

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*.

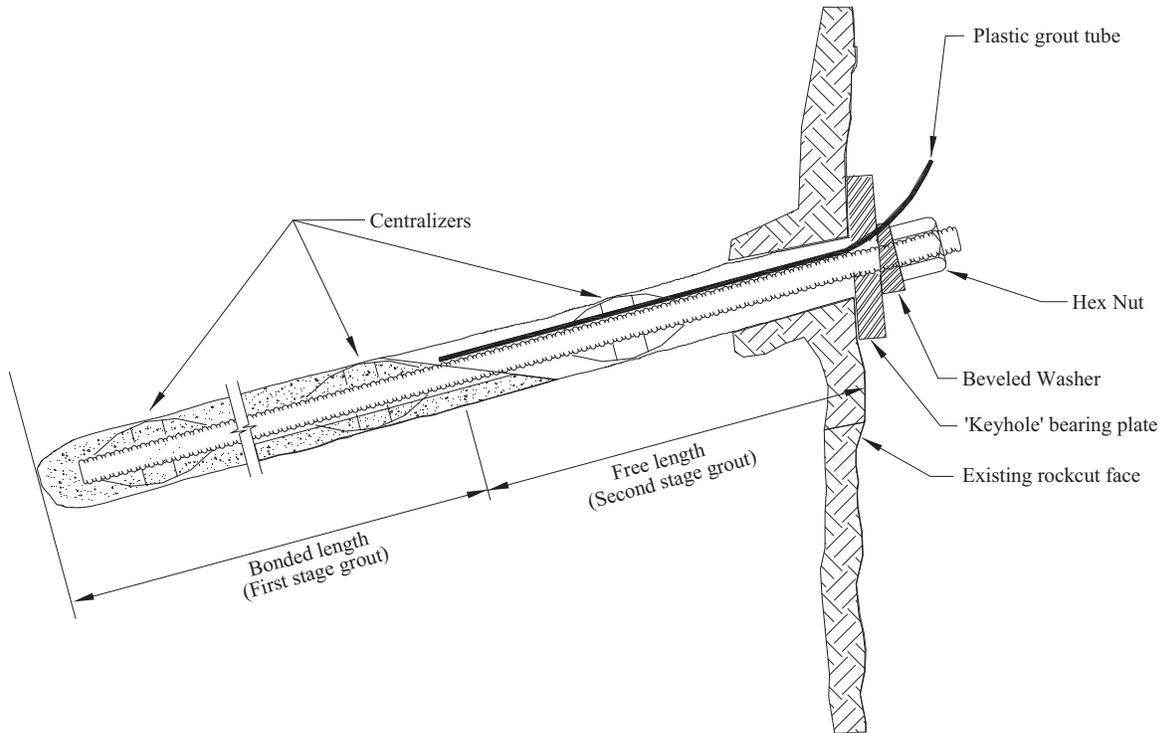
Tensioned Anchors (Rock Bolts):

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.

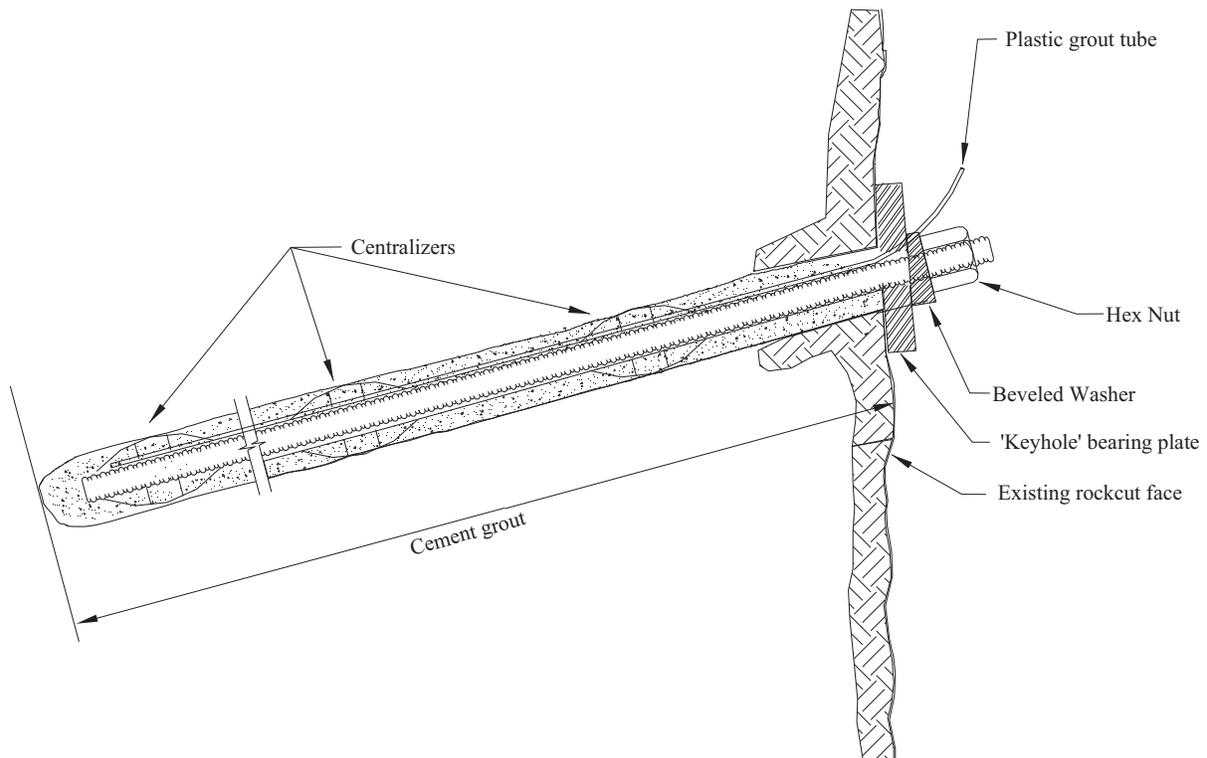


Figure 42. Illustration. Typical untensioned rock dowel.

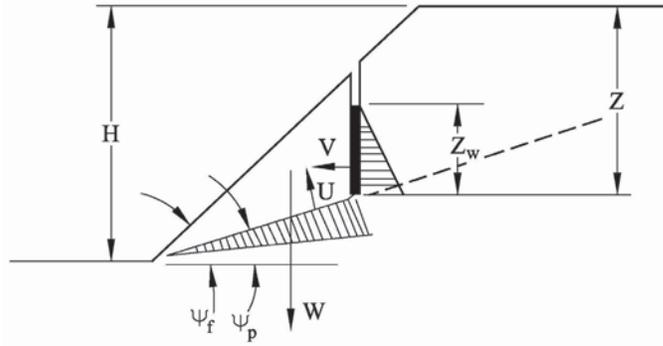
Shear pins are installed at the leading edge of a sliding block. They rely on the shear strength of the steel dowel cross section to provide resistance in the sliding plane of the block. In places where it is not possible to install shear pins directly into the block, the pins can be incorporated into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

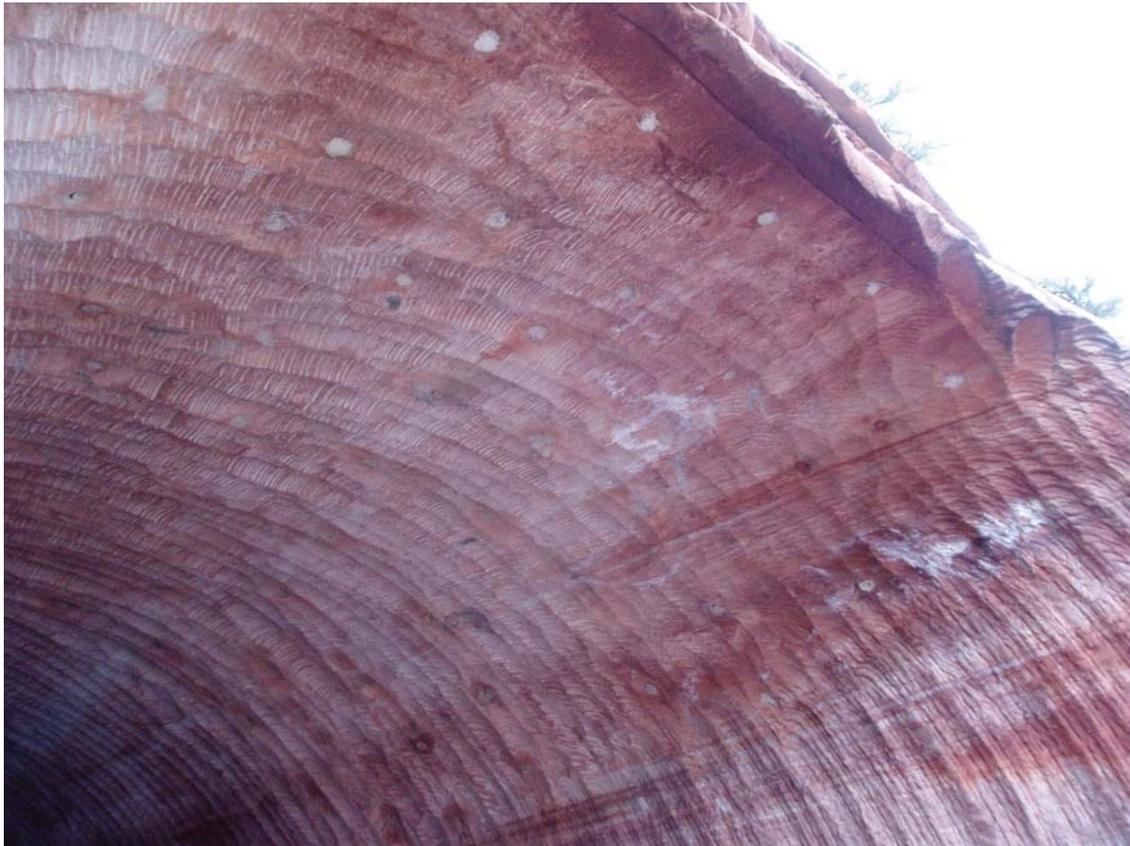


Figure 44. Photo. Tunnel crest supported with dowels that have been covered with colored grout.

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.

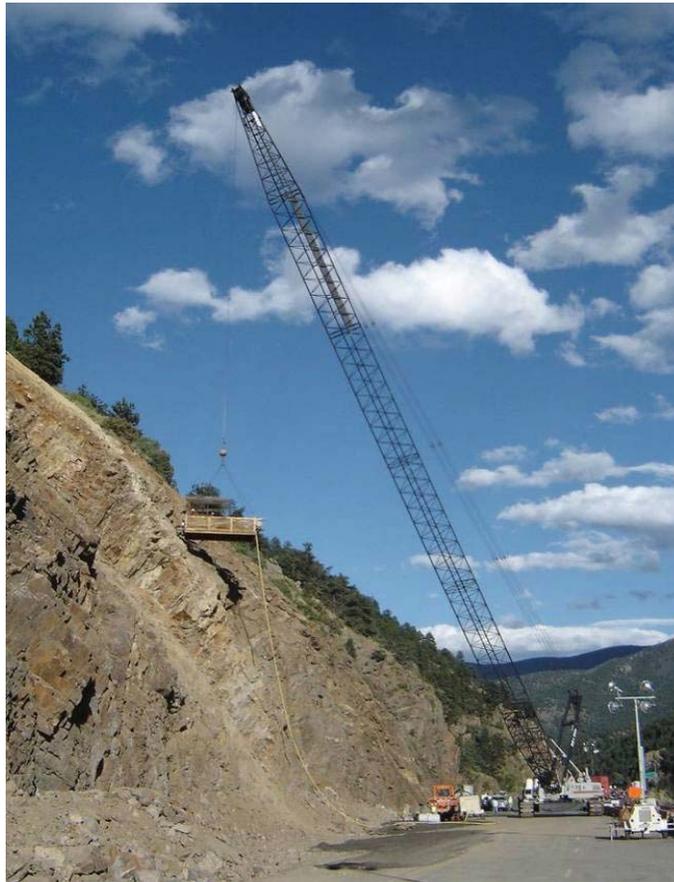


Figure 47. Photo. Installing rock reinforcement using a drill rig suspended from a crane.

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/m ³ (3 to 50 pcf)	Medium to High 320 to 1,100 kg/m ³ (20 to 70 pcf)	Low to High 80 to 960 kg/m ³ (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 m² (850 ft²) 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.

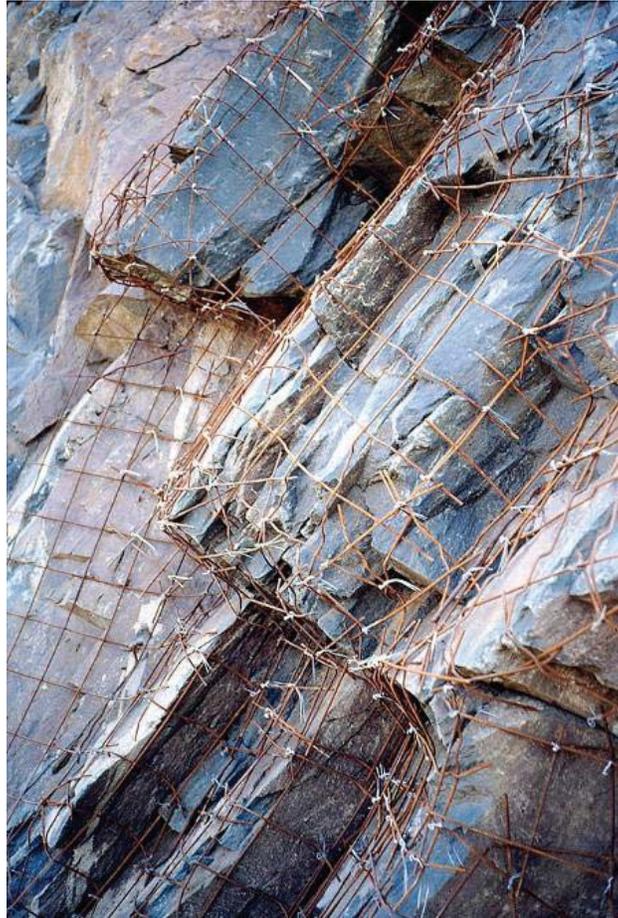


Figure 50. Photo. Welded wire mesh can be attached to the rock face before shotcrete is applied.

Shotcrete can vary in appearance from very rough—in its natural, “as-shot” (unfinished) condition—to moderately rough in the "rodged" 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 using 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.

