, landscaped open space around corporate buildings, and other such features. The disadvantages of this technique include increased cost due to a larger amount of required excavation and drilling, additional right-of-way, and increased long-term maintenance for scaling on slopes with erodible materials (as with any rock cut, it is very important to thoroughly scale the slope immediately after excavation and periodically thereafter to remove any loose rock that could potentially dislodge).

Table 7. Overview of rock slope/landscape integration techniques.

PROCEDURE	DESCRIPTION	BEST ROCK TYPES/ADVANTAGES	LIMITATIONS/DISADVANTAGES
Major Slope Warping	Rounds the ends of the cut to smooth the transition between the rock cut and the natural terrain.	Can be used on any rock type. Best used on inside turns of the roadway and ridge and valley systems.	Flatter portions of the slope will be more exposed to weathering and erosional processes. Requires blasting procedures capable of angled borings. Slope ends are visible to motorists for a longer time.
Expanded Slope Rounding	Rounds the crest of the cut slope to smooth the transition to the natural terrain.	Can be done on any rock type. Best on slopes with a minimal colluvial cover. The crest is often an area of increased weathering and blasting damage, removing it reduces rockfall hazard.	Areas of thick colluvial cover will require soil excavation techniques and possible access problems.
Drainage Intercepts	Specifically designed to transition topographical low areas to high areas by gradually decreasing the slope angle transiting to the low area.	Can be used in any rock type. Combining with expanded slope rounding and major slope warping will improve aesthetics.	Blasting procedure must be capable of different angles of borings. Rockfall launching features may result if the transition section is rough. Slope ends are visible to motorists for a longer time.
Ditch Width Expansion	Provides slope variation longitudinally along the slope and often extends throughout the slope height. Works well in areas of long monotonous cuts.	Can be used on any rock type. Ditch width variations can be used to hide drill hole traces. Effective in reproducing natural undulations in the slope.	May be difficult in moderately to highly fractured rock because of kinematics. Blasting procedure must be capable of variable angled borings. Can cause rockfall launching features.
Slope Angle Variation	Varies the slope angle laterally along the slope to accentuate prominent geological features or differences in weathering rates.	Design changes with rock type. Layered rocks result in a stair step pattern while massive rock depends on intrusions and competency variations. Very effective in sculpting the rock.	Very dependent on geological features. Rockfall prone areas can cause problems due to launching features. Often increases time of construction.
False Cut Embankment And Median Berm	Adds topography along the shoulder or median of divided highways for screening, variety, and areas of re-vegetation and landscaping.	Adds topography along the shoulder or median of divided highways for screening, variety, and areas of re-vegetation and landscaping.	Designer must ensure the barrier will not launch or overturn errant vehicles. Should not be left with an excessively regular surface.
Rock Staining	Stain is applied to the rock surface to help blend the freshly cut slope color to the natural weathered rock color.	Stain is applied to the rock surface to help blend the freshly cut slope color to the natural weathered rock color.	Must test several stains to find the correct color that fits the natural conditions. Slope should be thoroughly scaled and can be power washed to remove loose material.

Figure 27. Photo. Example of major slope warping on a cut slope.

Slope warping can be designed using a few different methods: using a slope offset and angle table, contour grading plans, or an equation relating cut slope height, distance, and slope angle (Cummings 2002). The desired transition from a steeper to a shallower slope angle is typically shown in the cross section portion of the construction drawings. The transition section is shaped like a circular segment, with the slope angle gradually decreasing from the angle of the main cut face to that of the natural slope. It's important to follow a common radius in the transition section (i.e., the area from the excavated slope face to the natural slope) because the viewshed is always tangent to the slope when seen from the side.

After excavating the main slope up to the transition section, the contractor will start decreasing the slope angle along the designed circular segment until the natural slope angle is reached. Conventional excavating equipment is generally used to achieve the desired effect. In hard rock major slope warping generally requires drilling angled borings (with equipment such as a track rig), blasting/ripping, and scaling. Following the excavation, revegetation in the transition sections and/or slope face provides additional natural enhancement and helps blend the cut slope into the natural environment even more.

Expanded Slope Rounding

Expanded slope rounding helps to blend the crest of a cut slope into the natural terrain by sculpting the upper portion of the cut, shown in Figure 28, using standard excavation techniques. In rippable material, this is typically accomplished with an excavator; in hard rock, the contractor will use explosives.

Expanded slope rounding can be done on a variety of rock types. It does not produce slope launching features, as the angle of the cut slope in unchanged, and does not require any blasting techniques other than those used in blasting the final finished rock face. Disadvantages include increased cost of excavation, blasting, and the potential for a small increase in right-of-way. Expanded slope rounding also requires thorough scaling after initial excavation and periodically thereafter.

Figure 28. Photo. Slope rounding using long-reach excavator, Hyampom Road, California.

Slope rounding is a very effective way to enhance slope aesthetics in areas where motorists or pedestrians have an unobstructed or extended view of the slope crest. It also provides an opportunity for creating ledges and encouraging revegetation. In many cases, the crest is the most weathered and blast-damaged section of the slope; therefore, removing part of the crest through expanded slope rounding helps to reduce rockfall and long-term erosion problems.

Figure 29 shows a slope on which slope rounding was not constructed. Note the areas of overhanging topsoil and vegetation mat, caused by excessive erosion at the top of slope.

Figure 29. Photo. Expanded slope rounding can prevent this type of erosion and overhang.

Currently, the FLHD shows the desired degree and location of slope rounding for any given project in the Typical Sections of standard construction drawings. Conceptual drawings depicting slope rounding and other techniques are provided in the Embankment Benching and Serrated Cut Slope special drawing, which is included in most FLHD projects.

Rounding generally requires drilling, blasting, excavation, and scaling equipment. When explosives are required, controlled blasting should be used to minimize the damage to the final slope face. In slopes with hard bedrock at the brow, a row of "satellite" holes can be drilled behind the main slope trim line, then lightly loaded and detonated to reduce backbreak and fly rock.

If the slope has a substantial amount of unconsolidated material along the brow, the material should be removed with a track-mounted excavator or by hand. Long-reach excavators are typically used in areas with steep terrain. Using large radii to define the rounded slope crest in the transition area is visually more appealing than using smaller standard radii, as the larger radii generally appear more natural.

Drainage Intercept Laybacks

Drainage intercept laybacks are a modification of major slope warping specifically designed to transition from the typically uniform cut slope to natural recessed areas or swales (the recessed area does not need to be actual water drainage). Drainage intercept laybacks are extremely effective visually because they break up the uniformity of both small and long sections of the cut slope to more closely resemble a natural slope shown in Figure 30. In the transition zone between the cut slope and the swale, the slope angle is decreased and the slope crest is rounded back as it would be in expanded slope rounding. Ledges can be incorporated into the design to help mitigate rockfall and to facilitate revegetation.

Figure 30. Photo. Drainage intercept layback cut into a slope, Hyampom Road, California.

Constructing drainage intercept laybacks is cost effective because it does not require a large amount of additional excavation. Also, because there is only a slight slope angle difference between the topographically high and low areas, it is effective even in highly fractured formations where the discontinuity orientations limit the slope angles that can be constructed.

In the area of the existing depression, the slope angle between the ridge area and the drainage is gradually reduced. The ditch width can also be widened for additional visual enhancement. The desired slope angle variation can be shown in the cross sections, but because this is a matter of the owner's criteria and choice, most successful projects require oversight by the owner's representative to achieve the appropriate amount of layback at each drainage feature.

The equipment used to construct drainage intercept laybacks is similar to that used in slope rounding, as described previously. In addition, drainage intercept laybacks require a drill rig capable of drilling angled borings, and may also require explosive, excavation, and scaling equipment. If the slope material is softer bedrock or a slope cover over bedrock, a conventional excavator and/or hoe ram can be used. Good accessibility to the top of the slope is another requirement.

Ditch Width Variation

In ditch width variation, engineers use blasting, ripping, scaling, and other excavation techniques to alter the width of a ditch that runs down the cut slope face. Ditch width variations are used in long monotonous cuts, at geologically significant locations, and at drainage intercepts. They are also used in places where the ditch is much wider at the center of the slope than at the top and bottom, which creates an unnatural concave shape in the center of the cut slope.

Figures 31 and 32 show examples of ditch width variations made along a vertically cut, presplit slope. The expansions add variation to the otherwise monotonous slope face, provide a wider catchment area for rockfall, and help camouflage the exposed drill hole traces.

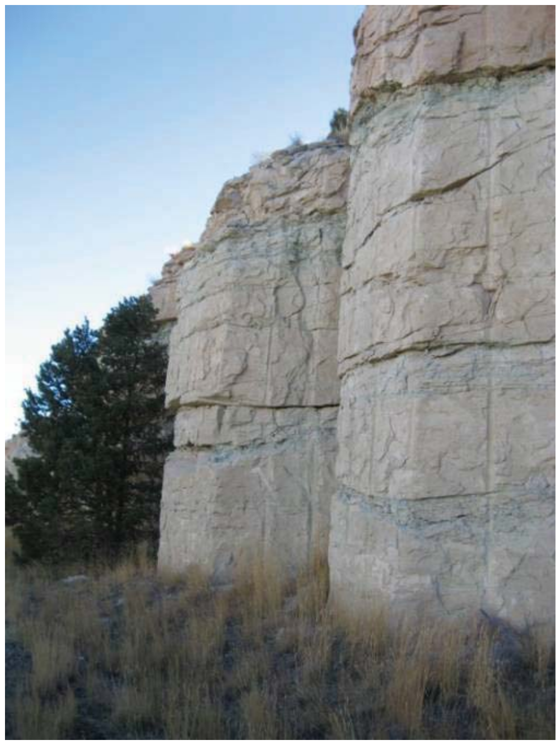


Figure 31. Photo. Ditch width variation used to break up the slope face and mask drill hole traces.

Slope and slope crest geometry are key factors in designing ditch width variations. In addition, because expanding ditch width can change the slope angle, the designer must also consider the structural characteristics of the rock mass in order to avoid constructing a potentially unstable slope (a scan line survey and kinematic analysis using an equal angle or equal area net will reveal potentially hazardous slope angles). When varying the slope angle, the blaster should gradually change the borehole inclination to prevent the intersection of two different slope angles, which could make the slope appear unnaturally flat.

When designing ditch width variations, the slope designer also should observe the natural slopes in the area and try to replicate their natural variations. For example, sedimentary formations often form steep, smooth-sided cliff faces, while igneous rock usually forms a much more irregular gradient.

The slope should be excavated from the top down and/or from the roadway inward. The slope should be thoroughly scaled after excavation to remove any potentially unstable material. If blasting is required, the blast plan should accommodate the variations in the slope and ditch. To reduce backbreak, blasting should be set up to follow the natural rock structure instead of with presplitting or line drilling methods. Ditch width variation requires drilling rigs capable of drilling angled borings, as well as excavation, blasting/ripping, and scaling equipment.

Figure 32. Photo. Ditch width variation can camouflage blast scars and drill traces.

Slope Angle Variation

Slope angle variations are used to break up the planar look of a blasted cut slope, see Figures 33 and 34. They can also be used to accentuate prominent geological features (such as intrusive units and variations in rock weathering rates); to replicate the roughness of the surrounding terrain; and to sculpt knolls, minor ridges, and drainages.

Engineers typically use rock mass discontinuities or existing seams, more resistant intrusions/rock units, and geologically significant areas to shape the cuts. If rockfall potential exists, mitigation methods such as rock bolts, expanded roadside ditches, or mesh may be needed as discussed in Chapter 5.

Figure 33 illustrates the effective use of slope angle variation to simulate the natural weathering patterns in interbedded sandstone, siltstone, and claystone. Special blasting and layout staking techniques were used to direct the contractor to the desired cut slope configuration along the corridor.

Figure 33. Photo. Slope angle variation helps match the natural topography of the surrounding area. The lower three tiers in the slope were excavated to simulate the natural benches in sedimentary units.

Slope angle variations can be most easily shown in the plans through a slope exception table or tabulation of station and offset to the slope toe and catch point, which is the point where the excavated slope meets the natural slope (Cummings 2002). Designers typically look to the surrounding natural rock outcroppings to determine the ideal degree of slope angle variation.

Because different rock types have different fracturing and weathering patterns, there is no universal design for slope variations. In general, rock formations that are good candidates for this technique are cliff-forming units (as opposed to slope-forming units), which can be seen in the surrounding topography as fairly steep exposed rock faces with easily discernable rock texture.

The excavation should proceed in a top-down fashion, and any loose rocks should be removed and the slope thoroughly scaled after completion to remove any potential rockfall sources. For added visual enhancements, vegetation (trees, grasses, shrubs) and/or boulders can be placed on benches or along the roadside.

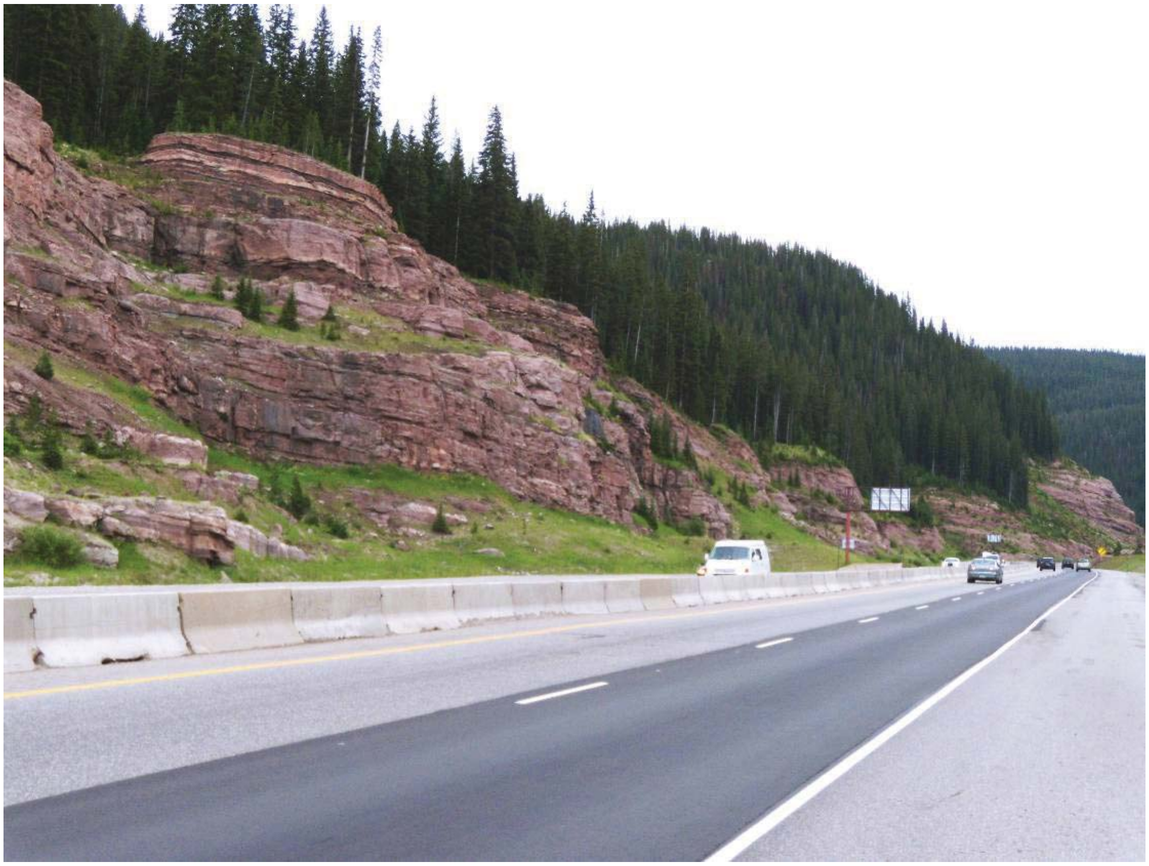


Figure 34. Photo. Steep, exposed rock faces are good candidates for slope angle variations.

Slope variation requires drilling equipment capable of angled boring, such as a track rig or hand drills, which can be used in competent material, or ripping equipment, which is a better choice in softer or fractured rock. Scaling equipment will also be required.

Figure 35 shows an example of slope angle variation and rock sculpting in a metamorphic rock. The existing rock structure was used to control the blast damage and shape the final configuration of the slope. Following each blast, excess and loose material was removed down to the more stable rock units. The overall slope angle was constructed at a 1:1 slope, with steeper zones nearby providing the appearance of a naturally exposed rock outcropping.

Figure 35. Photo. Rock slope excavated using slope variation and sculpting techniques.

COSMETIC ENHANCEMENTS

Rock slope/landscape integration also can involve cosmetic changes to the slope, including the application of stain to help blend the areas of cut rock into the existing terrain.

Rock Staining

Rock staining products, which are sprayed or dripped onto the fresh rock face, can bring the cut rock to its natural, weathered color within weeks. Some products are pigmented stains, while others create the new color by leaching minerals from the rock or through photoreactivity.

Before staining, the engineer should conduct several test sections on the excavated rock cut to determine the type of stain that will create the best match with the surrounding rock. Not every stain is compatible with all types of rock, and the final color depends on stain concentration and formulation. Several coats of stain may be required if the fresh and weathered faces look very different. Stain applied to highly fractured and/or absorbent rocks tends to fade; meaning these types of rock may not be good candidates for staining. The designer should use choose a color that matches the surrounding rock, including areas of natural dripping and streaking. Areas that feature vegetation (including lichens and moss) typically cannot be accurately simulated with staining. Figure 36 is an aerial oblique of a rock excavation shortly after construction and Figure 37 is a photograph of the completed slope from the roadway. The rock face was stained to help create a cut slope that is indistinguishable from the surrounding natural rock.

Figure 36. Photo. Rock excavation shortly after construction. Note the stark contrast of the freshly excavated material and the naturally weathered rock surfaces. Glenwood Canyon, Colorado.

Figure 37. Photo. Staining on the completed cut slope used to create a natural-looking rock face. Glenwood Canyon, Colorado.

Rock staining is a very effective and cost efficient way to quickly blend the color of fresh or faintly weathered excavated rock faces to that of the surrounding natural rock faces. This can create significant visual enhancements in both the short- and long-range perspectives.

Rock staining requires oversight by the owner or qualified expert during the application.

The slope should be dry and all loose material and vegetation removed before stain is applied. In many cases, the slope face is pressure-washed to remove fine-grained particles that would inhibit the stain penetration. Equipment required to perform rock staining usually includes an air compressor, hose, rock stain, application nozzle, and a man lift large enough to reach the top of the slope.

Figure 38 shows the application of rock stain using a hand-held sprayer and man lift (or crane).

Figure 38. Photo. Application of stain to a newly constructed rock slope.

CHAPTER 5 – ROCK SLOPE STABILIZATION

In many cases, engineered slopes require stabilization to ensure their long-term viability and reduce localized slope failure (which includes erosion and rockfall). Generally speaking, the most effective strategy is to prevent the failure at the source through stabilization, not to install structures to protect against them in the future.

There are many methods that can be used to stabilize a rock slope. These include altering the slope geometry, installing drainage, adding reinforcement, or a using combinations of these methods. Table 8 provides an overview of common stabilization procedures. A more detailed discussion of each is included in this section.

SLOPE GEOMETRY ALTERATION

These methods change the configuration of a slope by removing rock and/or soil.

Scaling

Scaling is the process of removing loose or potentially unstable material (or a small section of slope) that might dislodge or affect the trajectory of falling rock by creating a launching point for materials falling from above. It is accomplished by *hand* or *mechanical scaling*, or by small blasting operations called *trim blasting*. Scaling is effective on natural and newly excavated slopes, and is done as periodic maintenance for any slopes that pose a potential rockfall hazard to roadways.

Scaling is used to reshape slopes and to stabilize existing slopes and mitigate rockfall. For new construction, scaling should be completed immediately after the initial slope construction and periodically thereafter to remove any loosened rocks. Hand scaling on existing slopes may be required on a more regular basis, depending on the construction and condition of the rock face.

As a stabilization or mitigation measure, scaling is typically effective for a period of two to ten years, depending on site conditions, so it is not considered a permanent mitigation measure. However, it is relatively inexpensive and serves as an effective short-term strategy. Because it enhances site safety, it is routinely included with other mitigation efforts such as new rock excavation, rock reinforcement, or draped mesh.

Because of the obvious danger from falling debris, complete road closures are generally employed during scaling operations. In some cases, temporary measures such as draped netting suspended from a crane can be employed while traffic is flowing, but such cases are rare. Temporary barriers (including concrete Jersey barriers, cable net fences, bound or confined hay bales, and earthen berms) are often used to protect the roadway surface, bodies of water, buildings, or other critical features from rockfall.

In most cases, engineers will indicate areas that require scaling in the roadway layout plans. In all cases, scaling operations should be observed and carefully controlled to prevent the creation of unsupported or overly steep slope areas. This is particularly true when using heavy excavation equipment.

Table 8. Overview of stabilization procedures and their limitations.

MITIGATION MEASURE	DESCRIPTION/PURPOSE	LIMITATIONS
SLOPE GEOMETRY MODIFICATION		
Hand/Mechanical Scaling	Used to remove loose rock from slope via hand tools and/or mechanical equipment. Commonly used in conjunction with other stabilization methods.	A temporary measure that usually needs to be repeated every 2 to 10 years, as the slope face continues to degrade.
Trim Blasting	Used to remove overhanging faces and protruding knobs and to modify the slope angle to improve rockfall trajectory and slope stability.	Possible right-of-way issues, debris containment, difficulty with drilling, and undermining or loss of support by key block removal (blocks which exert major control the stability of other blocks).
REINFORCEMENT		
Internal Stabilization		
Rock Bolts	Tensioned steel bars used to increase the normal-force friction and shear resistance along discontinuities and potential failure surfaces. Applied in a pattern or in a specific block.	Less suitable on slopes comprising small blocks. Requires good access to slope. Visible bolt ends and hex nuts may need to be covered with shotcrete to improve aesthetics.
Rock Dowels	Untensioned steel bars installed to increase shear resistance and reinforce a block. Increase normal-force friction once block movement occurs. Less visible than rock bolts.	Passive support system requires block movement to develop bolt tension. Requires good access to slope. Visible bolt ends may need to be covered.
Shear Pins	Provide shear support at the leading edge of a dipping rock block or slab using grouted steel bars. Can easily be blended with surrounding rock by colored concrete.	Cast-in-place concrete needed around bars to contact leading edge of block. Requires good access to slope.
Injectable Resin/Epoxy	Resin/epoxy injected into the rock mass through a borehole; travels along joints to add cohesion to discontinuities. Decreases the number of rock bolts or dowels needed in a rock slope. Great for aesthetics as it cannot be seen.	Joint apertures must be greater than 2 mm (1/16 in) for migration of product. In slopes with excessive moisture, product will expand and provide little increase in cohesion. Should not be used as the only mitigative measure on a rock slope.
External Stabilization		
Shotcrete	Pneumatically applied concrete requiring high velocity and proper application to consolidate. Primarily used to halt the ongoing loss of support caused by erosion and raveling. Adds small amount of structural support for small blocks. Sculpted and/or colored shotcrete can be used for improved aesthetics and to cover rock bolts and dowels. Drainage must be installed.	Reduces slope drainage. Can be unsightly unless sculpted or colored. Wire mesh or fiber reinforcement required to prevent cracking. Must be applied in a minimum thickness of 50 mm (2 in) to resist freeze/thaw. Quality and durability are very dependent on nozzleman skills.
DRAINAGE		
Weep Drains	Reduce water pressures within a slope using horizontal drains or adits. Commonly used in conjunction with other design elements. Good for aesthetics because drains are rarely visible.	Difficult to quantify the need and verify the improvements achieved. Will need periodic cleaning to maintain water drainage.

Hand Scaling

Hand scaling is the most common and inexpensive form of scaling. Workers rappel from the top of the slope or work out of a crane or man lift basket and use steel pry bars or air bags (also known as pneumatic pillows) to remove any loosened rocks. In most cases, several workers are scaling a slope at one time. Hand scaling is effective on small areas that are accessible by workers and that have rocks that are not too big to be removed manually.

Scaling companies typically provide their own equipment, including rappelling ropes, harnesses, pry bars, air bags, air compressors, and safety equipment. If access from the roadway is not feasible, a helicopter may be used to transport the scalers to an area above the slope. Figure 39 shows a typical hand-scaling operation.

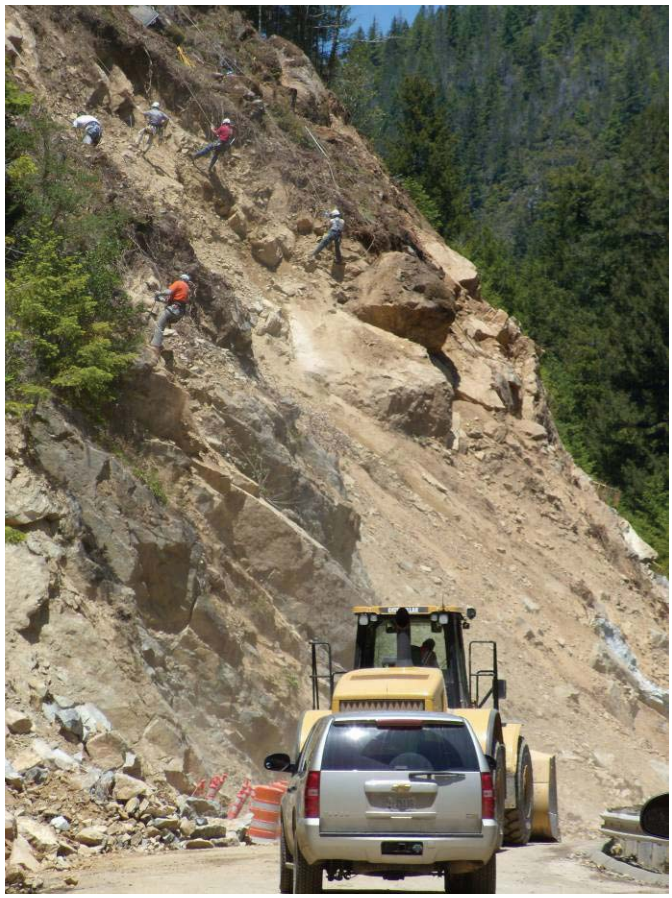


Figure 39. Photo. Hand scalers removing loose material from a cut slope South Fork Smith River Road, California.

Mechanical Scaling

Mechanical scaling is used on larger slope areas or to augment hand-scaling efforts. This process uses hydraulic hammers, long-reach excavators as shown in Figure 40, or cranes that drag a heavy object, such as a blasting mat or old "Caterpillar" track, across the slope (contractors have developed many ingenious scaling implements, including bundled cables, large steel rakes, and a used tread from a bulldozer, although not all methods have been equally successful). For removing very large rocks, power-assisted mechanical equipment such as pneumatic pillows or splitters can be inserted into open cracks, and then expanded to dislodge the rocks.

Mechanical scaling can also be performed by placing explosives into cracks and drilled holes (a process known as crack blasting) or using heavy construction equipment such as a trackhoe. It should be noted that without confinement, crack blasting can be relatively ineffective and can also produce loud explosions and flyrock.

Figure 40. Photo. Using a long-reach excavator for mechanical scaling.

The most important aspect of designing a rock scaling operation is ensuring the selected method is capable of handling the rock (or sections of rock) that need to be removed. Once scaling has begun on a feature, it will become unstable, and it cannot be left and the area re-opened to traffic restored until it is removed.

Most mechanical scaling operations use a crane or excavator, plus a front-end loader and dump truck to haul rock from the site.

Trim Blasting

Trim blasting, or trimming, is used to remove sections of rock that are too large for conventional scaling operations. Trimming typically uses cushion or smooth blasting techniques, as described earlier. After the rock section is blasted, the area should be hand scaled to remove smaller material. As with all blasting procedures, trimming can produce flyrock and loud air-blast.

Trim blasting requires drilling equipment and explosives. Spires of rock or large single rocks will require minimal blasting and drilling (which in many cases can be accomplished with hand drills), while bigger rocks, rock overhangs, or unstable rock faces may require more extensive drill and blast techniques.

REINFORCEMENT SYSTEMS

Most reinforcement systems work to strengthen the rock mass internally by increasing its resistance to shear stress and sliding along fractures. Other systems work externally to protect the rock from weathering and erosion and to add a small amount of structural support. An example of this is shotcrete (concrete or mortar that's "shot" onto the rock).

Internal Stabilization

Internal stabilization is accomplished by tensioned and untensioned rock anchors, injectable resin, and drainage.

Rock Anchors

The most common type of internal reinforcement are anchors, which are threaded steel bars or cables that are inserted into the rock via drilled holes and bonded to the rock mass by cement grout or epoxy resins. (Friction bolts are considered temporary measures and typically are not used in the transportation industry.) Because the bond strength between the cement grout or resin and the rock is less than the maximum yielding stress of the steel, it has a large impact on the design load of the rock reinforcement.

Rock anchors can be used to secure a single loosened block or to stabilize an entire rock slope that is affected by a prevalent rock structure. Bolt and cable lengths are highly variable and are compatible with a variety of rock types, structural characteristics, and strengths. Anchors can be combined with other stabilization techniques if they cannot mitigate the hazard alone. Disadvantages include relatively high cost, susceptibility to corrosion, and lengthy installation times, which can slow the construction of the rock slope.

The anchors used for slope stabilization are typically 6 m (20 ft) in length, 20 mm to 50 mm (5/8 to 2 in) in diameter and made of high-strength steel (bars can be coupled to increase the length up to 30 m or 100 ft, but the total length of a stabilization bar is generally limited to 12 m or 40 ft). Rock anchors can be *tensioned* or *untensioned.*

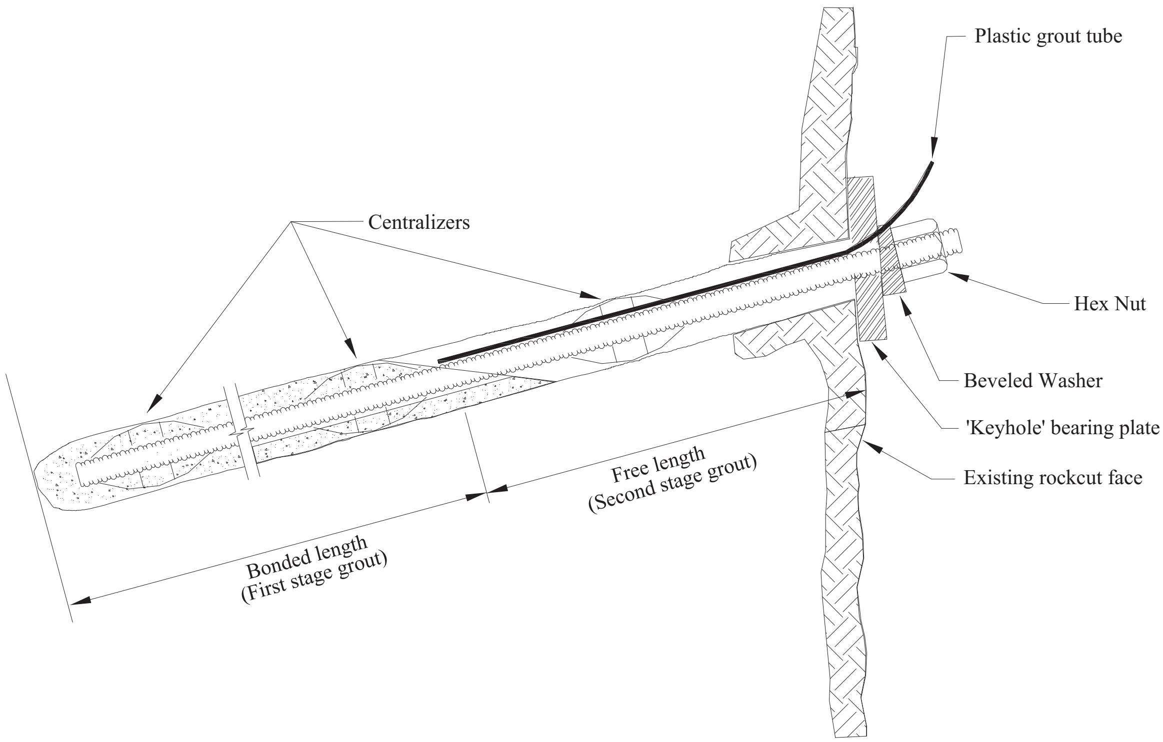
Tensioned Anchors (Rock Bolts):

Tensioned anchors (also known as *rock bolts*) are used on rock masses that already show signs of instability or on newly cut rock slopes to prevent movement along fractures and subsequent decrease of shearing resistance. A hex nut and bearing plate are used to distribute the tensile load from the bolt to the rock mass as illustrated in Figure 41.

Rock bolts are considered a type of active reinforcement due to the post-tensioning they provide, and are used to add compressive stress to joints within a rock mass. This force increases the friction along the fracture planes and helps to reduce block movement.

Tensioned rock bolts can require more time to install than dowels because installation involves several steps: drilling, grouting the bond length and inserting the bar or cable, then tensioning the anchor and grouting the free length. Because the tension in the bolt can reduce over time due to creep and become "seized" by small shears in the rock mass, rock bolts may need periodic re-tensioning.

Figure 41. Illustration. Typical tensioned anchor (or rock bolt).



Untensioned Anchors:

There are two types of *untensioned anchors* used in rock stabilization: *rock dowels* and *shear pins*. Both are untensioned, fully grouted steel bars used for passive reinforcement. Dowels are used on steep slopes in the same fashion as rock bolts, while shear pins are used on flatter slopes where bedding planes and discontinuities determine the slope angle and failure plane.

Rock dowels as illustrated in Figure 42, are typically used on newly excavated slopes. They can be installed in a grid pattern to support an entire face or used to support one block. They provide initial reinforcement through the shear strength of the steel, which increases friction along the potential plane of weakness. Once block movement occurs, depending on dowel orientation, the tensile strength of the bar is engaged and the normal force between opposing discontinuities is increased.

Dowels can be used in highly fractured and weak rocks that cannot hold a tensioned rock bolt. They also can create a more natural-looking slope face, as the plates can be removed in massive rock formations without close jointing that would inhibit the face support contribution of the dowel. The boreholes can be covered with grout that's been colored to match the surrounding rock. Because dowels are installed in one step, they are quicker to install than tensioned bolts.

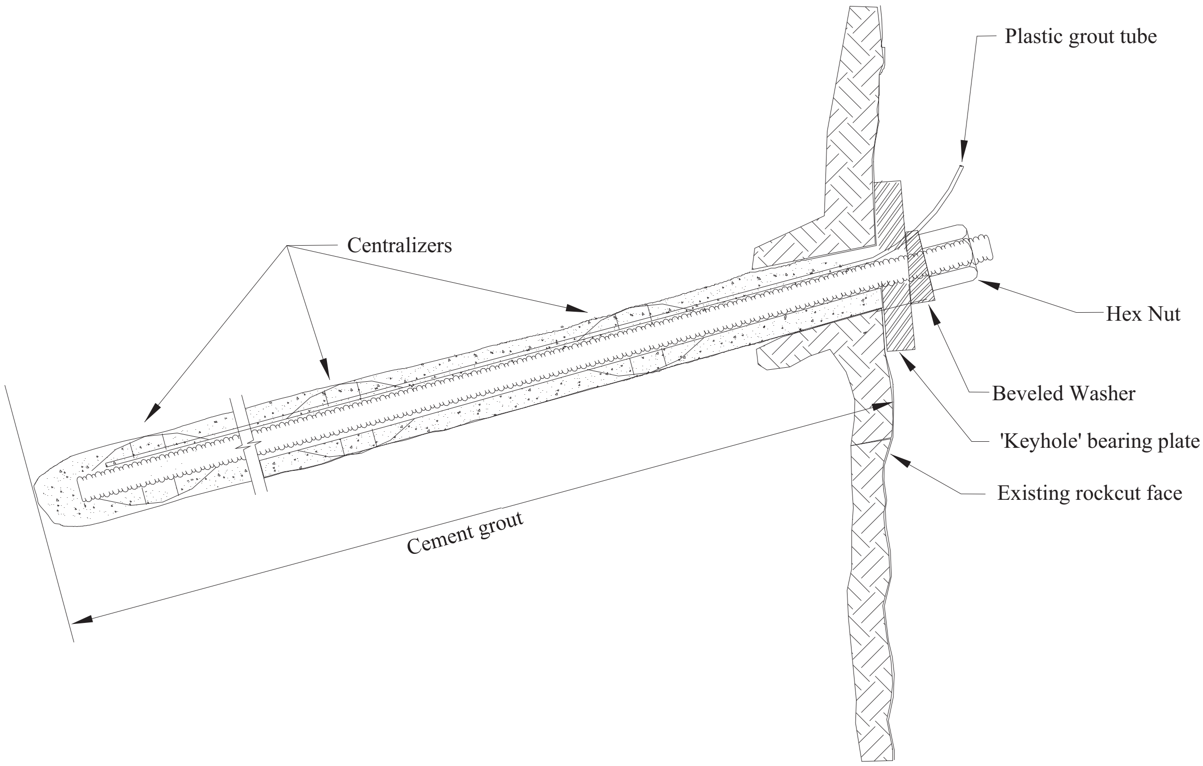


Figure 42. Illustration. Typical untensioned rock dowel.

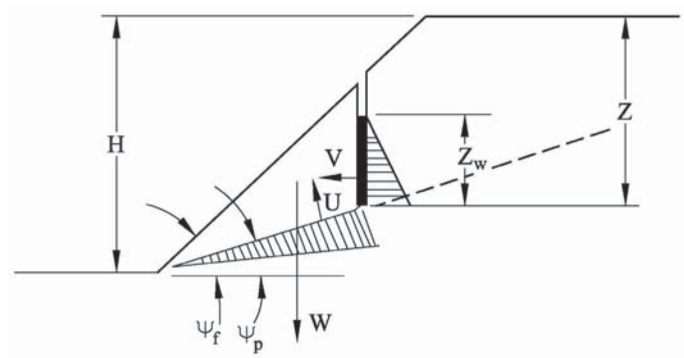
Shear pins are installed at the leading edge of a sliding block. They rely on the shear strength of the steel dowel cross section to provide resistance in the sliding plane of the block. In places where it is not possible to install shear pins directly into the block, the pins can be incorporated into a concrete buttress.

Rock Anchor Design and Installation:

Rock reinforcement design relies primarily on surface mapping and logging discontinuities from borehole data to assess fracture/joint patterns and other conditions, as discontinuities strongly control rock slope stability. Surface mapping is usually conducted as window mapping or scan-line mapping. In some cases, engineers should also obtain test hole data, especially if surface mapping is not feasible due to the presence of overburden soil or for other reasons. As is true in any slope assessment, it is also important to assess the groundwater present in the rock discontinuities to measure slope stability.

To determine the slope's safety, the following conditions should be evaluated: the height and thickness of the rock mass that requires stabilization, and the shear strength of the failure plane (determined by the friction and cohesion of the plane, as well as groundwater conditions, rock type, and other geologic features). Figure 43 depicts a rock slope stability analysis diagram assuming a tension crack in the slope face for a planar slope failure.

The reinforcement load is applied in the stability analysis either as a single stabilizing element or a series of reinforcing elements to achieve the desired factor of safety. The length of the bolt or cable is dependent on the bond strength (adhesion to the rock) and the discontinuity spacing that forms the deepest part of the block. Tendon lengths can range from 2 to 30 m (6 to 100 ft); however, in the transportation industry, the tendon length rarely exceeds 10 m (30 ft). The detailed requirements for site investigation and analysis of rock cuts are provided in FHWA HI-99-007 *Rock Slopes Reference Manual* (Munfakh, Wyllie, and Mah 1998)



Where:
V = Water force in tension crack
U = Uplift water force on base of sliding block
W = Weight of sliding block
ψ_f = Angle of slope face from the horizontal
ψ_p = Angle of the sliding plane from the horizontal
Z = Height measured from bottom of the tension crack to the crest of the slope
Z_w = Height of water column in tension crack
H = Overall height of the slope

Figure 43. Illustration. Example slope analysis diagram (modified from Hoek and Bray 1981).

Rock anchors are usually installed in a grid pattern, where each anchor is the same length and set at a predetermined distance from the surrounding bolts. Following a set pattern can improve the structural stability of an entire rock face, especially for weathered or highly fractured rock. On competent rock masses with large block sizes, engineers typically identify “key blocks" (i.e., blocks of rock that control support for surrounding blocks), then design a bolting pattern around them that makes it more difficult for the surrounding blocks to move. Designing a key block pattern requires engineers to map the three-dimensional fracture orientations, but can decrease the number of rock bolts required to stabilize a slope.

In both tensioned and untensioned anchors, the bearing plate and hex nut are used to distribute the load of the anchor to the rock face; a beveled washer is used to apply the load evenly when the bolt is angled in relation to the rock face. In rock masses with few discontinuities, the plate can be removed and the tendon (bar or cable) cut to allow for the installation of a grout cover or plug. This method is highly contingent on the quality of rock and stability of the rock mass.

In the tunnel shown in Figure 44, dowels were used to support a tunnel crest; the visible ends were covered with a colored grout to help mask their presence. Only the grout at the end of the tunnel is visible because the surrounding rock is darker and provides more contrast with the lighter-colored grout than the rock in the center of the tunnel.

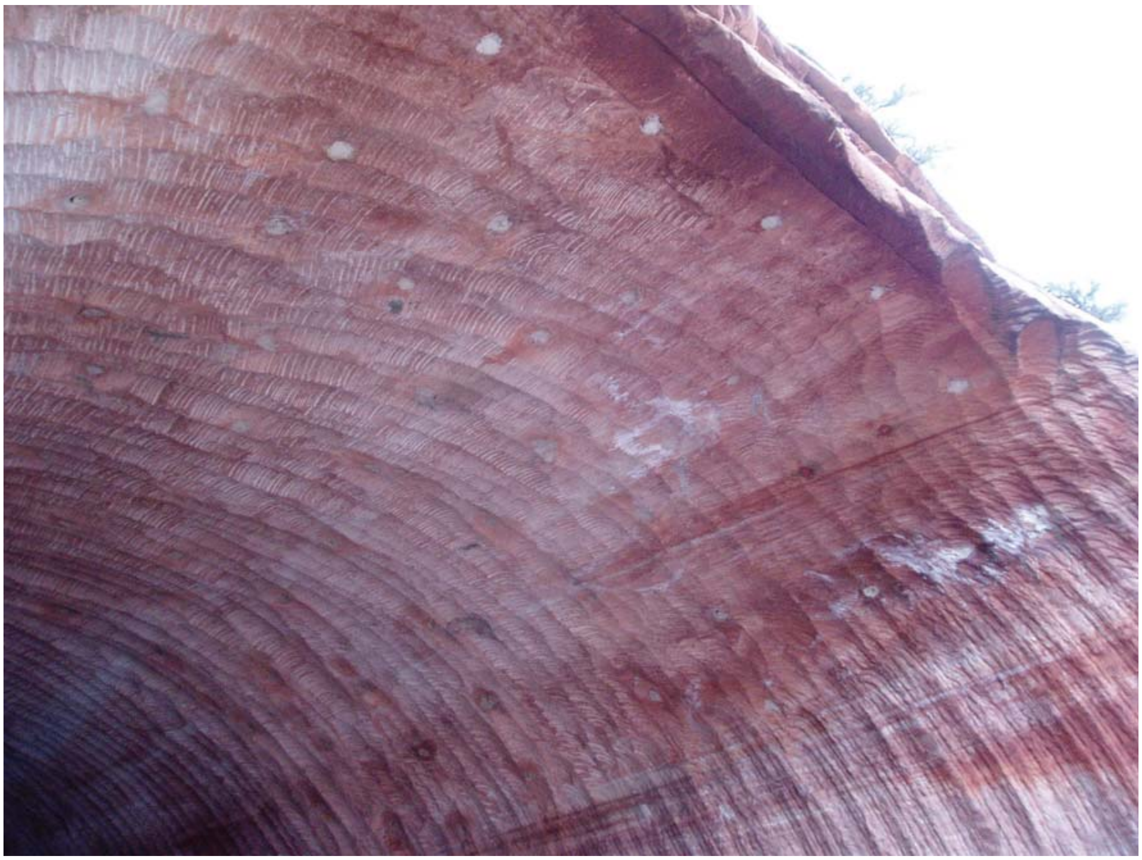


Figure 44. Photo. Tunnel crest supported with dowels that have been covered with colored grout.

Design analysis determines the depth of the boreholes required for rock bolts and dowels. The reinforcing element is grouted into place using either cement- or epoxy resin-based grout. Both bonding agents use either a one- or two-step application process, depending on the type of anchor being used.

Grouting for rock bolts is typically applied in two steps. In the first step, the grout or resin is injected into the base of the borehole—the section known as the "bond length" of the bolt—and allowed to set. After the bond length is dry, the bearing plate and hex nut are installed, the bolt is tightened, and the remaining length (the "free length") is filled with grout or resin. In some cases, contractors can accomplish the grouting in a single step, by using two types of grout or resin, each with a different set time. In this method, the bond length is filled with a quick-set product while the remainder of the hole is filled with a slow-set product; the quick-set resin is allowed to harden, then the bolt is tightened before the slow-set resin sets.

Shear pins and dowels can be grouted in one stage, using cement grout or a single resin.

When installing rock anchors, contractors often use polyester resin because of its ease of application and adjustable set times. It comes in a two-part package that is inserted into the borehole before the bolt. The bolt is inserted into the borehole and rotated in place to break up and mix the resin. (The two-part resin cannot be used with cable tendons, which are flexible and therefore do not effectively break up and mix the resin.) Polyester resin is generally used in short-term or temporary applications. Cement grouts are slower to set, but form a reducing environment that makes them better suited for corrosive environments and permanent applications.

The final location of the rock reinforcement is determined in the field during construction. It is imperative that the reinforcement is correctly located on a rock surface that is not prone to weathering, as erosion around the bearing plate can cause a loss of tension. Figure 45 shows bolts that have failed because of erosion of the surrounding rock.

Figure 45. Photo. Rock bolts installed in an area where the surrounding rock has eroded away, reducing the effectiveness of the bolts.

Installing bolts, dowels, and shear pins most often requires a hand-held or mounted rock drill (normally percussion style), reinforcing tendon (rod or tensionable cable), hex nuts, washers and bearing plates, either epoxy or cement grout for adhesion, and a hydraulic jack or torque wrench.

Figure 46 illustrates the typical track drilling equipment used to install rock reinforcement. In areas where access is difficult, a man lift or crane may be needed as shown in Figure 47.

Figure 46. Photo. Installation of rock bolts using a track drill.

Figure 47. Photo. Installing rock reinforcement using a drill rig suspended from a crane.

Rock Mass Bonding

In the mining industry, *injectable resin and epoxy* have been used since the 1960s to stabilize underground coalmines. Since then, they have also been used on numerous geotechnical and geological engineering projects. When injected into a rock mass via drilled boreholes as shown in Figure 48, these materials follow any fractures and discontinuities around the holes, thus increasing the rock's stability. Rock masses that are excessively fractured and/or contain voids will require large amounts of filler, which can result in excessive cost overruns (for proper resin/grout movement and to keep pumping pressures at a minimum, the discontinuity aperture spacing should be at least 2 mm, or 1/16 in.).

In suitable slopes, injecting resin or epoxy is very effective in providing additional slope stability without negatively effecting aesthetics. There is virtually no maintenance required after resin/epoxy injection. And while research on the application and effectiveness for the use of injectable resin/epoxy as the primary means of slope stabilization is ongoing, initial findings indicate that it can reduce the number of rock bolts needed for slope stabilization.

Figure 48. Photo. Installation of polyurethane resin from man lift, Poudre Canyon, Colorado.

The first step in installing resin/epoxy is to choose the proper product to use in the rock mass. The primary factor for determining this is the presence of water in the fractures. Products are characterized as either *hydrophilic* or *hydrophobic*.

Hydrophilic products, such as polyurethane resin (PUR) and polyurethane (PU), incorporate water into their chemical structure and will shrink (or swell) depending on the amount of water present. Typically, hydrophilic products will swell between 25% and 3,000% and/or elongate 10% to 500%, depending on the presence of water and available space for expansion (Arndt, DeMarco, and Andrew 2008). On the flip side, the product can shrink more than 10% in the absence of water, and can also become dry and crack. Typically, hydrophilic products are used as a water barrier or sealant. They perform best when in continuous contact with water. The shear strength of hydrophilic products is significantly less than the more dense hydrophobic products, but they permeate into moist or water-filled fractures and voids without requiring significantly more pumping pressure, as hydrophobic products do.

Hydrophobic products, such as epoxy grouts (EP), react less with water and therefore expand and contract considerably less than hydrophilic products. This results in a denser final product with greater shear strength. Hydrophobic products will not permeate as well into water and require higher pumping pressures when pumped into water-filled discontinuities because they need to overcome the hydraulic head to displace the water. A comparison between PU, PUR, and EP products is shown in Table 9.

Table 9. Properties of different rock-bonding products (Arndt, DeMarco, and Andrew 2008).

PROPERTY	POLYURETHANE (PU)	POLYURETHANE RESIN (PUR)	EPOXY (EP)
Component Mixing	One-Stage	Two Stage	Two-Stage
Injection Type	Foam/Gels/Grout	Grout	Grout
Injection Pressures	Low to High 700 to 21,000 kPa (100 to 3,000 psi)	Low to High 70 to 21,000 kPa (10 to 3,000 psi)	Low to Medium 200 to 5,500 kPa (30 to 800 psi)
Density	Low to Medium 50 to 800 kg/m3 (3 to 50 pcf)	Medium to High 320 to 1,100 kg/m3 (20 to 70 pcf)	Low to High 80 to 960 kg/m3 (5 to 60 pcf)
Compressive/Tensile Strength	Low 70 to 3,500 kPa (10 to 500 psi)	Low to High 100 to 140,000 kPa (15 to 20,000 psi)	Medium to High 34,000 to 140,000 kPa (5,000 to 20,000 psi)
Viscosity	Low to Medium	Low to High	Very Low to High
Water Interactions	Hydrophilic	Hydrophilic/Hydrophobic	Hydrophobic
Expansion/Elongation	Varies (10% to 3,000%)	Varies (10% to 3,000%)	Minimal
Shrinkage	Varies (1% to 10%)	Varies (0% to 3%)	Minimal
Relative Product Cost	Low	Mid to High	High

Estimating the pre-injection volume of resin/epoxy can be difficult because it is dependent on the moisture and interconnectivity of the fractures. Generally speaking, dry to slightly moist fractures will require about twice the amount of product being injected per hole compared to very moist to wet fractures.

Boreholes should be spaced approximately 2.5 to 5 m (8 to 16 ft) apart. Holes can be drilled ahead of time or right before injection. In cases where the migration distance of the product is unknown, drilling holes too close together can cause the resin/epoxy to extrude from adjacent holes, while drilling the holes too far apart can result inadequate product distribution. The placement and orientation of the injection boreholes should intersect as many fractures as possible. Ideally, the boreholes should intersect the major discontinuities at a 90° angle and/or at the intersection of fractures to maximize the injection potential of the product.

If possible, construction should take place during the region’s dry season so that fractures will contain minimal moisture. Injection should proceed from the bottom of the slope to the top. To ensure proper distribution of product around the borehole, the contractor should proceed until overrun is observed, then end pumping for approximately one minute to allow the product to start to set. The contractor should then resume pumping to push the new volume of product into other fractures and joint sets and continue this staged pumping procedure until overrun is seen above the injection site. Pumping pressures need to be closely monitored and kept at a minimum to prevent movement within the rock mass and/or the displacement of any rocks. Evidence shows that pressures more than 1,800 kPa (250 psi) can cause problems, even though the material specifications have ranges with upper ends exceeding this value. It is best to remove overrun product immediately, before it becomes hard (at this stage, it easily peels from the rock face). After the product dries, it will have to be chipped away.

Equipment required includes a man lift, shown earlier in Figure 48, capable of reaching the slope crest, plus a percussion-type drill, either hand operated or attached to the lift, an air compressor to operate the drill, a resin/epoxy pumping and mixing system, and an injection port with a diameter slightly smaller than the borehole diameter.

Polyurethane Resin (PUR) was used recently on a mountain highway in Poudre Canyon, Colorado, to stabilize 80 m^2 (850 ft^2) of a rockfall-prone slope adjacent to a tunnel portal. The geology consisted of gneiss with fracture sets spaced between 0.5 and 3 m (1.5 to 9 ft) apart with dry to slightly moist apertures with openings greater than 2 mm (1/8 in).

Sixteen holes, 38 mm (1.5 in) in diameter, were drilled between 3 to 3.5 m (10 to 12 ft) deep. Between 90 to 315 kg (200 to 700 lb) of PUR was injected into each hole, for a total of more than 2,250 kg (5,000 lb) of product. As shown in Figure 49, PUR was seen extruding out of the surface fractures more than 1.5 m (5 ft) from the injection point. Injection times ranged from 20 to 40 minutes. No rockfall was encountered during the drilling or injection process, and there is no visible evidence that any work has been done at the site.

Figure 49. Photo. Polyurethane resin used in a fracture, Poudre Canyon, Colorado.

External Stabilization

Shotcrete

Shotcrete is a wet- or dry-mix mortar with a fine aggregate (up to 23 mm, or 7/8 in) that is sprayed directly onto a slope using compressed air. Several applications may be needed to build the shotcrete up to the required thickness. Unreinforced shotcrete gives little structural support or protection against weathering, but can be used to prevent differential erosion between units, slope raveling, and loosening of blocks. Shotcrete can also be applied around the exposed ends of rock bolts to help prevent weathering around the bearing plates and limit slope degradation.

To increase tensile strength and structural support, the contractor can include fibers in the shotcrete mix or apply the shotcrete to welded wire mesh shown by Figure 50.

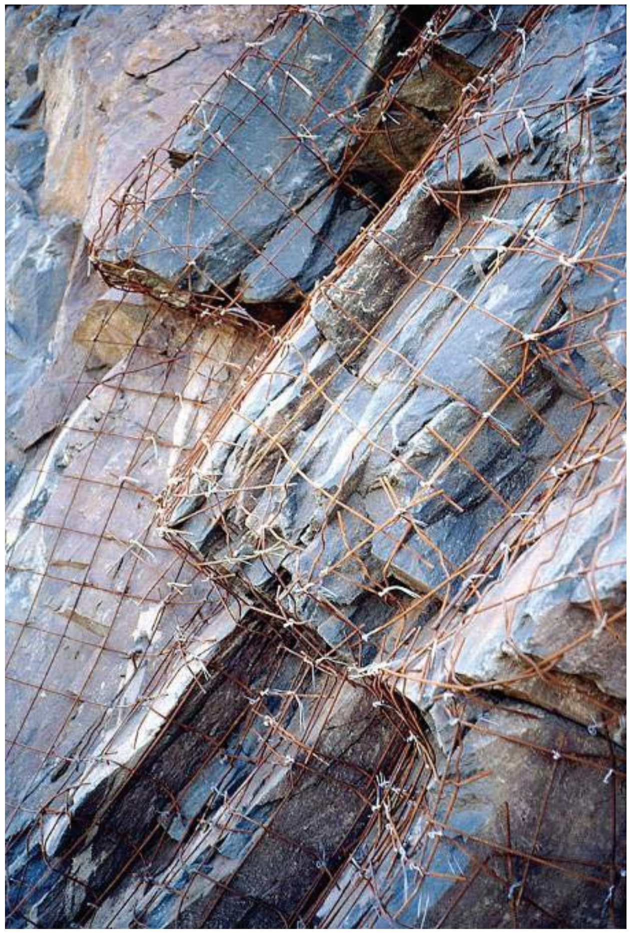


Figure 50. Photo. Welded wire mesh can be attached to the rock face before shotcrete is applied.

Shotcrete can vary in appearance from very rough—in its natural, “as-shot” (unfinished) condition—to moderately rough in the "rodded" condition, to as smooth as cast-in-place concrete (with appropriate finishing). Architectural shotcrete (known as façade or sculpted shotcrete) can produce a wide range of finished surfaces.

In contrast to cast-in-place concrete, shotcrete can be shaped, contoured, and colored to match the surrounding rock as shown in Figure 51.

Figure 51. Photo. Shotcrete can be used to protect a slope from erosion—and sculpted to mimic the natural rock face (Ada County Highway District 2003).

In most instances, structural shotcrete is applied to rock slopes to protect a surface which, left untreated, would erode (such as a fault zone or clay seam), or to provide structural support for otherwise sound rock that is either undermined by erosion or is unstable due to unfavorable orientations or degree of fracturing. This type of shotcrete application can be part of the original construction or part of the remediation of an existing unstable rock slope.

Structural shotcrete can also be used to form part of a retaining system supporting the rock slope as shown in Figure 52. The system typically includes other components such as welded wire mesh, rock bolts, and/or dowels (the shotcrete also may be fiber-reinforced to improve its tensile capacity). In these applications, the shotcrete will be required to resist or transfer loads and may also have an essential surface protection function in conjunction with its structural function.

Unreinforced shotcrete can be used to cover a well-defined strip (or strips) of rock with a higher rate of erosion than the surrounding rock (faults or shale lenses in sandstone, for example) or an entire slope composed of highly erodible material. In the latter case, the designer should consider laying the slope back to avoid a structured solution, as differential erosion of the rock slope will create stability problems that become worse with time.

Figure 52. Photo. Sculpted shotcrete used to stabilize a tunnel portal (the area directly below the dry-stack wall is the sculpted shotcrete).

A façade of sculpted (or architectural) shotcrete can be used to improve the appearance of structural shotcrete as well as an engineered slope.

In any shotcrete application, drainage (in the form of weep holes or wick drains) will be required to draw water from behind the shotcrete to prevent elevated water pressure from causing cracking and instability in both the shotcrete and localized blocks.

Color can be applied to the shotcrete surface to help it blend with its surroundings. To achieve the best results, the designer and contractor should consider the following:

- Although darker colors tend to be less intrusive than lighter ones, designers should avoid applying dark shotcrete to light rock (or light shotcrete to dark rock).
- Consider the overall color and tone of the undisturbed rock formations, determine the average color of the surrounding rock, and apply that color to the shotcrete.
- If the shotcrete is covering all the exposed rock, there is little point in aiming to achieve a color match; it's better to select an unobtrusive color that fits the local context.

- Instead of combining several colors in the shotcrete mix, start with a single color, and then apply at least two different colors as stain.
- Time always changes the color of both rock and shotcrete, through water staining, air particles, exhaust emissions, vegetation growth, and weathering.

The texture of the shotcrete is almost as important as color, but it is often overlooked in shotcrete applications. Most natural rock is characterized by a collection of planar surfaces, while shotcrete has a granular, amorphous finish. Designers can apply a variety of textures to shotcrete, such as these:

- Troweling the shotcrete to a pattern that matches the natural planes in the rock;
- Forming the shotcrete to a formal shape to create the impression of a purposeful element, such as a retaining wall;
- Stamping the shotcrete with timber boards or molds;
- Leaving areas of exposed aggregate finish combined with a modest trowel finish to provide natural-looking texture;
- Sculpting the surface of the shotcrete to mimic the surrounding rock (the success of this technique is heavily dependent on the skill of the operator). Welded wire mesh can be used to construct a sculpted rock appearance.

Before shotcrete application, the rock face should be scaled and cleaned to remove any loose material (rock, dirt, ice, vegetation, etc.) that may hinder bonding. Highly fractured or weak rock should be removed to expose more competent material (if the shotcrete is incorporated with welded wire mesh and rock bolts/dowels, this is not necessary). In any case, the face should be free of flowing water but damp enough to facilitate proper curing. Any wire mesh should be attached securely to the area of application, as it will act as a frame to hold the shotcrete in place.

As mentioned earlier, shotcrete comes in both wet and dry applications. The wet application is mixed with water before it enters the application nozzle, while dry applications are mixed with the water at the nozzle. Air entertainment is not possible with dry mixes, so resistance to climatic freeze/thaw can be reduced.

Applied shotcrete varies in thickness, from 50 mm to 0.6 m (2 in to 2 ft). For thicker applications, shotcrete should be applied in multiple layers of about 50 to 100 mm (2 to 4 in) each and allowed to cure between applications. Installing shotcrete requires an air compressor, application nozzle, and cement mixer. The application nozzle is either hand held or attached to a man lift or crane. Reinforcing the shotcrete with welded wire mesh or fibers can greatly increase its tensile strength, stand-up time, and rock-bonding potential, as well as the overall stability of the rock mass.

Figures 53 through 56 show the installation of sculpted shotcrete in a combined structural/sculpted façade application. The first image, Figure 53, shows the shotcrete being applied by hand from a man lift. The shotcrete was sprayed onto the rock at a slight angle downward and built from the bottom up, to prevent slumping. Note the elements protruding from the face: The white pipes are weep drains composed of 50 mm (2 in) PVC pipe. The large-diameter steel bars are rock anchors, while the small-diameter bars were used as a guide to help the contractor build the shotcrete to the required thickness.

Figure 53. Photo. Application of the first layer of structural shotcrete.

Figure 54 shows the installation near completion of the first layer of shotcrete on the slope, which took three days to achieve. It is necessary for each layer to dry and gain enough strength for the application of the subsequent layer.

Figure 54. Photo. Installation of the first layer of structural shotcrete.

After installation of the structural shotcrete is completed, the sculpted shotcrete façade is installed. In Figure 55, the contractor has installed a grid of rebar and pockets of welded wire mesh to help form and suspend the façade.

Figure 55. Photo. Application of the final sculpted shotcrete façade.

Figure 56 shows the finished sculpted shotcrete façade prior to the application of stain.

Figure 56. Photo. Completed structural shotcrete support, ready for staining.

DRAINAGE SYSTEMS

Slope stability can also be improved through the installation of drainage systems, which most often consist of *horizontal weep drains*.

Water in a rock slope often contributes to slope instability, as excessive pore pressure acts on the rock mass and lowers the shear strength along any discontinuities. Water also contributes to rock degradation and fracture expansion and during the process of freeze-thaw weathering.

Normally, drainage systems are used in weak, highly fractured, or layered rock where instabilities could occur along a potential sliding surface. Drainage is generally used to mitigate larger rockslides and failures. In most cases, the drains are installed as uncased holes in massive rock units, drilled with a track rig or portable drill. In weak or highly fractured rock, the drain may be cased with a slotted polyvinylchloride (PVC) pipe to maintain the drain opening. Drains are installed at the base of the slope, and require periodic maintenance to prevent clogging. Usually, they are used in conjunction with other stabilization measures.

Horizontal drains can be installed in a rock slope to reduce pore pressure and improve stability, and are a cost-effective, aesthetically pleasing, and relatively low-maintenance option for most slopes with excessive flowing water. They are most effective for large-scale slope instability, where the potential sliding planes are deeply seated within the rock mass.

The most important factor in designing horizontal drains is to orient the holes so they intersect the maximum number of water-carrying fractures, as very little water is contained within the intact rock. Drainage holes should be spaced about 3 to 10 m (10 to 33 ft) apart and drilled to a depth of at least one-third of the slope height. Once the water is drained from the slope, it must be diverted away from the slope base to prevent infiltration, which could create additional stability issues. In addition, the slope base must be protected from motorists and any obstructions that could damage the drains or inhibit water movement.

Piezometers installed in the slope can monitor the water pressure and the effectiveness of the installed drainage, allowing engineers to determine if the drainage is sufficient or if additional drains are needed.

Horizontal drains are constructed used conventional rock drilling equipment. The hole location, orientation, and angle are determined based on the fracture patterns in the rock. The installer may need to adjust the assumed orientation and angle based on water conditions encountered. Normally, drainage holes in rock can be drilled using a track rig or hand-held drill (hand-held drills are limited to relatively shallow drainage holes). In highly fractured or weak rock, the hole should be cased with a perforated PVC pipe to prevent collapse. Perforation size should limit the amount of fine particles that infiltrate into the pipe. Surface drainage produced from slope de-watering can be diverted or contained using a lined gutter, culvert, or collection system.

CHAPTER 6 – ROCKFALL PROTECTION

Structures designed to protect the areas around a slope from falling rocks include mesh or cable nets, barriers and fences, and catchment areas (ditches at the toe of a slope, designed to prevent rockfall from reaching the highway). These devices allow rocks to fall but prevent them from causing any damage to a structure or the public. The protection can stop a rock, control its trajectory, reduce its energy, and/or provide a catchment. In many cases, a catchment is used in conjunction with an inclined deceleration zone.

However, because they are external to the slope, these structures are typically more difficult to hide—or to fit within the context of the surroundings—than structures that are integrated into the slope.

Another option for protecting against rockfall is the use of avoidance measures, such building a tunnel, realigning the roadway, or constructing an elevated portion or portions, which ensure that the road will be out of the path of any foreseeable rockfall.

ROCKFALL PROTECTION DESIGN

Because of the significant amount of information on protective methods and design available today, only a brief overview of the most frequently used methods will be covered here. Table 10 provides an overview of the most common protective measures used in the transportation industry.

To develop effective rockfall protection, the engineer should evaluate the slope through a thorough site investigation. Factors affecting rockfall that must be considered include slope height, topographic profile, variable slope angles, potential launch points, rock type variations, soil cover, vegetative cover, potential runout areas, and impact zones.

A cross section and contour map that identifies geometric characteristics of the slope should be developed. The cross section should begin at the source area (the origin of the falling rock) and end past the runout zone as illustrated in Figure 57. This will help establish the rockfall height as well as its potential energy. Significant features such as slope angle changes, launch points, ridges, and gullies largely define the path of travel by channeling, launching, and/or hindering the falling rock. They also affect the rockfall's mode of travel: rolling, bouncing, or free falling. Existing impact locations on structures, trees, or other impediments allow the engineer to make rudimentary estimates of bounce heights and launch points. Slope height and angle play a major role in the amount of energy that is carried by the falling rock, but they are not the only factors to consider.

Table 10. An overview of rockfall protection measures and their limitations.

PROTECTION MEASURE	DESCRIPTION/PURPOSE	LIMITATIONS
MESH/CABLE NETS		
Draped Mesh/Nets	Hexagonal wire mesh, cable nets, or high-tensile-strength steel mesh draped over a slope face to slow erosion, control the descent of falling rocks, and restrict them to the catchment area.	Require a debris-collection catchment area. Must consider debris and snow loads on anchors. Typically limited to areas with rocks smaller than 1.5 m (5 ft) in diameter. Visible to passing motorists.
Anchored Mesh/Nets	Free-draining, pinned/anchored-in-place nets or mesh. Used to apply active retention force to retain rocks and soil on a slope.	May form pockets of accumulated rock. Can be difficult to clean out. Can be visible to passing motorists.
BARRIERS		
Earthen Barriers	Barriers constructed of natural soil and rocks (berms) or mechanically stabilized earth (MSE), placed at the distal end of a catchment area to improve its effectiveness. MSE walls, in particular, can withstand large kinetic energies and repeated impacts. Easily repaired. Earthen material blends well with surrounding landscape.	Catchment area must be periodically cleaned to remove accumulated material. Berms of considerable height require a wide base area.
Concrete Barriers	Rigid barriers that provide protection from low-energy impacts. Relatively cheap, easy to obtain, and fast to install. Normally used as temporary barrier in context sensitive areas.	High stiffness causes barriers to crack and/or shatter in high-energy impact. Not visually appealing.
Structural Walls	Rigid barriers used to intercept falling rocks and restrict them to a prescribed catchment area. Can withstand significant kinetic energies and repeated impacts. Facing can be installed on road side of walls to improve aesthetics.	Catchment area must be periodically cleaned to remove accumulated material. Prone to damage by high-energy events
Flexible Barriers	Flexible barriers made of wire ring or high-strength wire mesh with high energy-absorption capacity, supported by steel posts and anchor ropes with a braking system. Fence is fixed at the bottom to hold rocks. Effective on high- to low-energy events.	Require room for rocks deflected by barriers during impacts. Must be cleaned out periodically. Fairly expensive to construct and prone to damage by higher-energy events. Do not blend well into surrounding landscape.
Attenuators	Flexible barriers similar to fencing (above) but not attached at bottom (an extra length of fence lies on the slope face); allow rocks to move beneath the two sections of fence and direct them into a catchment area. Require less maintenance than standard fencing.	Visible to passing motorists. A catchment area is required and must be periodically cleaned.
CATCHMENTS		
Ditches/hybrid ditches	Shaped catchment areas normally placed along the roadside or slope base and used to contain rockfall. Aesthetically pleasing. Hybrid ditches are a combination of a barrier and a ditch.	Tall or rough slopes require a wide fallout area. May have right-of-way issues. Catchment area must be periodically cleaned. Costly to install along existing roadways.

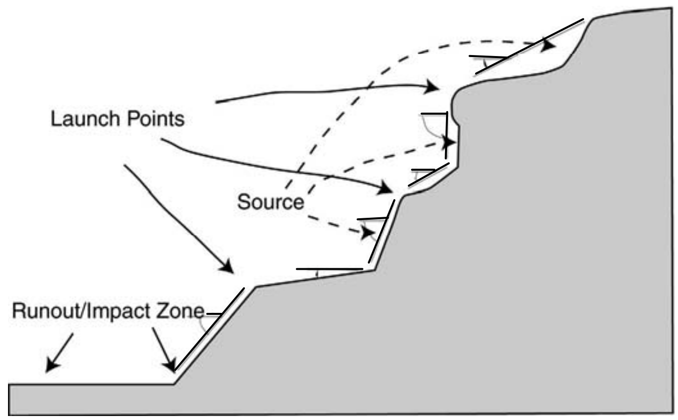


Figure 57. Illustration. Effective rockfall protection design requires an accurate slope profile, which identifies source areas, launch points, and runout zones (Brawner 1994).

Rockfall is also affected by slope cover, which, depending on its thickness, can significantly reduce rock velocities and bounce heights and stop or stabilize falling rock, even on very steep slopes. Similarly, the characteristics of the soil can also play a role: A layer of thick, loose soil will dampen the velocities and bounce heights of falling rock upon impact, whereas a solid smooth surface, such as a rock slope or compacted soils, does very little to hinder rock travel.

Slope roughness, a measure of the slope irregularities relative to the rock, can also affect rockfall. For most rockfall analysis, roughness is described as a smooth, irregular, or ragged portion of the slope. In steep terrain, a rough slope can cause rocks to bounce, but it can decrease rockfall energy on flatter slopes.

Once a rockfall area has been evaluated, it can be further analyzed and quantified by both empirical and computer methodologies. Several large-scale empirical rockfall studies have been conducted over the last 40 years. One of the first important studies was conducted by Arthur Ritchie in 1963. Further analysis, published by the Oregon Department of Transportation (ODOT) in 1994 and 2002, advanced Ritchie's framework and provided statistically significant data by rolling more than 11,000 rocks (Pierson, Davis, and Pfeiffer 1994; Pierson, Gullixson, and Chassie 2002). The result was a complete set design guidelines for catchment areas based on a set of given slope parameters.

Computer modeling allows engineers to simulate rockfall, particularly in places where a catchment ditch is not a viable option for rockfall control, as in areas where roadway widths are constrained by narrow canyons and valleys. The Colorado Rockfall Simulation Program (CRSP) was developed by the Colorado DOT to provide a reasonable model of falling rock based on a set of slope input parameters. CRSP (which is currently undergoing major updating to a three-dimensional approach, which will be known as CRSP-3D) is widely used in the North American transportation industry and has proven useful in estimating rock velocity, kinetic energy, bounce height, and runout distance. This information is critical in determining the most appropriate type and installation of rockfall protection measures (Andrew 1992).

Mesh and Cable Nets

Mesh and cable nets are used to control rockfall in two ways: They either hold the rocks behind the mesh/net or direct them to a catchment area at the bottom of the slope. They also work to control erosion. Mesh and nets can be both unsecured (attached to anchors at the top of the mesh or net only) or secured at both top and bottom. The most common configurations are *draped mesh/nets* (also known as *drapery systems*) and *anchored mesh/nets.*

Draped Mesh/Nets (Drapery Systems)

A drapery system consists of wire mesh or cable netting that's suspended by anchors and hung over a near-vertical slope (drapery systems can be used on slopes ranging from 35º to overhanging, although rock slopes between 60º and 80º are the most common site). Drapery systems are typically used on slopes between 15 and 45 m (50 and 150 ft) high, but they have been used successfully on slopes up to 120 m (400 ft) high. They can be used on both uniform and highly irregular slopes, and are not limited to a distinct rock/slope material type. These systems are used to contain rockfall occurring beneath the mesh or net and control the descent of detached material as it travels down the slope. They are designed to protect against raveling-type rockfall that involves small-volume slope failures (up to about 7.6 m^3 or 10 yd^3) or blocks up to 1.5 m (5 ft), depending on the strength of the mesh used (Muhunthan et al. 2005), although maintenance considerations may serve to reduce this maximum size.

Drapery systems can be either unsecured or secured. *Unsecured systems* attach the wire mesh only at the top of the slope, allowing rockfall to occur between the mesh and the slope but slowing it as it travels down the slope face shown in Figure 58, a process known as attenuation. These systems also have the advantage of being self-cleaning, as they let the rocks out at the bottom and therefore do not need to be cleared of debris.

Secured drapery systems incorporate breakaway tethers throughout the mesh, which work to hold the mesh closer to the face but release it when impacted by falling rock. Mesh that is secured this way is less likely to pillow and/or create the "bridal veil" appearance in areas with overhanging features. The use of anchors also improves the performance of the system by containing the rockfall closer to the face.

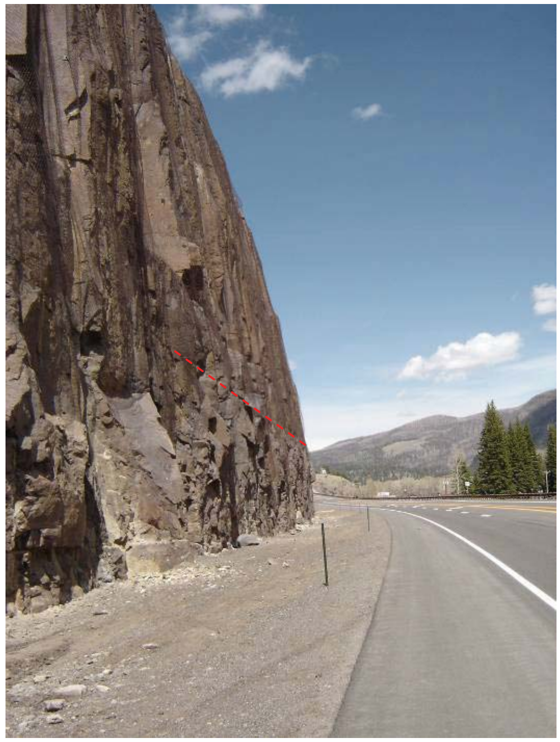


Figure 58. Photo. A rockfall-prone slope draped with unsecured wire mesh. Wolf Creek Pass, Colorado.

If properly designed, drapery systems require little maintenance and generally have a long design life. They can also be visually mitigated so that they're less visible and blend more into the surrounding landscape (see below).

Design and Construction of Drapery Systems:

The first step of the design procedure is estimating the anticipated load that will be transferred to the body of the mesh system. In cold climates, snow loading also should be considered. Muhunthan et al (2005) conducted numerous back calculations on drapery systems and found that wire mesh is capable of withstanding a full transfer of load from approximately 7.6 m^3 (10 yd^3) of rock material or blocks up to 1.5 m (5 ft) equivalent diameter. Rock sizes of 0.6 m (24 in.) are often used as the design limit when considering maintenance requirements.

The mesh or net should cover the entire section of slope that will be affected by rockfall, from the area where rockfall begins to the paved surface of the roadway. In all cases, the upper perimeter of the mesh should be anchored a minimum of 3 to 4 m (15 ft) above the rockfall area or behind the degraded portion of the slope. Figure 59 shows a site where ongoing slope degradation caused failure of a mesh drapery system that was installed too close to the area of degradation.

Along roadways, drapery is usually designed to allow rocks to travel behind the mesh to the base of the slope, where a catchment area has been constructed to prevent the rocks from traveling onto the roadway. The catchment area will need to be cleaned periodically to remove accumulated material. On steeply inclined slopes, the mesh normally terminates approximately

1.5 m (5 ft) from the slope base to keep rocks within the catchment area. In areas of high snowfall, this termination height may need to be increased so that the bottom of the mesh is not pinned to the slope by accumulated snow.

Figure 59. Photo. Erosion can lead to failure in a drapery system if the mesh is not secured sufficiently beyond the area of slope degradation at the top of the slope.

Many types of mesh material have been used in drapery systems, and each is available with several different wire diameters and grid/opening sizes. Most North American DOTs use either double-twist hexagonal wire mesh, high-strength wire mesh, or cable/spiral rope net. The cable and spiral rope net is much stronger than the double-twist wire, but also is also more expensive. High Strength steel wire mesh is relatively new and fills an intermediate role between double twist wire mesh and cable /spiral rope net. In many cases, cable net is combined with wire mesh, a combination that has been particularly effective on slopes with larger rocks and to decrease the rate of erosion of any slope. Table 11 summarizes the current guidelines for the use of mesh drapery systems in North America.

Table 11. Recommended mesh material usage as a function of block size and slope angle (modified from Muhunthan et al. 2005).

Mesh Material	Block Size	Slope Angle
Double-twist hexagonal mesh	≤ 0.6 – 0.9 m (2 – 3 ft)	50º - vertical
Cable/spiral rope net	≤ 1.2 – 1.5 m (4 – 5 ft)	35º - overhanging

Appropriate anchor design for the drapery system should consider the weight of the system and additional dynamic loading caused by rockfall and accumulation of snow. For more detailed information on anchor load vs. anchor spacing design for various mesh and net systems, see Muhunthan et al. (2005).

Several designs have been implemented to mitigate the aesthetic concerns of drapery systems, particularly in context sensitive areas. They include:

- Limiting the coverage area,
- Securing the drapery more closely to the slope,
- Promoting revegetation, and
- Coloring system components.

On some slopes, engineers can limit the area covered by the drapery—generally at the bottom of the slope—and still provide adequate rockfall protection. However, eliminating the mesh more than 1.5 m (5 ft) from the slope base may require a wider and/or deeper catchment area to prevent rocks from entering the road.

Anchoring the mesh more tightly to the slope reduces the gap between the slope and the mesh, making the mesh less visible when viewed from the side. On moderately dipping slopes, increased mesh contact helps to increase the normal force on the slope rock face reducing the frequency of rockfall. Increasing mesh contact also reduces erosion and allows for revegetation of soft bedrock slopes. However, on near-vertical to overhanging slopes, increasing mesh contact can cause accumulation of material and increased static loads on the mesh. In these cases, engineers can use breakaway systems, which pull the mesh closer to the slope face yet allow the restraining elements to fail under larger rockfall events. These systems typically use wire (e.g., No. 9 AWG) to anchor the draped mesh, which will yield on impact before the body of the mesh ruptures.

Because of the lack of topsoil on many rock slopes, revegetation of constructed slopes can be difficult. Placement of erosion control fabric behind the mesh can provide an area for small shrubs and grasses to become established.

Many state DOTs routinely treat the mesh in their drapery systems with colored PVC or powder coating that can help it blend with the surrounding rock. Although these products are available in a range of earth tones, the darker colors (particularly dark brown) have proven to be the most effective for reducing the visual impact of drapery systems. Figure 60 shows an example of a mesh that was treated with a dark brown coating to help it blend into the natural setting. In this photo, the rock cut in the distance was also treated with rock staining, while the lighter-colored cut slope in the foreground was not treated. Note how the mesh is more visible in the area that was not treated with the rock staining. Combining mesh coloring with other visual enhancements such as revegetation, rock staining, or increased mesh-to-rock contact is an effective way to reduce the visual impact of the mesh.

Figure 60. Photo. Rock slope treated with colored draped rockfall mesh.

Figure 61 shows a slope that was mitigated with draped wire mesh that was left untreated. Although this installation has been an effective rockfall mitigation measure, its visual impacts are significant: The mesh retains its shiny galvanized finish and, because the drapery was not secured in close contact with the slope face, it has a distinct "bridal veil" effect.

Figure 61. Photo. A drapery system that was not visually mitigated.

Before a drapery system can be installed, the slope must be thoroughly scaled and the anchors installed. Unless the drapes will be rolled out from the top of the slope, a staging area at the slope base will be required to prepare the drapes for installation. For large installations or for high slopes, a helicopter is usually the fastest and most cost-effective way to get the drapery to the installation point. However, helicopter placement requires an emergency landing area as part of the staging operations.

Equipment required for installing a drapery system includes the following:

- Drill for installation of mesh anchors. A hand-held drill with a man lift or a track drill is typically used for the anchor installation.
- Crane or helicopter to place the wire mesh. The hourly rate of a crane is less than that of a helicopter, but excessive slope heights, large mesh quantities, and difficult access often make it faster and less costly to use a helicopter.

The majority of maintenance on a drapery system consists of removing trapped material in order to prevent overloading of the wire mesh. Limited vegetation growth within the mesh area does not reduce the effectiveness of the mesh, but large shrubs or trees can cause problems and should be removed. Toppling of trees can cause both global and localized failure.

Anchored Mesh/Nets

Anchored systems consist of wire mesh or cable net that is anchored to the rock face in either a grid pattern across the entire face or via a row of anchors along the upper and side perimeters of the wire mesh, see Figures 62 and 63. They work to inhibit erosion, contain rockfall, and direct rocks to the catchment area at the bottom of the slope. Anchored mesh differs from secured drapery in a few important ways: While secured drapery systems are meant to contain small rocks or channel larger rocks safely down a slope, an anchored mesh/cable net system is intended to reinforce a slope face and, if possible, prevent rocks from ever detaching and falling. The mesh or cable net used in an anchored system is vastly stronger than that used for a drapery, and its fastening method consists of closely spaced rock bolts with plates that anchor the mesh to the slope. These anchors are not designed to break away, but instead to provide a more robust and permanent approach to stabilizing the slope.

Design and Construction of Anchored Mesh Systems:

In an anchored mesh system, rock bolts are typically used to attach the mesh or net to the slope; the mesh is stretched between the bolts to increase its contact with the slope, which adds a normal force to protruding blocks, thus increasing slope stability. Anchored systems are more expensive than unsecured draped systems and, if not designed and constructed correctly, may require periodic maintenance to remove accumulated material from behind the wire mesh.

Figure 62. Photo. An anchored Tecco mesh system secured by a grid of rock bolts, US 299 in Northern California.

Figure 63. Photo. A detail of the anchors used to secure the mesh system shown above.

In some cases, the visual impact of mesh or net systems has made them unsuitable for use on an otherwise natural-looking slope. Engineers have used the methods discussed above for drapery systems to mitigate these impacts.

Barriers

Barriers provide rockfall protection by stopping falling rocks: They absorb the kinetic energy of the rocks, block their trajectory, and detain them before they reach the highway. Barriers can be *earthen barriers*, *concrete barriers*, *structural walls*, *flexible barriers*, and *attenuators*. They can be used in conjunction with ditches when space does not allow for a ditch big enough to provide adequate protection on its own.

Barriers can sustain large kinetic energies and repeated rockfall impacts. Generally speaking, they are not as aesthetically pleasing as other protective measures, although proper placement and color enhancements can help blend them into the surrounding area. Barriers and fences must be placed in accessible areas to facilitate periodic maintenance and removal of accumulated material. Figure 64 shows an example of an installation where the body of a cable net fence was colored with a tan PVC coating and installed above the roadway, thus reducing its visual impact.

Figure 64. Photo. Installation of a flexible rockfall barrier on Guanella Pass, Colorado.

Earthen Barriers

Earthen barriers provide a steepened foreslope, which can provide considerable energy dissipation due to its large mass and loose surface characteristics and therefore improve the effectiveness of an adjacent catchment area. They can be berms or walls made of mechanically stabilized earth (MSE).

Earthen Berms:

Berms are constructed from natural rocks and soil as shown in Figure 65. They hold up very well to repeated impacts, and any damage that occurs to the berm can be repaired with an excavator or backhoe.

Figure 65. Photo. A conventional earthen berm can protect a highway from rockfall with low bounce height and low rotational energy.

Mechanically Stabilized Earth (MSE) Walls:

MSE walls are reinforced, engineered earthen walls designed to withstand medium- to high-impact energies (they are structurally much stronger and more cohesive as a unit that a conventional earthen berm). An MSE wall is constructed by layering horizontal mats of structural material (e.g., geo-fabric or wire grids) between coarse soil layers approximately 600 mm (24 in) thick to form a barrier up to 4 m (13 ft) high illustrated in Figure 66.

Testing has shown that MSE walls are highly effective in sustaining high kinetic energies and repeated rockfall impacts. In many cases, timber facing is installed on the impact side of the barrier to dissipate the rocks’ energy, while the road-side facing can feature full-height concrete panels, timbers, or vegetation.

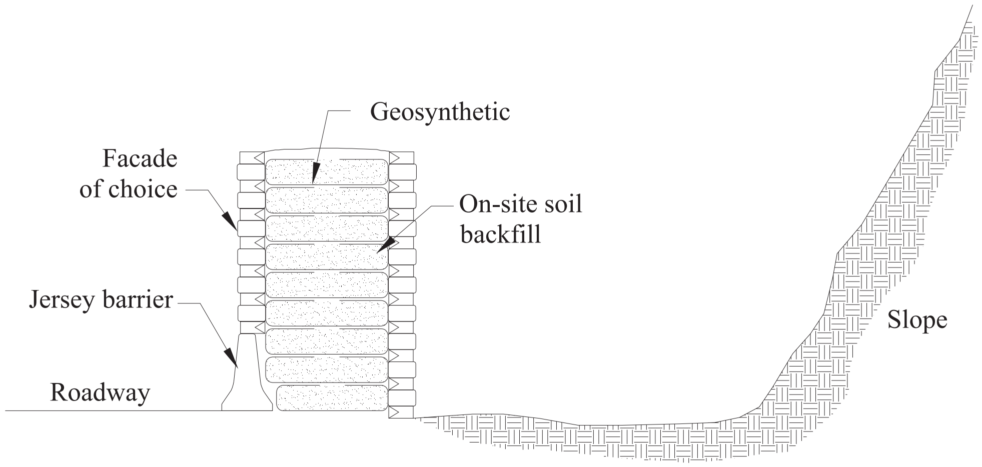


Figure 66. Illustration. A MSE wall design (modified from Transportation Research Board 1996).

Concrete Barriers

Concrete barriers, shown in Figure 67, commonly known as Jersey barriers, are designed to block low-energy impacts (generally less than 80 kJ or 30 ft-tons).

Due to their rigidity, Jersey barriers will shatter with high-energy impacts. They are relatively inexpensive and easy to obtain, which contributes to their widespread use. Concrete barriers are not aesthetically attractive, and therefore rarely used in context sensitive areas unless as a temporary barrier.

Concrete barriers are normally placed adjacent to the roadway. Facing materials and colors that fit within the project setting can be incorporated on the traffic side of these barriers to help them blend into the landscape. Installation of simple concrete barriers requires a fork lift, backhoe, or excavator to place the barriers.

Structural Walls

Structural walls are rigid structures, such as reinforced concrete walls, that are generally placed adjacent to the roadway. As with concrete barriers, structural walls can be fitted with appropriately colored and textured facing materials, which can help them fit within the existing landscape.

Equipment required for structural walls varies depending on the type of wall and materials used. All structural walls require a catchment area, and in many cases an excavator can be used to excavate the base of the barrier (in some areas, blasting will be required).

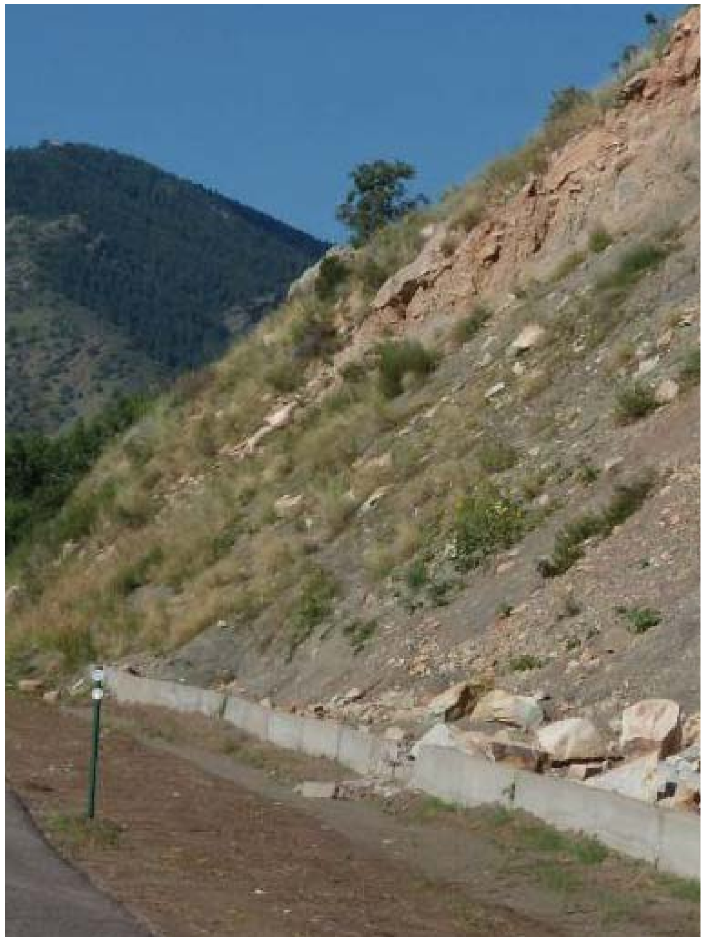


Figure 67. Photo. Concrete barriers used as a rockfall protection measure. Notice the damage caused by a large rock impact.

Flexible Barriers

Rockfall fences are designed as a flexible barrier, absorbing energy through deformation of the fence material and braking elements as shown in Figure 68. The fencing material is most often deformable cables and/or mesh, the most common types of which are woven wire-rope mesh net or interlocking ring nets.

Testing has shown that interlocking rings can provide the greatest deformation and energy absorption. The mesh is usually (though not always) supported by a series of steel beam posts anchored to a foundation with grouted bolts. The foundation usually consists of a concrete cap secured to rock bolts or a large concrete mass. The braking elements are incorporated into up-slope anchor ropes, which use friction brakes that are activated during high-energy events to absorb energy and provide additional support to the fence. Some of the largest fences are able to withstand impact energies up to 5000 kJ (1,844 ft-tons).

Figure 68. Photo. Example of a ring-net flexible barrier.

Fences require a variety of equipment for installation. The fence posts and brake cables are anchored into the ground using grouted anchors. Hand-held drills can be used to drill the anchor holes, and a pump is used to place the grout. Steel H-beams (e.g., W8x48, as shown in Figure 69) are typically used as fence posts to support the fence. A substantial amount of woven steel cable is used to construct the braking system, to attach the net to the fence, and to attach sections of fence to one another.

In areas with difficult access, helicopter support may be needed, which will present additional cost. Maintenance of fences involves periodic cleaning to remove accumulated rocks and debris.

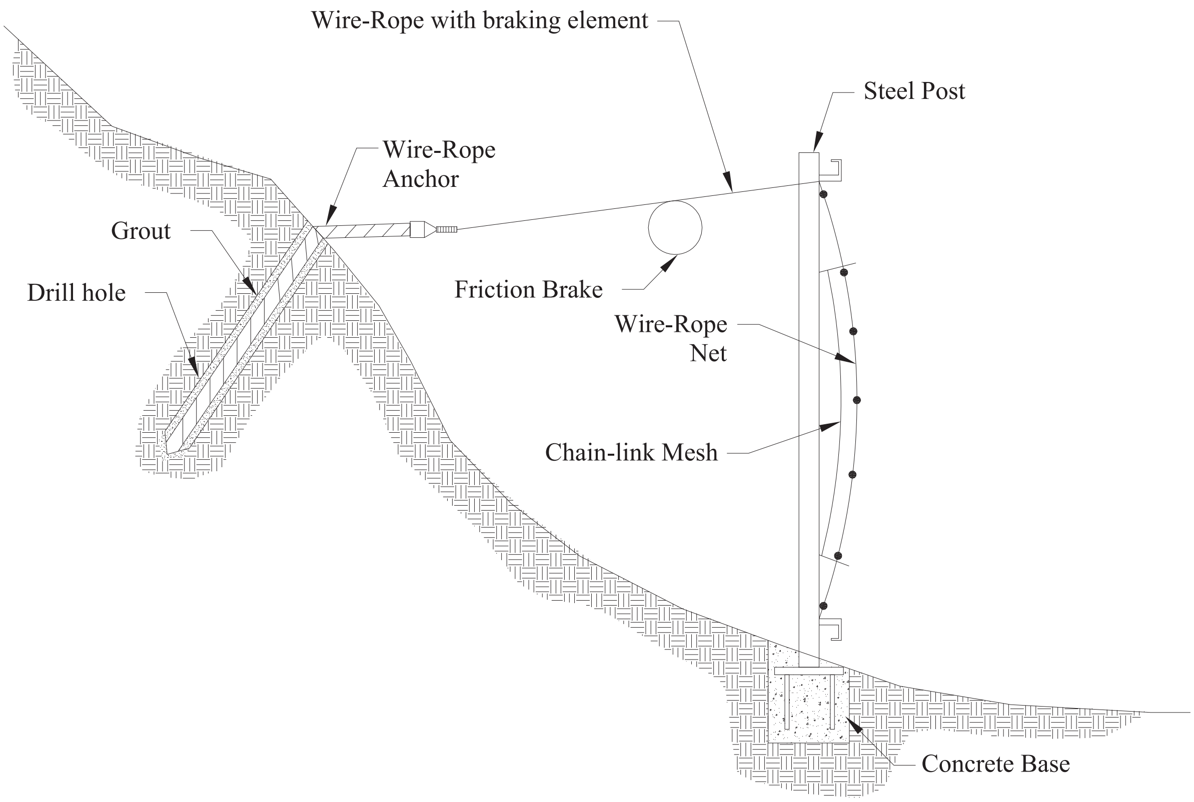


Figure 69. Illustration. Design of a typical rockfall fence (modified from Transportation Research Board 1996).

Attenuators

Attenuators are a combination of traditional fencing and drapery systems. Unlike traditional rockfall fences, they are not fixed to a bottom support wire rope but include a draped section that lays on-slope, below the main body of the system as shown in Figure 70. This design is superior to other types of rockfall protection in several ways:

- The system is able to withstand much greater energies because it is designed to attenuate the energy of the rockfall, not arrest the rock.
- The system slows and redirects the rock so that it can be captured in a catchment area.
- In areas of snow avalanches or debris flows, the flow can travel under the system without causing damage.
- Rocks do not accumulate in the system but are allowed to pass through, resulting in less maintenance.

Figure 70. Photo. An attenuator combines a standard fence with a draping system. Georgetown, Colorado.

Figure 70 shows a slope that runs along I-70 near Georgetown, Colorado, an area that is known to produce very high-energy rockfalls. A series of attenuators were installed to control the rockfall and ensure that rocks traveling down the slope would be deposited in a catchment area adjacent to the highway. Many of the attenuators have been placed high on the slope, above the average viewshed of motorists.

Barrier Design

The first step in designing a rockfall barrier of any kind is evaluating the behavior of the typical rockfall event. Barriers should be placed in the most likely rockfall path. This can be found by talking with maintenance personnel or by observing rockfall scarring on the slope (tree scars, rockfall chutes, etc). Once the rockfall path has been found, the barrier should be placed where the rockfall bounce heights and average kinetic energy are at their lowest, to maximize catchment.

As discussed previously, computer models have proven to be a useful tool in evaluating rockfall behavior. The model will guide the designer on the most effective location of the fence. No protection system will be able to stop 100% of the rockfall, so systems are designed to stop an approximate percentage of the rocks that fall. Barriers and fences used today are generally designed for retentions of greater than 85%, but each slope is different and a balance must be found between cost of mitigation and level of safety.

Correct placement on the slope is essential in managing the height and capacity of the barrier, which in turn will reduce the cost and visual impact of the system. The placement of barriers can also be key in helping to mask their presence. They can be placed high on the slope or out of view from passing motorists, although engineers must keep in mind that the area must be accessible for periodic maintenance and removal of accumulated material.

Site selection will have the largest effect on the means and methods used by a contractor to construct a barrier or fence. Barriers located in difficult access areas will require experts in installation. For sites with difficult founding conditions, foundation elements using rock dowels and/or small-diameter piles (micropiles) for support may be required. Barriers located adjacent to the roadway typically use more conventional construction techniques.

Catchment Areas

Catchment areas are sections of flat or negatively sloped ground used to dissipate rockfall energy and to collect rocks and other debris that have detached from the slope. Catchment areas can be ditches—trenches dug along the foot of a slope—or hybrid ditches, which combine a ditch with a barrier (typically a wall or berm).

Ditches

Ditches have been used for many years to stop rockfall before it reaches the road. In most cases, they are located along the side of the road, but in cases where rockfall source areas are not adjacent to a roadway ditches have been constructed upslope from the travel corridor. In all cases, the ditch must be accessible to the machinery needed to remove accumulated rockfall material. Because ditches require additional right-of-way, constructing ditch catchment areas along existing roadways can be cost prohibitive if a substantial excavation is required. Ditches are aesthetically appealing because they are located below the road grade and out of view from the passing motorist. Moreover, they do not require imported material that may appear foreign to the setting.

Ditches are a very effective rockfall protection measure. They are the most used and probably the most aesthetically acceptable protective measure because they do not obstruct the motorists' view of the surrounding area. In steep terrain, however, the rock slope cut height can be excessive when a wider catchment area is constructed. The designer should always bear in mind that increasing the catchment width could potentially increase the height of the slope significantly, thereby impacting its overall stability.

Current ditch design criteria assume the rock cut is fairly uniform in slope. Natural rock slopes or slopes with incorporated warping may have undulations that cause rockfall launching features, resulting in the rocks to traveling further from the slope base than anticipated. Rockfall modeling programs such as the new Colorado Rockfall Simulation Program (CRSP-3D) can be used to estimate the rockfall parameters and develop a basis for ditch design. In all ditch designs, the ditch must remain accessible to machinery for periodic removal of accumulated material.

Ditch Design:

Ritchie was the first to research the effectiveness of ditches, and he produced a ditch design now known as the "Ritchie Ditch Criteria" in 1963. In 2002, the Oregon Department of Transportation (ODOT) produced the "Rockfall Catchment Area Design Guide," which modified the Ritchie criteria to make them more compatible with today's highway design standards. Both ditch designs are currently being used, although the Ritchie guidelines are not generally used as a design method because they do not comply with the current AASHTO design regulations.

To upgrade the design criteria and address limitations of the Ritchie Criteria, ODOT conducted an in depth study into ditch design. They developed a collection of design charts that gives ditch widths for slope heights of 12.2 m, 15.2 m, 18.3 m, 21.3 m and 24.4 m (40 ft, 50 ft, 60 ft, 70 ft and 80 ft) with slope angles ranging from vertical through 1V:1H. ODOT's guidelines also include approximate percent of rocks retained (30 to 99%) and catchment area grades (4H:1V, 6H:1V, and Flat). The slopes used in this study were all smooth presplit slopes, meaning the ditch width may have to be adjusted for natural slopes or for slopes with incorporated ledges.

A sample cross-section of slope using Oregon ditch design guidelines is shown in Figure 71.

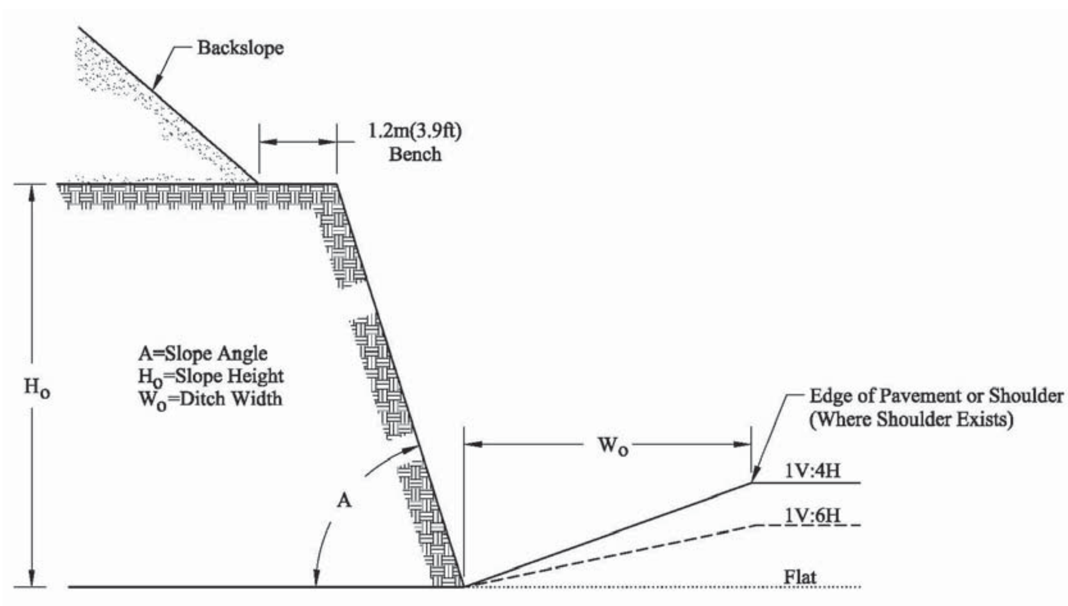


Figure 71. Illustration. Cross-section of a typical Oregon ditch design (modified from Pierson, Gullixson, and Chassie 2002).

Ditch construction generally requires standard earth moving equipment, such as a grader, backhoe, or excavator. An exception is in areas where the ditch is to be constructed into rock; in those cases, blasting may be required.

Hybrid Ditches

For slopes with heights greater than those provided in the ODOT criteria (24 m, or 79 ft) and for slopes with potential launching features, a barrier can be constructed on the roadway side of the ditch as Figure 72 shows. Numerous types of barriers can be used for hybrid ditches, including MSE walls, concrete (Jersey) barriers, and earthen berms. Hybrid barriers increase the effectiveness of the catchment ditch without increasing its required width.

Figure 72. Photo. A hybrid ditch design.

Hybrid ditch construction requires equipment similar to that used in conventional ditch construction, plus equipment necessary for constructing the additional hybrid element.

CHAPTER 7 – ROCKFALL MITIGATION SELECTION

Selecting effective rock slope stabilization and rockfall protection measures (collectively referred to as rockfall mitigation) is critical for protecting the public and structures from falling rock. Population growth, past practices, and the deterioration of older constructed rock slopes has brought more attention to the need to mitigate existing rockfall hazards. In addition, there are many naturally occurring rockfall areas that have become hazardous because of the presence of roads or structures.

CONSIDERATIONS

Mitigation selection should be based on several things:

- The degree of security or reliability necessary for a site.
- The constructability of the potential options.
- The service life required.
- The suitability of potential mitigation options with respect to the characteristics of the specific rock mass.
- Aesthetics.
- The cost effectiveness.

Security/Reliability

The reliability of rockfall mitigation is related to the potential or probability for damage or harm in the event of a rockfall. The likelihood of a rockfall event causing immitigable damage would determine the degree of increased security or level of hazard reduction. If the prospects of a rock falling do not potentially cause a hazard or damage, then it is likely that mitigation is unnecessary.

Constructability

The constructability of the mitigation plays a large role in its selection, and there are many facets to this issue. For example, many sites along highways have unique space and right-of-way characteristics. In these cases, typical issues may include the difficulty of installing a wide, double-sided, mechanically stabilized earth (MSE) barrier, trimming and scaling of rocks located above residences, or limited access to slopes for installing reinforcement or netting.

Service Life

The duration that rockfall mitigation is expected to be effective for (service life), can be related to how fast the rock erodes and how fractured the rock is, as well as the most economical type of mitigation for the site. For example, rock bolts placed in highly fractured shale may last only three to five years and mitigate only large blocks. Maintenance costs on these bolts would be expected to be high, and the rock face would probably need additional reinforcement on a regular basis, but that cost might still be lower than reshaping the slope. However, if a client prefers a long-term, low-maintenance solution, then a different mitigation solution would be selected.

Suitability

The suitability of rockfall mitigation is determined by several factors, and should be determined based on a thorough analysis of the rockfall hazard and slope characteristics, which include the presence of weak materials, discontinuities adverse to the slope strike and angle, block size, and the presence of tension cracks and/or groundwater. The site should also be evaluated to determine the potential effects of rockfall and the desired effects of the selected mitigation.

Aesthetics

Another consideration in rockfall mitigation selection is the aesthetic effect of the mitigation method, as well as its potential impact on the natural scenery and historic setting and any native wildlife. When developing mitigation alternatives, the measures should be constructed in such a way as to minimize impacts to the setting while also reducing the potential rockfall hazard.

Cost Effectiveness

The effectiveness of mitigation relative to the initial and maintenance costs plays as substantial role in its selection. More often than not, cost is the primary factor in selecting the type of rockfall mitigation. Cost effectiveness can be difficult to measure in advance of installation and is related to the probability of how much of the potential significant damage will be mitigated.

COMPARISON OF MITIGATION METHODS

Table 12 shows a qualitative comparison of different stabilization and protection measures. This table is intended to be used as a quick reference. Roadway layout and rock characteristics will have a large influence on each of the criteria and may alter the range of values for each.

MAINTENANCE CONCERNS

Following construction, maintenance personnel should perform daily patrols of rockfall-prone areas to keep the travel way clear of hazardous debris. Patrol frequency can range from a few times per shift during low-frequency periods to 24 hours per day, seven days a week during high-rockfall periods. Seasonal occurrences of freeze/thaw or heavy precipitation as well as wild fires and other events, all can increase rockfall potential.

Managing Rockfall Incidents

Documentation

Rockfall events should be documented to establish areas of increased rockfall activity and help with future mitigation selection and design. Information that should be included in the rockfall documentation includes:

- date and location of rockfall event (including a mile marker or other location description);
- size and number of rocks involved;
- rockfall source area, if known;
- rockfall stopping point in relation to the travel corridor; and
- possible triggering mechanism(s).

Table 12. Properties of different rockfall and slope stability mitigation measures.

MITIGATION MEASURE	CRITERIA							
	Complexity	Effectiveness	Durability	Constructability/ Special Expertise	Road Closure/ Traffic Restrictions	Aesthetic Impacts	Cost	Maintenance Requirements
STABILIZATION METHODS								
Excavation								
Hand/Mechanical Scaling	L-M	L-H	L-M	M	Y	L	L-M	L-M
Trim Blasting	L-H	L-H	M-H	L-H	Y	L-H	L-H	L-M
Reinforcement								
Rock Bolts	M-H	M-H	H	H	P	L	M-H	L
Dowels	M	M-H	H	H	P	L	M-H	L
Shear Pins	M	M	M	M	P	M	M	L
Shotcrete	M-H	M-H	M-H	H	P	M-H	M-H	L
Injectable Resin/Epoxy	M-H	M-H	M-H	H	P	L	M-H	L
Wire Mesh (anchored)	M	M	M	M	P	H	L-H	M-H
Drainage								
Weep Drains	L	L-H	M	L	P	L	L	H
PROTECTION METHODS								
Mesh/Cable Nets								
Draped Mesh	L-M	M-H	M-H	M	Y	M-H	L	L-H
Suspended Systems	L-M	M-H	M-H	M	Y	M-H	L-M	L-M
Barriers and Fences								
Earthen Berms	L	M-H	H	L	P	L-M	L	M-H
Concrete Barriers	L	M	L-M	L	P	M-H	L	M-H
Structural Walls	L-M	M-H	M	M	P	M	L-M	M-H
Fencing	M-H	M-H	M-H	M	Y	M-H	M	M-H
Attenuators	M-H	M-H	M-H	M	Y	M-H	M	M
Ditches								
Ritchie/ODOT	L	M-H	H	L	P	L-M	L-H	H

L = low, M = medium, H = high, VH = very high, N = no, Y = yes, P = possibly

Action Plan

In all areas where rockfall occurs, a maintenance team should have a set action plan in case of a large rockfall event. In high-risk areas, the plan must be well defined and routinely practiced by maintenance personnel. The action plan should include:

- roles and responsibilities of early responders;
- contact information for emergency and traffic control personnel;
- site-assessment procedure for qualified personnel, including slope stability evaluation and possible remedial measures; and
- location and/or procurement procedures for all machinery required for rockfall removal.

Maintenance Procedures

All cut slopes and their attendant stabilization and protection systems must be monitored for damage, weathering, stability, and rock accumulation. Periodic maintenance will be needed to uphold safety. In previous chapters, maintenance issues and possible rockfall-induced damage were discussed with each mitigation method covered. Table 13 summarizes common maintenance procedures for each of these measures.

Table 13. Maintenance procedures for mitigation measures.

MAINTAINED ITEM	MAINTENANCE PROCEDURE
STABILIZATION MEASURES	
Cut Slope	Periodic scaling (every 2 to 10 years) to remove loosened and/or unstable material.
Rock Bolts	Check to ensure hex nuts and bearing plates are flush with rock face. Tighten any loosened hex nuts to appropriate load.
Rock Dowels	If bolt extends from slope face, end may be cut for aesthetics. If grout adhesion has failed or slope surface has eroded (i.e., slope extends past dowel end), conduct stability analysis on slope.
Shear Pins	Ensure bending or shearing of pins has not occurred from block movement. If it has, shear pins may need to be re-installed or block removed.
Shotcrete	If shotcrete is cracked or separated from rock face, remove and reapply. Clear any drains that are plugged or blocked with obstructions.
Injectable Resin/Epoxy	Maintenance of resin/epoxy is not needed after injection. If rockfall or stability problems persist after injection, additional stabilization or protection measures may be needed.
Wire Mesh (Anchored)	Remove any accumulated material suspended in mesh or at slope base. If mesh is damaged, repair or replace damaged section(s).
Weep Drains	Clear drains periodically; remove any obstructions.
PROTECTION MEASURES	
Draped Mesh/Suspended Mesh	Remove any accumulated material suspended in mesh or at slope base. If mesh is damaged, repair or replace damaged section(s).
Earthen Berms	Clear accumulated material periodically. Repair any damaged section(s) of berm.
Concrete Barriers	Clear accumulated material periodically. Replace any damaged section(s) of barrier.
Structural Walls	Clear accumulated material periodically. Repair damaged section(s) of wall.
Fencing/Hybrid Fencing	Clear accumulated material. Check fence, cables, braking devices, and posts for damage and repair/replace any damaged part(s).
Ditches	Clear accumulated material periodically.

CHAPTER 8 – CONCLUSIONS

Developing context sensitive solutions for rock slope design and rockfall mitigation is a stepwise process that must involve all stakeholders early in the scoping and design process. Excavation and mitigation design must take into account the area's scenic concerns, historical significance, and wildlife corridors, as well as the safety, cost, and capacity of its roadways. Design specifications should allow the project staff flexibility to modify the slope geometry and engineer mitigation method(s) that fit regional characteristics, roadway theme, and geological features. Context sensitive projects require frequent communication between the contractor and the project owner to ensure the final product meets all stakeholders' interests.

One of the most important considerations in a context sensitive transportation project is developing a slope angle and configuration that fits within the context of the project setting. The cut slope is typically visible to the motorists for a long distance as they move through the corridor. Proper slope angle with respect to kinematics will have a large effect of the long-term stability of the cut.

Rockfall mitigation—incorporating both stabilization and protective measures—is another key concern, and can have tremendous impact on roadway safety. Stabilization measures reduce the frequency of rockfall by either removing the source of the rockfall or increasing the stability of the rock face by increasing the resisting forces and/or decreasing the driving forces. Stabilization measures are normally installed within the rock mass and are much less visible than protection measures. Protection measures accept the reality that rockfall will occur and act to stop, divert, or control it. These practices are installed external to the rock mass and therefore are much more visible.

Maintenance for rock cuts, stabilization, and protective measures is essential to maintain a level of safety required for the roadway. Continual weathering and erosion causes ever-increasing rockfall potential and can decrease the effectiveness of stabilization methods. Protective structures need to be monitored for damage, and accumulated material removed, to ensure their proper functioning.

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