Rock Cut Slopes

This module presents the standard of practice for the investigation, design, and reporting of rock cut slopes. Rock cut slope design considers the structural characteristics and strength properties of rock masses to develop designs that address constructability and long-term performance.

The primary goal of a rock cut slope evaluation and design is to determine the steepest stable cut slope angle for a continuous slope, without intermediate slope benches. The design accounts for cut slope performance and safety while optimizing excavation quantities. Slope stabilization and rockfall protective measures may be required to minimize localized or small-scale instabilities within the overall cut. Environmental requirements, right-of-way impacts, and other project goals may at times also warrant slope stabilization measures. The investigation and analyses also provide excavation characteristics (blasting, ripping) and earthwork factors for material disposal or reuse. Three primary references used to develop this module are “Rock Slopes” by Manfakh et. al. 1998 (40), “Rock Slope Engineering” by Wyllie and Mah 4th Edition 2004 (51), and “Rock Slope Engineering” by Hoek and Bray 1980 (34).

In addition to standard site reconnaissance and geotechnical investigation requirements, rock cut slope design relies heavily upon surface mapping, geomaterial identification, and discontinuity logging. Logging rock structure discontinuities (fracture/joint patterns) and their condition in boreholes and mapping them on surface outcrops is essential to rock cut slope design, as discontinuities strongly influence rock slope stability. Assessment of groundwater conditions in the rock discontinuities, as is true of any slope, is also critical to the assessment of stability (01, 28, 32, 49, and 40). “Rock Slopes” (40) presents an overview of design in Chapter 1 on pages 1-1 to 1-3.

Context sensitive designs are key to developing facilities that fit within the engineered setting, preserving scenic, aesthetic, historic, and environmental resources while maintaining motorist safety and mobility. Developing context sensitive solutions for rock slope design is a stepwise process that should involve all stakeholders early in the scoping and design process. Excavation and mitigation design should consider 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.

Investigation

Refer to the *Geotechnical Investigations* module for general instructions on performing the planning-phase site investigation (e.g., literature review, site visit) and the design-phase site investigation (e.g., site visit, selection of investigative methods, locations, and depths).

Field Mapping

For widening projects with existing cuts, reviewing the performance of existing slopes (both cuts and natural) in the area or region must be performed. For new alignments, field observations of naturally formed cuts in drainages or along the ocean and cuts outside the State right-of-way can provide valuable information where cuts are proposed.

The areas should be mapped on both the local and regional level. Geologic maps on a wide variety of scales are available from the USGS, CGS, local county and government entities and private organizations. The Landslide module should be referenced as appropriate. “Rock Slopes” (40) presents a good overview of planning an investigation program in Chapter 2 and in Appendix 2.

Collect the following information:

- Slope length (both horizontal and vertical): physically measure with tape, range finder, or pace.
- Slope Ratio: physically measure with Clinometer, Brunton or Clar Compass.
- Slope surface: smooth, planar, undulatory, and blocky; if undulatory or blocky, note the difference in height from the peaks to the valleys.
- Describe lithology of the soil and/or rock.
- Estimate or physically measure native slope ratios above and below cuts, as well as on nearby slopes of similar geology. Note presence of boulders, including average size, maximum size, shape, and rock type, as well as their location (top of slope, on slope (embedded or loose), at base of slope).
- Local Stability - Note erosion features, rockfalls, slumps, rills, washes etc.
- Global Stability - Note presence of landslides and rockslides.
- Note moisture features, such as seeps, springs, wet areas, and their likely causes.
- Assess condition of existing slopes.
- Describe vegetation.

Where applicable rock structure data should be collected and recorded. In addition to basic field observations a scan line analysis should be performed on open cut slopes or natural slopes. This information can be used in estimating the Rock Mass Quality (Q) and/ the Geological Strength Index (GSI). An organized table should be developed which includes the following information of the nature of the rock discontinuities. “Rock Slopes”

(40) presents a thorough description of the following geological terms in Chapter 2, Section 2.3.

- Location
- Station
- Dip/Dip Direction
- Type of Discontinuity (bedding, jointing, fractures, faulting, etc.)
- Persistence
- Spacing
- Filling
- Asperities
- Roughness
- Rock Quality Designation (RQD)
- Discontinuity Sets
- Discontinuity Roughness
- Discontinuity Alteration
- Discontinuity Presence of water
- Weakness Zones intersecting the excavation

Existing Roadway Conditions

- Number of lanes.
- Lane width.
- Paved shoulder width and unpaved shoulder width, and slope ratio of both.
- Catchment Area (width of roadway between the base of the slope and the edge of traveled way available for rock and debris containment) and back slope ratio.
- Observations of pavement condition, location of cracking, settlement, patching. Make educated guess as to why pavement is in the condition it is in.

Existing man-made structures

- Walls, foundations, building types, culverts, under-crossing, utilities etc.
- Note general conditions of each structure.
- Note if roadway work might impact the structure.

Provide notes on additional geologic investigations that may need to be performed to adequately characterize the site, ie: additional boring locations, geophysical studies, etc.

- Field drawings
  - Develop a scaled field drawing of the area of concern.
  - Develop one or more typical cross sections of the area of concern.
  - Develop cross section with initial mitigation approach if appropriate.
- Photographs of area of concern
  - Photos of problem area (direct/overall).
  - Photos of main features or any other important feature inside or outside of the area.

Subsurface Investigation

Determining the nature of the subsurface material provides valuable information for cut slope design. Two methods to obtain subsurface data which are readily available are drilling subsurface borings both vertically and horizontally and performing geophysical studies. Please also refer to the “Caltrans Soil and Rock Logging” manual (13) and reference (23).

Geophysical Studies

Seismic refraction studies are commonly used to determine rock structure and excavation characteristics, i.e., rippability and earthwork (grading) factors. Some references are provided. These studies should be combined with field mapping to refine estimates of rippability and grading factor. Seismic data may also be used to estimate varying rock quality and degree of weathering with depth when combined with nearby existing road cut observations, subsurface borings and experience. Acoustic televiewer, optical televiewer, and sonic and density downhole logs in a subsurface boring can be useful tools to evaluate the mechanical properties of the rock (03, 12, 14, 19, 32, 44, 45 and 46).

Borings

Coring can be obtained by various techniques and is very valuable. Oriented core techniques, optical televiewer and acoustic televiewer downhole logging are valuable in determining the orientation of the rock structure at depth. General coring is valuable in determining the characteristics of the geomaterials at depth and the changes with depth from the surface. This is especially valuable on new alignment projects where existing cuts do not exist. The geologist/engineer should assess the value of new coring versus the information already available from exposures in existing man-made and natural cuts, as well as existing outcrops, and weigh that with support cost and risk (23). Refer to *Geotechnical Investigations*. Also, FHWA “Subsurface Investigations” (23), Chapter 3, section 3.2 provides a thorough discussion on rock drilling and sampling.

Slope geomorphology/topography

Plan maps and cross sections are required for any project. The plan maps can be acquired by traditional surveying methods and/ or using LIDAR to generate digital terrain maps. Cross sections can be generated from the maps. Cross sections can also be obtained in the field using a tape measure, clinometer or a slope-a-scope. Where this data is not available preliminary slope angles and slope heights can be estimated using topographic maps and cross sections generated from the maps but these should be verified and/or refined based on site (slope) specific data (40).

Rock Strength Properties

The rock suitability for engineering applications is commonly expressed through indices such as the Rock Structure Rating (RSR), Modified Q-Rating System, Rock Mass Rating System (RMR), Unified Rock Classification System (URCS) and the Slope Rock Mass Rating System (SMS). Strength parameters can also be estimated from empirical methods (09, 35, and 49). Refer to the “Geotechnical Laboratory Testing” Section. FHWA “Subsurface Investigations” (23), Chapter 8 for an introduction to laboratory testing for rocks.

Rock Identification/ Rock Classification, (13, 21, 24 and 30).

- Igneous
- Metamorphic
- Sedimentary
- Transitional Materials

Rock Durability

Rock characteristics that affect long-term stability of the slope such as the degree of weathering, potential for weathering (physical, chemical), hardness, erodibility, and slake durability should be considered in the design. Durable rock is considered rock-like in character and relatively unweathered and hard. Nondurable rocks are rock-like in character in place but will weather during the proposed life of the cut to soil like materials. The depth and degree of weathering is dependent on the original material and weathering environment. Indices that might be used that can add to the rock durability quantification are the LA rattler test, and the slake durability test. Moh’s hardness scale is also easily applied and evaluated (04, 13, 24, 29, 30, 35, and 40).

Rock Structure

The presence and characteristics of discontinuities, such as joints, foliations, shears, fractures, and faults are important factors in the stability of rock slopes. The orientation, frequency, persistence, and shear strength of rock discontinuities are measured in the field from existing cuts, rock core and/or outcrops. Projections of the dip and dip direction of the measured discontinuities and discontinuity shear strength are typically presented and evaluated on stereonets to determine if failure is kinematically possible. Hoek and Bray's "Rock Slope Engineering" (34) presents a good overview of the relationship between discontinuities and rock slope stability in Chapter 2.

If outcrops do not occur within the project area, they should be sought on nearby slopes that are composed of the same formation. If nearby outcrops are not available, the "type section" of the formation is the next most useful resource in determining the rock structure.

When rock properties and discontinuities need to be investigated beyond their ground surface expressions or when no outcrops are available, coring exploration is used to obtain rock cores. Non-oriented cores provide information on the density, persistence, roughness, and infilling of discontinuities. Oriented coring exploration or down hole geophysics may be used to obtain information on the dip and dip direction of discontinuities (10, 20, 30, 34 and 41).

Rock Shear Strength

The shear strength developed along potential rupture surfaces within a slope is an important influence on the stability of rock slopes. The rock mass is the term used to describe the material on the rupture surface. Rock mass strength (UCS) and shear strength along discontinuities must be evaluated to determine potential for failures. If field mapping identifies adversely oriented rock structure it will be necessary to determine the shear strength of the discontinuities (friction angle and cohesion). This information can be obtained by laboratory testing or by reviewing published tables of rock strength parameters. Testing is typically performed using a direct shear box developed to accommodate rock core and similar sized rock samples. There are many tables to empirically estimate rock strength parameters that are available in the references. It is also important to determine the rock strength parameters of rock durability and compressive strength. Durability is typically measured with a slake durability test. This test is commonly used to establish weathering characteristics of the rock mass. Compressive strength can be obtained from rock core by performing an unconfined compressive strength test or a point load test on rock core or similarly sized rock samples (07, 24, 34, 40, 51 and 52). "Rock Slopes" (40) presents a good overview of rock strength properties throughout Chapter 3.

Hydrology

Groundwater and surface water conditions must be evaluated for the design and analysis of rock cut slopes. Hydraulic pressure acting within the discontinuities can cause significant destabilization by decreasing the shear strength due to uplift and/or increasing the driving forces acting on the block. Typically, the groundwater level within a slope can be estimated by observing seepages from and around the rock slope. When groundwater conditions are unknown, and groundwater is expected to influence the stability of the slope, groundwater pressures can be measured using piezometers (34, 40 and 51). "Rock Slopes" (40) presents a good overview of groundwater flow, permeability and pressure throughout Chapter 4.

Analysis

Slope Stability Analyses

The stability of hard rock slopes is typically controlled by discontinuities (joint and joint sets) within the rock. Failures tend to occur as discrete blocks. Discontinuities form intersecting planes of weakness. Without discontinuities, rock slopes, even some composed of relatively weak rock could stand hundreds of feet tall without the potential for failure. Kinematic analysis of the discontinuities is performed to determine the potential modes of failure (wedge, planar, toppling, and circular). This is followed by a static slope stability analysis to determine the factor of safety of potential failure modes. The stability of highly weathered to decomposed rock slopes is often not controlled by discontinuities, but rather by a Mohr-Coulomb failure mode (circular) more typical of soil slopes. Limit equilibrium analysis utilizing the shear strength and cohesion of the rock mass is performed to determine the most likely failure surfaces and the global stability in terms of a factor of safety. Highly fractured rock slopes in which there is likely no single or distinct discontinuity surface on which movement will occur should also be analyzed in this fashion. These analyses require a value for φ (friction angle) and c (cohesion), which can be determined with lab tests such as a direct shear test (shear box) or by back analysis of similar slopes that have failed (25, 30, 33, 34, 37, 40 and 51). “Rock Slopes” (40) is a recommended reference for its discussion of the mechanics of rock slope stability (Chapter 1, Section 1.4) and plane (Chapter 5), wedge (Chapter 6), circular (Chapter 7) and toppling (Chapter 7) instabilities.

Kinematic Stability Analyses

A kinematic (limit equilibrium analysis) analysis is the first step in evaluating rock slope stability. Kinematics refers to the motion of bodies without reference to the forces that cause them to move (30). This analysis establishes the possible failure modes of the blocks that comprise the slope. The analysis determines if the orientations (dip and dip direction) of the various discontinuities will interact with the cut slope orientation and

inclination to form discrete blocks with the potential to fail. Failure modes typically fall within one of three categories: plane failure, wedge failure, or toppling failure. The analysis involves a comparison of the orientations of the dominant discontinuity sets with the orientation of the cut slope. Where discrete blocks are formed and where the failure surfaces that bound these blocks dip out of the slope (daylight) at an angle steeper than the shear strength along the discontinuity, failure is kinematically possible. A stereonet is used to perform a discontinuity analysis where the discontinuities and slope data are displayed. After the kinematic analyses have identified the most likely mode(s) of failure, the next step is to perform a stability analysis using the shear strength of discontinuities and groundwater conditions. The objective is to calculate the factor of safety of the slope or individual block being analyzed. Limit equilibrium methods for evaluating slope stability analysis focus on the relative magnitude of the resisting and driving forces. Hoek and Bray “Rock Slope Engineering” (34) presents a good overview of the stereonets, the graphical presentation of the data and kinematic analysis in Chapter 3. More advanced stereonet analyses are presented in Goodman (30) Appendix 5.

Discontinuity Analysis

Interpretation of the geological structure data requires the use of stereographic projections onto stereonets that allow the 3- dimensional orientation of data to be represented and analyzed 2-dimensionally. The most commonly used projections are the equal area net and the polar net. An important limitation of stereographic projections is that they consider only angular relationships between lines and planes, and do not represent the position or size of the feature (30, 34, 41, and 40). Chapter 2 in “Rock Slope Engineering” (51) presents a thorough review of a discontinuity and kinematic analysis. Figure 2.18 on page 38 presents a good graphical presentation of the limits of possible sliding for wedge, planar and toppling failures.

Seismic Considerations

Earthquake shaking can result in failures of cut slopes. The common types of instabilities prone to seismic-induced failure in rock cut slopes are rockfalls, rock slides and debris avalanches. The standard procedure for evaluating the stability of a nonliquefiable slope is the pseudostatic analysis, where, while performing a limit equilibrium analysis, a lateral force is applied to the center of gravity of a mass having a failure potential. The selection of shear strength in slope stability analyses involving seismic loadings should be based on short-term undrained shear strengths. The pseudostatic procedure does not provide an estimate of potential seismic deformations. In many instances, the stability of a slope during an earthquake may drop below a factor of safety of 1 for only a brief period of time during the transient shaking. In this case, a pseudostatic analysis would indicate an unacceptable factor of safety below 1, but the actual deformation of the slope may be minimal and the overall performance acceptable. For this reason, the effects of seismic shaking are not regularly considered in rock cut slope design.

When critical facilities are impacted and an analysis including seismic shaking is required one accepted method of estimating seismic deformations of non-liquefiable slopes is the Newmark Sliding Block Analysis. This method uses the yield acceleration of a slide mass and a seismic time history to estimate the permanent seismic deformation. This seismic analysis of slopes, however, is not used on a routine basis (26, 27, 40 and 51). Chapter 6, Section 6.5 in “Rock Slope Engineering” (51) presents a thorough review of the seismic analysis of rock slopes.

Rebound/Relaxation

When a slope is first excavated or exposed, there is a period of initial response resulting from the elastic rebound, relaxation and/or dilation of the rock mass due to changes in stress induced by the excavation (51). Newly excavated slopes commonly experience small local instabilities as the result of changes of the strain due to the removal of overburden. This condition is not necessarily indicative of long-term instability, but rather local adjustment. Experience has shown this to occur within days or weeks or, in rare instances, months after construction (22, 30, 37, 43 and 51). “Landslides Analysis and Control” (42; p. 196-197), provides an overview of the loss of strength in the rock mass over time and the impact of residual and induced stresses on stability. Another good discussion can be found in “Rock Slope Engineering” (51) in Chapter 13, Section 13.2.

Convex and Concave Slopes

The radius of curvature can have an important effect on slope stability. In slopes that are concave in plan the horizontal tangential stresses tend to be compressive. In slopes that are convex in plan, the horizontal tangential stresses tend to be tensile. Rock is stronger in compression than in tension (34, 37, 43 and 51). “Landslides Analysis and Control” (42, p. 196), provides an overview of the effects of slope geometry on stability.

Factor of Safety (FS)

Typical target design Factor of Safety (FS) values range from 1.3 to 1.5; however, based on engineering judgment, values outside of this range may be appropriate, depending on the circumstances.

The minimum FS to be used in stability analyses for a specific rock slope depends on factors such as:

1. The degree of uncertainty in the stability analysis inputs; the most important being the amount of intact rock, rock mass strength, discontinuity spacing, discontinuity shear strength and groundwater conditions
2. The level of investigation and data collection
3. Costs of constructing the slope to be more stable
4. Costs, risks to the travelling public, risks to the roadway, and other consequences should the slope fail
5. Whether the slope is temporary or permanent

Rock Slope/ Landscape Integration

A major component of context sensitive design is the final appearance of an engineered slope: how the slope 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 techniques, 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 geo-professional and the contractor should strive to develop a slope that is safe, looks natural, and satisfies the interests of all project stakeholders. Factors to consider are slope warping, slope rounding, drainage, catchment ditches, slope angle, slope sculpting, and rock staining (01).

Design

Rock slope design consists of determining (1) the orientation of the cut, (2) the inclination of the cut, and (3) the need for mitigation measures if the resulting factor of safety is deemed too low or the rockfall potential onto the facility is unacceptably high and (4) the effects on the general physical character of the surrounding area of the proposed slope construction (01, 30, 34, 40 and 51).

Selecting Cut Slope Ratio(s)

Several factors affect how steep a rock slope should be cut, including the orientation and strength of the discontinuities within the slope, the height of the cut slope, the strength of the rock mass and discontinuities, the anticipated method of construction, and whether additional measures will be used to enhance global/local slope stability and/or mitigate potential rockfall. “Landslides Analysis and Control” (43) provides a guide for selecting safety factors in the Existing Natural and Excavated Slopes section on page 197.

The strength and orientation of the discontinuities, relative to the azimuthal orientation and slope ratio of the proposed cut slope, will have the greatest and most direct effect on the Factor of Safety (FS). The height of the cut slope will also influence the global stability, with the greater height producing more driving force towards failure. If the FS does not meet the project requirements, a flatter slope ratio will be required, unless additional measures to mitigate instabilities are planned. When the primary discontinuities are oriented favorably for a steep cut, but the overall strength of the rock is low due to significant weathering and/or decomposition, a Mohr-Coulomb circular analysis will be required to determine the FS of the proposed slope inclination. Multiple slope ratios on a single cut may sometimes be the best and most efficient solution when the material shear strength increases with depth. For example, a cut slope determined by Mohr-Coulomb limit equilibrium analysis to have a sufficient FS might consist of soil overburden at a 1.2:1 slope ratio, overlying a zone of moderately weathered rock at 0.75:1, which, in turn, overlies a zone of unweathered rock at 0.5:1.

In some cases, steeper cut slopes may be determined through limit equilibrium analysis (kinematic and/or Mohr-Coloumb) to have a sufficient global FS but rockfall potential is found to increase. The slope designer should then determine if the positive effects of increased space at the toe of the cut slope (increased rockfall catchment and sight-distance) gained by steepening are more than sufficient to mitigate the negative effects of increased rockfall.

Some methods of slope construction damage the rock such that the finished cut slope has an increased likelihood of long-term local instabilities (rockfall). Uncontrolled blasting, for example, can cause fracturing and open existing fractures tens of feet into the slope. A finished cut slope can be constructed by excavating the rock using heavy equipment ripping or production blasting techniques. The use of either presplitting (preshear) or trim (cushion) blasting, in conjunction with production blasting, produces a cut slope with significantly less potential for local instabilities (rockfall).

Local experience with similar rock type should be investigated. In some cases, right-of way limitations or other factors, such as economics, may require the design slope to be steeper than desirable. If the resulting factor of safety is determined to be too low, or the potential for rockfall is estimated to be unacceptably high during the design life, rock slope stabilization and rockfall mitigation measures should be included in the design (01, 30, 34, 40 and 51).

Benches

Mid-slope benches are flat catchment areas typically constructed at regular elevation intervals within rock cuts (Highway Design Manual Section 304.3). The primary purpose of these benches is to control the degradation of the slope and contain rockfalls. They are commonly employed within inter-bedded strata that contain weak, poorly indurated beds, such as shale or coal, that lie between more durable sandstone or limestone layers. For these applications, they are often referred to as lithologic benches. Lithologic benches are typically constructed at the base of the durable strata with variable widths, depending on the thickness of the underlying less-durable strata. The design attempts to account for degradation of the less-durable strata. For effective, long-term rockfall control, the bench needs to be placed directly beneath a near-vertical (0.25H:1V or steeper) section of slope. Like any catchment area, mid-slope benches require cleanout to maintain their effectiveness. In the 1970s, the widespread practice of incorporating mid-slope benches for highway cuts experienced a schism in North America. Prior to the onset of modern rock-slope engineering design, and the use of controlled blasting for the excavation of highway cuts in the early 1970s, slope designs for many high rock cuts used mid-slope benches. Due to a limited awareness of adverse rock-mass conditions and often poor blasting results, many of these slopes deteriorated and these benches filled with debris. Access difficulties, or loss of access due to slope failures, as well as insufficient maintenance resources, prevented their necessary cleanout. As a result, these debris-filled benches began to act as launching surfaces for rockfalls, imparting undesirable horizontal components to their trajectories. With improved characterization of rock-mass conditions and the use of controlled blasting, many designers, particularly in western North America, avoided the use of mid-slope benches, opting for uniform steep cuts that account for potentially adverse structural control, combined with ditches to control rockfall and with localized slope reinforcement, such as anchors or shotcrete. The elimination of mid-slope benches provided the added benefit of reducing excavation quantities. Where inter-bedded limestone/sandstone and shale sequences are common, mid-slope benches remain standard practice with decades of proven effectiveness in containing rockfall, when properly maintained (49 and 51).

Excavation

Excavation of rock cut slopes is done by blasting the rock, removing the rock (ripping) with equipment such as tractors and excavators, or by chemical or hydraulic expanders. Rock excavation for highway construction often requires the formation of cut slope faces that will be stable for many years, and that will also be as steep as possible to minimize excavation volume and land use. While these two requirements are somewhat in conflict, the stability of cuts will be enhanced, and the steepest safe slope ratio increased by using the proper excavation method that does the least possible damage to the rock behind the final face (01).

Ripping

The physical characteristics that affect rippability are:

1. Frequent planes of weakness
2. Weathering
3. Moisture
4. High degree of stratification
5. Brittleness
6. Low strengths
7. Low seismic refraction velocity

Ripping refers to the removal of rock using tractors, excavators and scrapers. Not all materials or formations can be ripped. The factors used to determine rippability are collected during the field investigation. Three important studies need to be done in order to determine rippability: 1) rock mechanics analysis, 2) geologic site inspection, and 3) seismic refraction evaluation. Determine the conditions to be considered in determining whether ripping is appropriate. First and foremost, the geomaterial must be rippable. Secondly, will blasting damage the slope face or cause damage to the surrounding structures or environment? Finally, which is more cost effective, blasting or ripping (01, 31 and 45)?

Blasting

The physical characteristics of a rock mass that favor blasting over other methods of excavation are:

1. Massive
2. Crystalline rock
3. Non-brittle, energy absorbing rock fabrics
4. High strengths
5. High seismic refraction velocity

The preferred method of blasting for rock cut slopes employs lightly loaded, aligned, and closely spaced blast holes that form the final cut slope face in a manner that minimizes the effects of the intense detonation gas pressures caused by production blasting. This technique, which is referred to as presplitting or trim blasting, is performed either before the main production blasting is detonated (presplit blasting) or after the production blasting (trim blasting). In presplit blasting, the row of control blast holes is detonated to form a break in the slope along the final cut slope, which serves to vent production gas pressure and keep it from penetrating and damaging the rock that will form the final cut face. In cushion blasting, the row of control blast holes is detonated last, to trim off the rock outside the cut slope. The cushion blasting technique is most commonly used in weaker rock conditions or wherever the thickness of rock to be excavated is less than 15 feet. Controlled blasting is routinely used for rock cuts that are 0.75H: 1V or steeper. Maintaining blast hole alignments on flat slopes is a limiting factor when considering the use of controlled blasting (01, 15, 36, 40 and 51).

Rock Slope Stabilization

Mitigation measures to enhance stability include rock reinforcement, drainage, rock removal, and protection against rockfalls (01, 25, 34, 40 and 51). “Rock Slopes” (40) serves as a good single reference for stabilization and blasting; however, all the listed references provide information on the various stabilization measures.

- *Reinforcement* - Structural reinforcement can be provided by rock bolts, dowels, and cable lashing. Tensioned rock bolts are used to increase the normal stress along the discontinuity where sliding is possible, thus increasing the shear strength of the discontinuity. They may also be used to anchor potentially unstable rock blocks in place. Dowels are untensioned rock bolts or shear pins used to resist lateral movement of rock blocks by their shear capacity. Cable lashing uses tensioned cable(s) to increase the normal force against the face of an isolated block to increase sliding resistance. Other designs to consider are shear keys and ground anchor walls (01, 02, 46, 49, 40, 51 and 52).
- *Buttresses* - When an overhanging rock is large and it is impractical to remove or reinforce it, buttresses can be used to support the overhanging rock and increase its stability. Buttresses serve two functions: (1) protect or retain underlying erodible material, and (2) support the overhang.
- *Rock Removal* - One method to mitigate an unstable rock slope is to remove the potentially unstable rock by resloping and unloading the rock mass by rock scaling, trim blasting, or other excavation techniques. In the construction of new rock cuts, rock scaling is generally required and treated as incidental to the payment for the type of excavation performed. Rock trimming can be done with light explosive charges, hydraulic splitters, chemical expanders or pneumatic hammers (01 and 49).
- *Drainage* - Dewatering to reduce groundwater pressures acting within the rock slope improves slope stability. Reduced groundwater pressure within a discontinuity increases the shear strength, while lowering the groundwater height within tension cracks reduces the driving force on a rock block. Proper drainage of rock slopes can be achieved by installing drain holes (weep holes, horizontal drains) or vertical relief wells. Various measures, such as construction of surface drains and ditches, minimize water infiltration, thereby preventing the buildup of groundwater pressures (05, 15, 19, 38 and 48).

- *Erosion Protection* – Hard rock is typically resistant to erosion and/or erodes over long periods of time i.e., 100’s or more years. Soils, decomposed rocks, highly fractured rocks, and certain types of rocks that are susceptible to erosion or degradation can erode on the order of days, weeks and months. When hard rock that is resistant to erosion is underlain by an erodible or degradable layer the loss of support of the overlying rock may develop over time through differential erosion, which may create an unstable condition. Stopping this process can be accomplished by applying shotcrete to the surface of the less resistant zones or by applying an anchored mesh to the slope face. Weep holes are installed to prevent the buildup of groundwater pressures behind the shotcrete where the anchored mesh is free draining. Where applicable (soils and some transitional geomaterials) sustainable erosion control measures can be implemented (01 and 17).
- *Protection Measures*– Draped mesh systems apply limited normal force against the rock face, and primarily serves to control the descent of falling rocks into the roadside catchment area. Barrier systems stop rocks during the rocks’ descent. Barrier types can range from rigid concrete, timber, gabion walls to flexible fencing (01, 11, 49, 40 and 51).

Reporting

Present Rock Cut Slope recommendations in accordance with the *Geotechnical Design Report* (GDR) module.

Include the following in the *Analysis and Design* section of the Preliminary Geotechnical Design Report and Geotechnical Design Report:

- Present design information provided by the district (e.g., slope geometry, height).
- Geological interpretations and models.
- Techniques used for data processing and interpretation.
- Names and descriptions of any software applications used for data reduction and interpretation.
- Results of analyses, and associated risks to the project, if any.

Include the following in the *Recommendations* section of the Preliminary Geotechnical Design Report and Geotechnical Design Report:

- Recommended cut slope ratio or geometry (e.g., benches, rockfall catchment).
- *Excavation Characteristics* table (below) that presents the excavation characteristics of the rock (e.g., rippable, moderately rippable, difficult ripping to light blasting, or blasting required), earthwork factors as they relate to the seismic velocity layers and excavation characteristics.

Table X: Excavation Characteristics

Station	Velocity Layer	Thickness	Excavation Characteristics	Earthwork Factors
0+00 to 10+00	V1	10 feet	Rippable	0.9
0+00 to 10+00	V2	10 to 30 feet	Blasting Req.	1.1

- Locations or limits for rock excavation, including controlled blasting and presplitting.
- Residual rockfall recommendations (see *Rockfall* module).
- Optional - provide tables and/or figures such as plan views, elevations, and cross-sections, to detail the limits of specific recommendations.
- If the recommendations include rock excavation, include a statement to request the opportunity to review the draft final PS&E.

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