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HIGHWAY AND RAILROAD SLOPE MAINTENANCE
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ROCK SLOPE STABILIZATION AND PROTECTION MEASURES

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ABSTRACT

Engineered procedures for control of rock fall hazards on transportation routes have been in use for the past 15 to 20 years approximately, in a wide range of geological environments. As a result of this experience, these methods have been well proven and can be used with confidence.

The methods of controlling rock falls can be divided into two broad categories. First, methods which involve stabilization of the slope itself, and second, protection methods that prevent rock falls from reaching the highway. Stabilization methods can be further subdivided into techniques involving stabilization of the rock slope, such as rock bolting and shotcrete, and those involving rock removal such as scaling and re-sloping. Protection measures include such techniques as ditching and construction of rock fences. These methods encompass approximately 15 different techniques, and it is important that conditions at each site be carefully studied so that the most appropriate method is selected.

Selection of the most appropriate stabilization measure for each site will depend on geotechnical factors including the geological, rock strength and ground water conditions at the site. Other factors to consider are weather conditions, construction access, traffic closure times, aesthetics, availability of waste rock and soil diposal areas, and the construction costs.

1. EFFECT OF ROCK FALLS ON TRANSPORTATION SYSTEMS

The safe operation of transportation routes in mountainous terrain often requires that measures be taken to control the incidence of rock falls. The types of events and accidents that can be caused by rock falls include minor falls that damage tires and bodywork, larger falls that impact vehicles, or cause vehicles to swerve off the road, and substantial slope failures that block the highway. The effect of these events can be damage to vehicles, injury and death to drivers and passengers, and economic loss due to road closures. Figure 1 shows a rock slide that occurred from a height of about 300 m (1000 ft) above the road and closed both the road and a railway below. The closure of these transportation routes resulted in significant economic loses for the owners and users.

Figure 1. Highway blocked by rockfall in very strong, massive granite that originated from approximately 300 m (1000 ft) above the highway and destroyed a 3 m high concrete wall.

In areas where there is a potential for rock falls being a hazard to highway users, and causing substantial costs to the operator of the system, a rock slope stabilization program is often justified. This program will be most effective if it is conducted in three stages as follows. First, an inventory is carried out to identify the most hazardous slopes (Pierson et al, 1990; Wyllie, 1987). Second, a stabilization schedule is drawn up, in which the most hazardous sites are given the highest priority rating. Third, stabilization work is carried out, starting with the highest priority sites.

In areas where the slopes have been excavated for 20 to 30 years there may be a great many slopes that require stabilization, either due to poor initial construction practices, or weathering since construction. Under these circumstances, the stabilization work may take 10 to 15 years to complete if funds available for stabilization are limited; the priority system will help to identify the most hazardous sites so that the most effective program can be drawn up (Wyllie et al, 1979).

A successful rock slope stabilization program requires the performance of a number of interrelated tasks involving geotechnical engineering, and a thorough understanding of environmental and safety issues, construction methods and costs, and contracting procedures. Methods for the design and construction of stabilization measures for rock slopes were first developed in the 1970's (Hoek and Bray, 1974; Brawner and Wyllie, 1975; Fookes and Sweeney, 1976; Groupe d'Etudes des Falaises, 1978; Piteau and Peckover, 1978), and have been continuously developed since that time (State of California, 1985; FHWA, 1989). This paper provides an overview of these methods and describes the conditions under which they can be used.

2. PRINCIPLES OF ROCK SLOPE STABILIZATION

There are a wide variety of stabilization measures for rock slopes, and it is important that the most appropriate method(s) be used for the particular geologic and topographic conditions at each site. Figure 2 shows that stabilization and protection measures can be divided into three classes as follows:

1. **Reinforcement** - improvement of the resisting forces by increasing the shear resistance on the potential sliding plane;
2. **Rock removal** - reduction of driving forces by removal of loose rock;
3. **Protection** - construction of structures to protect the highway from rock falls.

The resisting and driving forces in a rock slope are shown in Figure 3 where a block of rock, of weight W, has a potential sliding plane of area A which dips at an angle ψ_p out of the slope face. The water table is at a level above the base of the tension crack so that water forces U and V are developed within the slope and act in directions normal to the sliding plane and tension crack respectively. The shear strength of the sliding plane is defined by the cohesion (c) and friction angle (ϕ) of the fracture surface, assuming that the rock is a Mohr-Coulomb material.

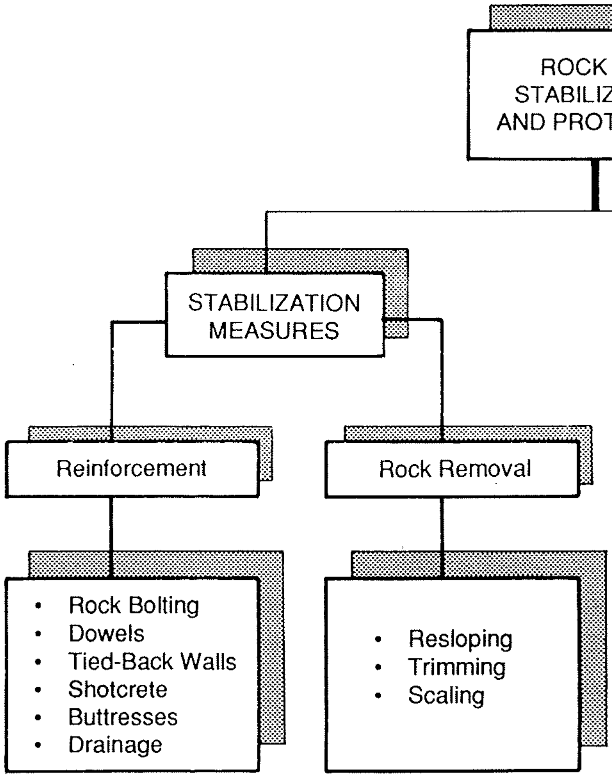


Figure 2. Classes of rock slope stabilization measures.

For the simple sliding block failure shown in Figure 3, the factor of safety of the block is defined by the following equation (Hoek and Bray 1981):

$$F = \frac{\text{resisting forces}}{\text{displacing forces}}$$

$$= \frac{cA + N \tan \phi}{S} \quad \text{(1a)}$$

$$= \frac{cA + (W \cos \psi_p - U - V \sin \psi_p) \tan \phi}{W \sin \psi_p + V \cos \psi_p} \quad \text{(1b)}$$

where N and S are the normal and shear forces, respectively, acting on the sliding surface.

Examination of the terms in equation 1 shows that the resisting forces can be improved by increasing the normal force by, for example, the installation of tensioned rock bolts, and the displacing force can be reduced by removing rock to diminish the weight of the block. Furthermore, both the resisting and displacing forces are improved by reducing the water pressure within the slope. These concepts of rock slope stability are applied to the design of stabilization measures as described in the following sections.

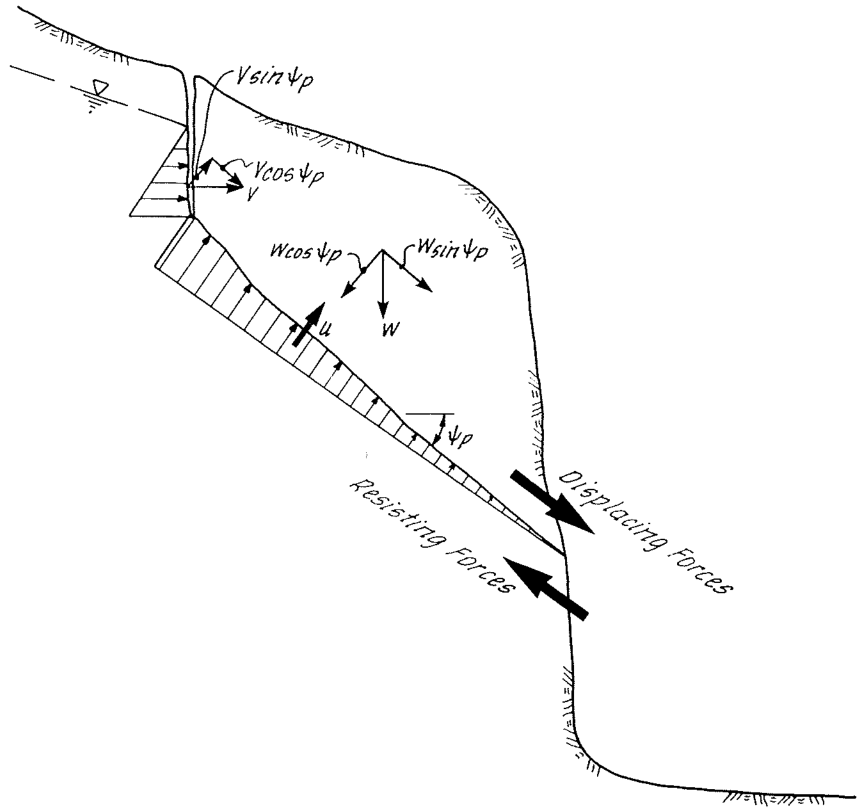


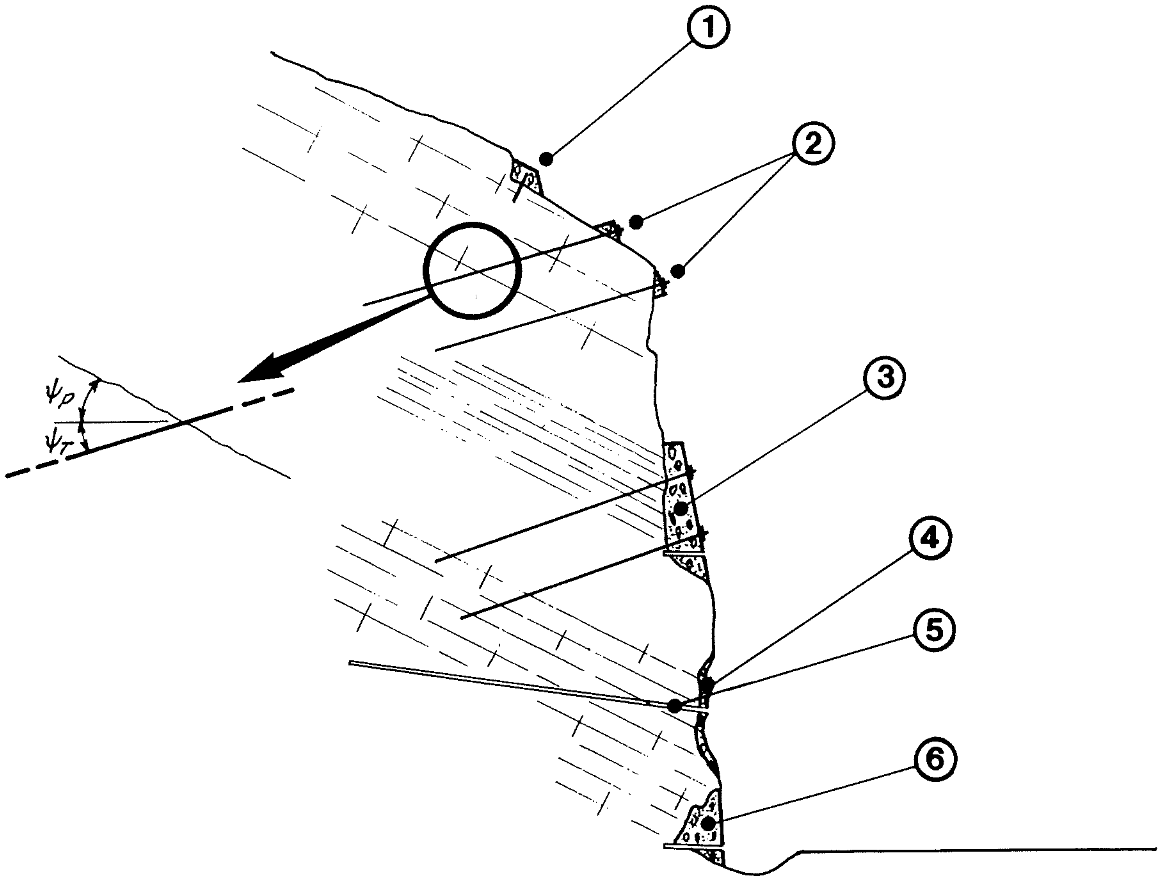
Figure 3. Stability condition of rock slope with potentially unstable block formed by fracture dipping out of face.

3. REINFORCEMENT

Where investigation of slope stability conditions indicates that the most appropriate stabilization measure is to secure potentially loose rock on the face, there are a number of reinforcement techniques that may be implemented (Figure 4). The common feature of all these techniques is that they minimize relaxation and loosening of the rock mass that may take place as a result of opening of rock fractures. Once relaxation has been allowed to take place, there is a loss of interlock between the blocks of rock, and a significant decrease in the shear strength.

3.1 Rock Bolts

Tensioned rock bolts are installed across potential failure planes and anchored in stable rock beneath the plane. The application of a tensile stress in the bolt results in an increased normal stress and decreased shear stress on the failure plane. Under these conditions, the equation defining the factor of safety of the block, as shown by equation (1b), is modified as follows:



1. Reinforced concrete dowel to prevent loosening of slab at crest.

2, Tensioned rock anchors to secure planar type failure along crest.

3. Tied back wall to prevent sliding failure on fault zone.

4. Shotcrete to prevent ravelling of zone of fractured rock.

5. Drain hole to reduce water pressure within slope.

6. Concrete buttress to support rock above cavity.

4. Rock slope reinforcement methods.

$$F = \frac{cA + [W \cos\psi_p - U - V \sin\psi_p + T \sin(\psi_p + \psi_T)] \tan\phi}{W \sin\psi_p + V \cos\psi_p - T \cos(\psi_p + \psi_T)} \qquad (2)$$

Equation 2 shows that the effect of the forces produced by the rock bolt is maximized when the bolt is installed at a dip angle flatter than the normal to the plane. It is found that the required bolt force to produce a specified factor of safety is minimized when the dip angle (ψ_T) of the bolt is

$$\psi_{Topt} = \phi - \psi_p \quad \text{or} \quad \psi_{Topt} + \psi_p = \phi \qquad (3)$$

where ψ_p is the dip angle of the potential failure surface (Figure 4, inset). Savings in bolting costs can be usually realized by installing bolts at the optimum angle, rather than at an angle normal to the failure plane.

The three main requirements of a permanent, tensioned rock bolt installation are:

- a method of anchoring the distal end of the anchor in the drill hole,
- application of a known tension to the bolt without creep and loss of load over time,
- protection of the complete anchor assembly from corrosion for the design life of the project.

Anchorage: methods of securing the distal end of the bolt in the drill hole include resin, mechanical, and cement-grout anchors. The selection of the appropriate anchor will depend on such factors as the design tension of the anchor, the required speed of installation, the strength of the rock in the anchor zone, the access to the site for drilling and tensioning equipment, and the level of corrosion protection required (Wyllie, 1991).

Cement grout is the most common method of anchoring permanent rock bolts because the materials are inexpensive, the installation procedure is simple, it is applicable for a wide range of rock and soil conditions, and the steel is protected from corrosion. The grout mix usually comprises a non-shrink cement and water at a water:cement ratio in the range of 0.4 to 0.45. This ratio will produce a grout that can be readily pumped down a small diameter grout tube and will produce a high strength, continuous grout column with minimal bleed of water from the mix.

A tensioned rock bolt anchored with cement grout has two components - a bond length (l_b) and a free-stressing length (l_f). The bond length is that portion of the bolt below the failure plane where the bolt is anchored in the rock, and the free stressing length makes up the remainder of the bolt. The design of rock anchors to sustain the necessary tension load requires the selection of an appropriate hole diameter, and free-stressing and bond lengths to suit the geological conditions.

The free-stressing length should extend several meters beyond the failure plane to ensure that the bolt tension is transmitted to the failure plane. The length of the bond zone is calculated from equation (4) assuming that the shear stress at the rock/grout interface is uniformly distributed along the bond:

$$l_b = \frac{T}{\pi \, d_h \, \tau_a} \qquad (4)$$

where T is the design tension force, d_h is the hole diameter, and τ_a is the allowable bond stress. Values of τ_a can be estimated from the uniaxial compressive strength of the rock (σu) in the anchor zone according to the following relationship (Littlejohn and Bruce, 1975):

$$\tau_a = \frac{\sigma_u}{30}$$

Approximate ranges of allowable bond stress (as a function at rock strength are as follows:

Strong rock:	1000 - 1400 kPa	150 to 200 psi
Medium rock:	700 - 1000 kPa	100 to 150 psi
Weak rock:	350 - 700 kPa	50 to 100 psi

Tensioning - where tensioned rock bolts are to be installed, it is important that a procedure be carried out to check that the full design load is applied, and that there will be no loss of load with time. A suitable testing procedure has been drawn up by the Post Tensioning Institute (PTI, 1985) and comprises the following four types of test:

- Performance test
- Proof test
- Creep test
- Lift-off test

The usual method of tensioning rock bolts is to use a hollow-core hydraulic jack that allows the applied load to be precisely measured, as well as cycling the load and holding it constant for the creep test. The deflection of the anchor head is usually measured with a dial gauge, to an accuracy of about 0.1 mm (0.004 in), with the dial gauge mounted on a reference point that is independent of the anchor (Figure 5).

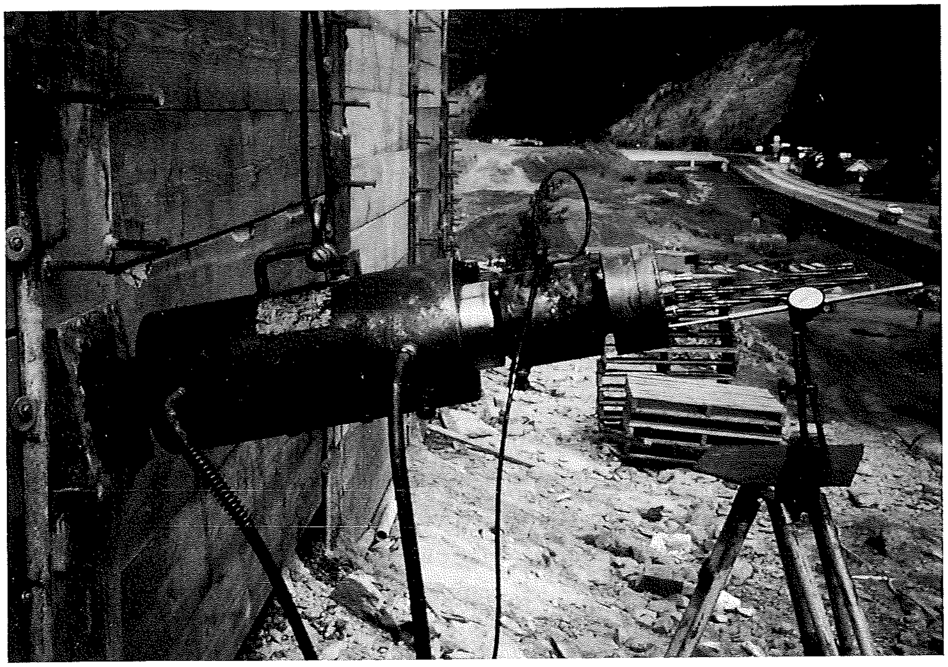


Figure 5. Typical set up for measuring applied tension, and deflection of the anchor head, during performance and proof tests of a grouted, multi-strand anchor.

Corrosion protection - corrosion protection is provided for almost all permanent anchors to ensure their longevity. Even if anchors are not subject to corrosion at the time of installation, conditions may change with time which must be accounted for in design. The following list describes conditions that will usually create a corrosive environment for steel anchors (Hanna, 1982; King, 1977):

- Soil and rock containing chlorides;
- Seasonal changes in the ground water table;
- Anchorages in marine environments where they are exposed to sea water, which contains chlorides and sulphates;
- Fully saturated clays with high sulphate content;
- Anchorages that pass through different ground types that possess different chemical characteristics;
- Anchorages subject to stray direct electrical current that develops galvanic action between the steel and the surrounding rock.

A number of rock anchor manufacturers have proprietary corrosion protection systems. The material most commonly used for corrosion-protection is cement grout, primarily because it creates a high pH environment that passiveates the steel by forming a surface layer of hydrous ferrous oxide. Because of the brittle nature of grout and its tendency to crack, particularly when loaded in tension or bending, it is usual that the protection system comprises a combination of grout and a plastic (high-density polyethylene) sleeve. In this way, the grout produces the high pH environment around the steel, while the plastic sleeve provides protection against cracking. In order to minimize the formation of shrinkage cracks that reduce corrosion resistance of the grout, it is usual to use non-shrink grout for all components of the installation.

3.2 Dowels

Loosening and failure of small blocks of rock on the slope face can be prevented by the installation of passive dowels. Dowels are blocks of reinforced concrete that are installed at the toe of potentially loose blocks of rock, and are anchored, with lengths of fully grouted reinforcing steel, to the underlying, stable rock (Figure 4, item 1). It is important that the concrete is in intimate contact with the rock that it is supporting so that movement and loss of interlock on the potential sliding plane is minimized. The reinforcing steels used to anchor the concrete to the rock are usually about 35 mm ($1^{-3}/_{8}$ in) in diameter, embedded about 0.5 m (1.5 ft.) into sound rock, and spaced about 0.5 to 0.8 m (1.5 to 2.5 ft) apart.

Because dowels provide passive, shear resistance to sliding, they can only be used to support slabs of rock with thicknesses up to about 1 m (3 ft). Dowels are also most effective when there has been no prior movement of the rock so that there is interlock on the potential sliding surface. For slabs thicker than about 1 m, or where there has been rock movement, the required support should be provided with tensioned anchors.

3.3 Tied back walls

Figure 4, item 3 shows an example where there is a potential for a sliding type failure in closely fractured rock. Tensioned rock bolts are required to support this portion of the slope, but there is a potential for the rock to degrade and ravel from under the reaction plates of the anchors so that eventually the tension in the bolts will be lost. In these circumstances, a reinforced concrete wall is constructed to cover the area of fractured rock, and then the holes for the rock anchors can be drilled through sleeves in the wall. Finally the anchors are installed and tensioned against the face of the wall. The wall acts as both a protection against ravelling of the rock, and as a large reaction plate for the rock anchors.

3.4 Shotcrete

Zones of closely fractured or highly degradable rock can be protected by applying a layer of shotcrete to the rock face. When used on surface excavations, shotcrete provides little support for the overall slope against sliding, and its primary function is surface protection (Figure 4, item 4).

Shotcrete is a pneumatically applied, fine-aggregate mortar (less than 13mm or 1/2 in. aggregate size) that is usually placed in a 75 to 100 mm (3 to 4 in.) thick layer (ACI, 1990). The effectiveness of shotcrete depends to a large degree on the condition of the rock surface to which it is applied. The surface should be free of loose and broken rock, soil, vegetation and ice, and should also be damp to improve the adhesion between the rock and the shotcrete. It is also important that drain holes be drilled through the shotcrete to prevent build up of water pressure behind the face; the drain holes are usually about 0.5 m (1.5 ft) long, and on 1 to 2 m (3 to 6 ft) centres. In massive rock it is important that the drain holes are drilled before the shotcrete is applied, and located to intersect fractures that carry water. The holes are temporarily plugged with wooden pegs or rags while the shotcrete is applied.

For all permanent applications, shotcrete should be reinforced to reduce the risk of cracking and spalling. The two most common methods of reinforcing are welded wire mesh and steel fibres. Welded wire mesh, fabricated from light gauge (3.5 mm or 0.13 in. diameter) wire on 100 mm (4 in) centers, is used where the face is uniform and the mesh can be closely attached to the rock. Under these conditions the mesh can be fully encased in shotcrete with no voids behind the mesh.

On irregular rock faces an alternative to mesh reinforcement is to use steel fibres that are a component of the shotcrete mix and form a reinforcement mat throughout the shotcrete layer. The steel fibres are manufactured from high strength carbon steel with dimensions of 30 to 38 mm (1.2 to 1.5 in) long and 0.5 mm (0.02 in) equivalent diameter. The fibres have deformed ends, or are crimped to resist pull-out, and their principal function is to significantly increase the tensile and post-crack strength of the shotcrete compared to non-reinforced shotcrete.

3.5 Buttresses

Where a rock fall has occurred to form a cavity in the slope face, it may be necessary to construct a concrete buttress in the cavity to prevent further falls (Figure 4, item 6). The buttress fulfills two functions: first to retain and protect any areas of weak rock, and second to support the overhang. This type of stabilization should not be used where there is a potential for a significant sliding type failure unless it is designed to also resist shear forces.

If the buttress is to prevent relaxation of the rock, it should be founded on a clean, sound rock surface and anchored to the base using steel pins to prevent movement. Also, the top should be poured so that it is in contact with the underside of the overhang. In order to meet this second requirement, it may be necessary to place the last pour through a hole drilled downwards into the cavity from the rock face, and to use a non-shrink agent in the mix.

3.6 Drainage

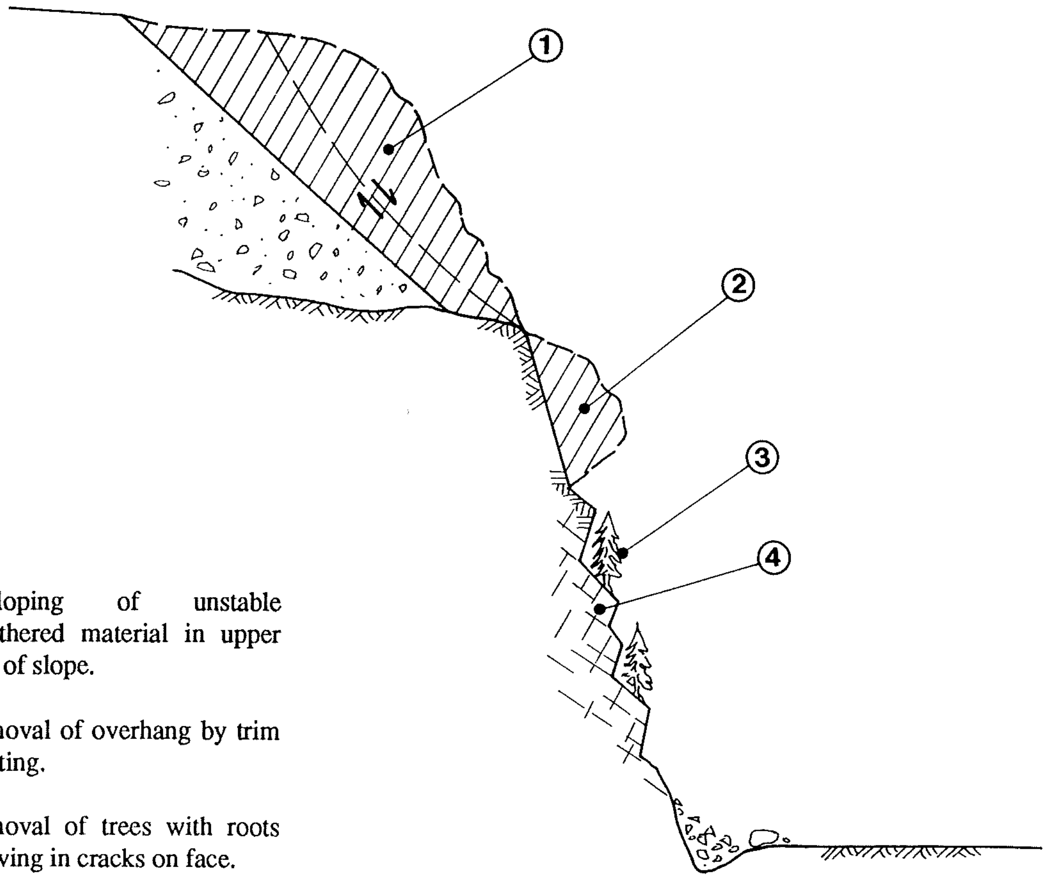
The presence of ground water in rock slopes is often a contributory cause of instability - see equation 1b above. The usual method of reducing water pressures within rock slopes is to drill drain holes along the toe of the slope to create a series of low pressure outlets for the water (Figure 4, item 5). The most important factor in the design of drain holes for rock slopes is to locate the holes so that they intersect the fractures that are carrying the water. As a guideline on hole spacing, holes are usually drilled on a spacing of about 3 to 10 m (10 to 30 ft), and to a depth of at least one third of the slope height. The holes are often lined with a perforated casing, with the perforations sized such that there is no infiltration of fines that are washed from fracture infillings.

4.0 ROCK REMOVAL

Stabilization of rock slopes can be accomplished by the removal of potentially unstable rock (Figure 6). Figure 6 illustrates typical removal methods - resloping zones of low strength rock, trim blasting of overhangs, and scaling of individual blocks of rock.

The advantage of removing unstable rock, in comparison to stabilization by the installation of tensioned rock anchors for example, is that removal can be a permanent stabilization measure, and the construction work is usually less expensive. However, removal of loose rock on the face of a slope will only be an effective stabilization measure if there is no risk of undermining the upper part of the slope, and if the rock forming the new face is sound. An illustration of where rock removal should be carried out with care is area 4 on Figure 6. It would be safe to remove the outermost loose rock, provided that the fracturing was caused by blasting and only extended to a shallow depth. However, if the rock mass was fractured, then continued scaling would soon develop a cavity that would undermine the upper part of the slope.

Another example of a condition where removal of loose rock on the face of a slope is not effective, is highly degradable rock. In these circumstances, exposure of a new face will start a new cycle of weathering and instability. For both the conditions described above, a more appropriate stabilization method would be protection of the face with shotcrete, if adequate adhesion to the face can be achieved, or excavation of a ditch at the toe of this slope.



1. Resloping of unstable weathered material in upper part of slope.
2. Removal of overhang by trim blasting.
3. Removal of trees with roots growing in cracks on face.
4. Hand scaling of loose blocks in shattered rock.

Figure 6. Rock removal methods for slope stabilization.

4.1 Resloping

Depending on the depth of weathering along the upper portion of a rock cut, it may be necessary that the slope angle in this material be flatter than that in the lower part of the slope where the rock is more competent (Figure 6, item 1). However, if the depth of weathering and the strength properties of the weathered rock are not evident during the design of the project, then the excavated slope may be at too steep an angle for the conditions. Under these circumstances, slope instability may develop in the weathered material and resloping of the cut in this material would be required. Another condition that may require resloping occurs when weathering takes place after the cut has been excavated and instability does not develop until some years after construction.

Resloping will usually be carried out with excavating equipment such as back-hoes and bulldozers. Consequently, the cut must be designed to accommodate suitable excavating equipment on the slope, which requires that the cut width be about twice the width of the equipment - that is, a minimum of 6 m (20 ft.).

4.2 Trimming

Failure of a portion of a rock slope may form an overhang on the face (Figure 6, item 2), which could be a hazard to traffic if it were to fail. Where the rock forming the overhang is strong and massive, it may not be possible to remove it by hand scaling, and trim blasting would be required. Trim blasting involves drilling a series of closely spaced, parallel holes on the required break line. These holes should be loaded with just sufficient explosive to break the rock along this line without damaging the rock behind the required face (Langefors et al, 1967; FHWA, 1985).

4.3 Scaling

Scaling is the term to describe the removal of loose rock, soil, and vegetation on the face of a slope using hand tools such scaling bars, shovels, and chain saws. On steep slopes workers usually work off ropes anchored at the crest of the slope, and tied to belts and karabiners around their waists (Figure 7). The most appropriate type of rope for these conditions is a steel-core, hemp rope that is highly resistant to cuts and abrasion. The scalers work their way down the face to ensure there is no loose rock above them.

An important component of any scaling operation is the removal of all trees and vegetation on the face, and to a distance of several meters behind the crest of the slope. Tree roots growing in fractures on the rock face can force open the fractures and eventually cause rock falls. The general loosening of the rock on the face by tree roots also permits increased infiltration of water, which in temperate climates will freeze and expand and cause further opening of the cracks.

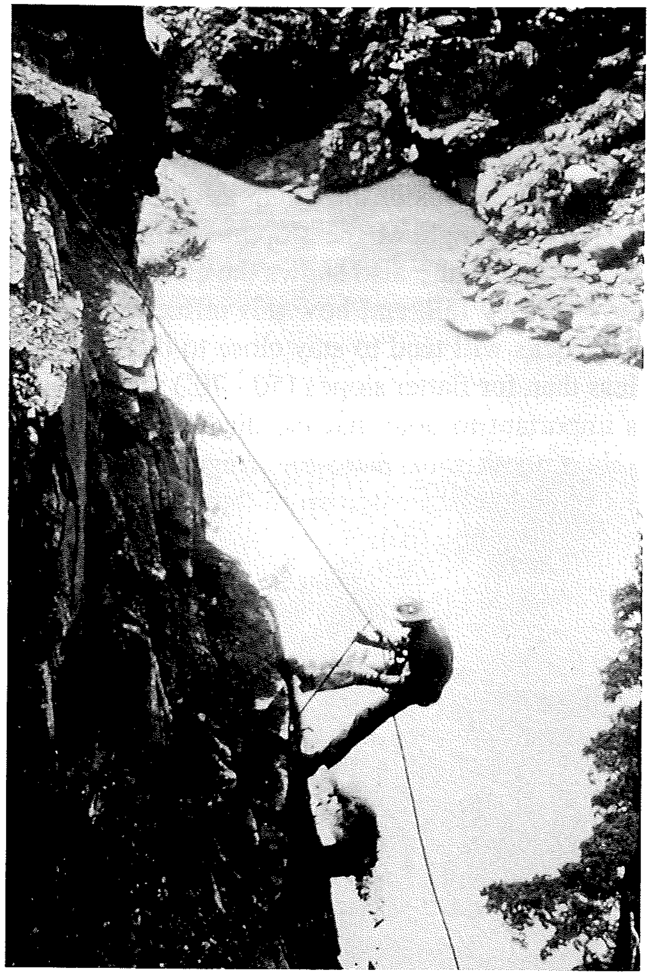


Figure 7. Photograph of high scaler, suspended on a rope and belt, removing loose rock on a steep rock slope.

5. PROTECTION MEASURES

Where conditions are suitable, an effective method of controlling rock falls is to let the falls occur, and provide protection by means of one of a variety of structures at the toe of the slope. These protection structures include catchment ditches, mesh hung on the face of the slope, fences to trap rock falls, and rock sheds. A common feature of all these protection structures is their energy absorbing characteristics in which the rock fall is either stopped over some distance, or is deflected away from the facility that is being protected. As described in this section, it is possible, by the use of appropriate techniques, to control rocks with diameters of as much as 2 to 3 m falling from heights of several hundred meters. In contrast, rigid structures such as reinforced concrete walls are rarely effective for catching rock falls; the rock fall in Figure 1 completely destroyed a 3 m (10 ft.) high concrete wall.

5.1 Ditches

Catch ditches at the toe of rock slopes are often a cost effective means of stopping rock falls. The required dimensions of the ditch, as defined by the depth and width, are related to the height and face angle of the slope as shown in the ditch design chart in Figure 8 (Ritchie, 1963). The figure also shows the effect of slope angle on the path that rockfalls tend to follow as they fall, and how this influences ditch design. On steep cut faces (70 - 90°) falling rocks will tend to stay close to the face. Consequently, the ditch dimensions will be less than for flatter slopes (50 - 70°) where rock will bounce outwards from the face. It is important to note that the ditch design charts have been drawn up assuming a reasonably smooth rock face; for irregular slopes with protrusions on the face, the ditch widths should be increased from those shown on the chart to account for possible random bounces of falling rock.

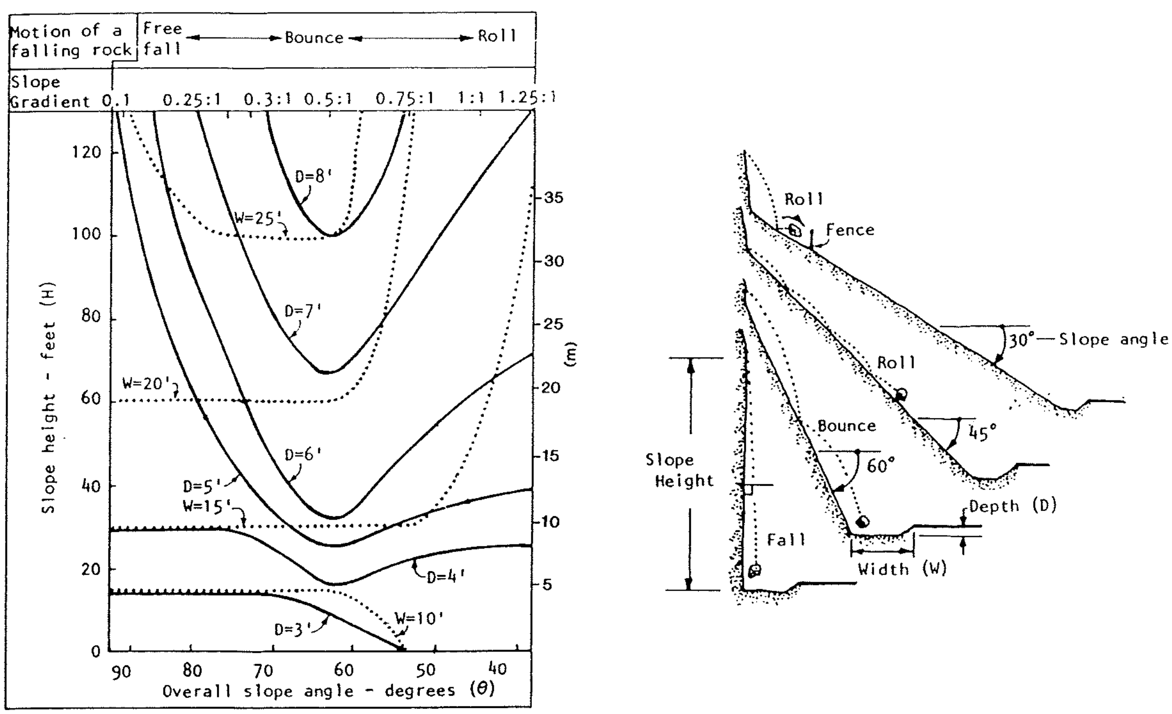


Figure 8. Design chart to determine the required width and depth of rock catch ditchs in relation to the height and face angle of the slope (Ritchie, 1963).

5.2 Mesh

Wire mesh hung on the face of rock slopes can be an effective method of containing rock falls close to the face of the slope and preventing them from bouncing out on to the road. Figure 9 shows an example of mesh installed on a near-vertical face. Because the mesh absorbs some of the energy of the falling rock, the dimensions of the ditch at the toe of this slope are considerably reduced from those shown in Figure 8.

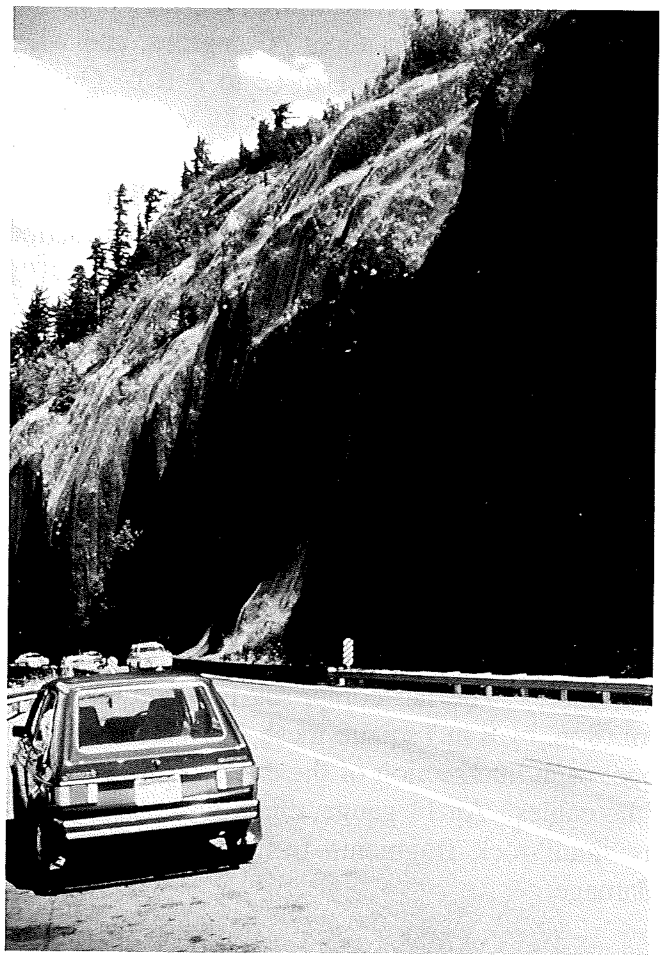


Figure 9. Wire mesh hung on vertical face to direct falling rock in to the ditch at the toe of the slope.

The features of the mesh installation shown in Figure 9 are:

- it is securely anchored along the crest with steel cable that is attached to pins grouted into holes drilled into the rock, and then is threaded through the mesh,
- the bottom of the mesh is left open so that loose rock can fall into the ditch and is not trapped on the face; if rocks accumulate behind the mesh they will eventually pull the mesh off the face. The mesh is usually fabricated from triple twist gabion mesh that does not unravel if a wire is cut. For very high installations, the mesh can be reinforced with steel cables threaded through the mesh.

Mesh is a suitable method for controlling rock falls on slopes with angles steeper than about 75 degrees and flatter than about 40 degrees, and where the blocks of rock have dimensions less than about 0.6 to 1 m (2 to 3 ft.). On slopes with face angles between 75 and 40 degrees, and where the blocks will be greater than about 1 m in diameter, the blocks will tend to bounce and spin as they fall down the face with sufficient energy to destroy the mesh. Under these conditions, control of rock fall will require either a wide ditch at the toe of the slope, or construction of a catch fence as described in Section 5.3.

5.3 Rock Fences

At locations where blocks of rock are rolling and bouncing down talus slopes (slope angle of about 35 to 38 degrees), an effective protection measure is the construction of a fence. A number of such fences have developed and thoroughly tested by the Colorado Department of Highways and the California Department of Transportation. One of these fences, which is manufactured by the Brugg Company, is shown in Figure 10 (Caltrans 1990). The features of this fence are a series of steel posts, on 5.2 m (17 ft.) centers, with the base anchored to the ground and the top attached to an upslope cable and anchor. The net comprises two components. The main net is an 200 mm by 200 mm (8 in. by 8 in.) square mesh fabricated from 8 mm ($^5/_{16}$ in.) diameter galvanized wire rope; each intersection of the cables is secured with metal fasteners that are crimped on to the cables. An 11 gauge, chain link mesh, attached to the front of the main net, prevents small rock fragments from passing through the main mesh, and reduces localized damage.

Full scale tests conducted by Caltrans showed that the fence was able to stop boulders with weights of as much as 30 kN (6000 lbs), moving at speeds of up to 18 m per second (60 ft. per second). Computer programs have been developed to simulate the path of rockfalls down slopes, and calculate bounce height, velocity, and run-out distance (Colorado Department of Highways, 1990; Descoeudres et al, 1989).

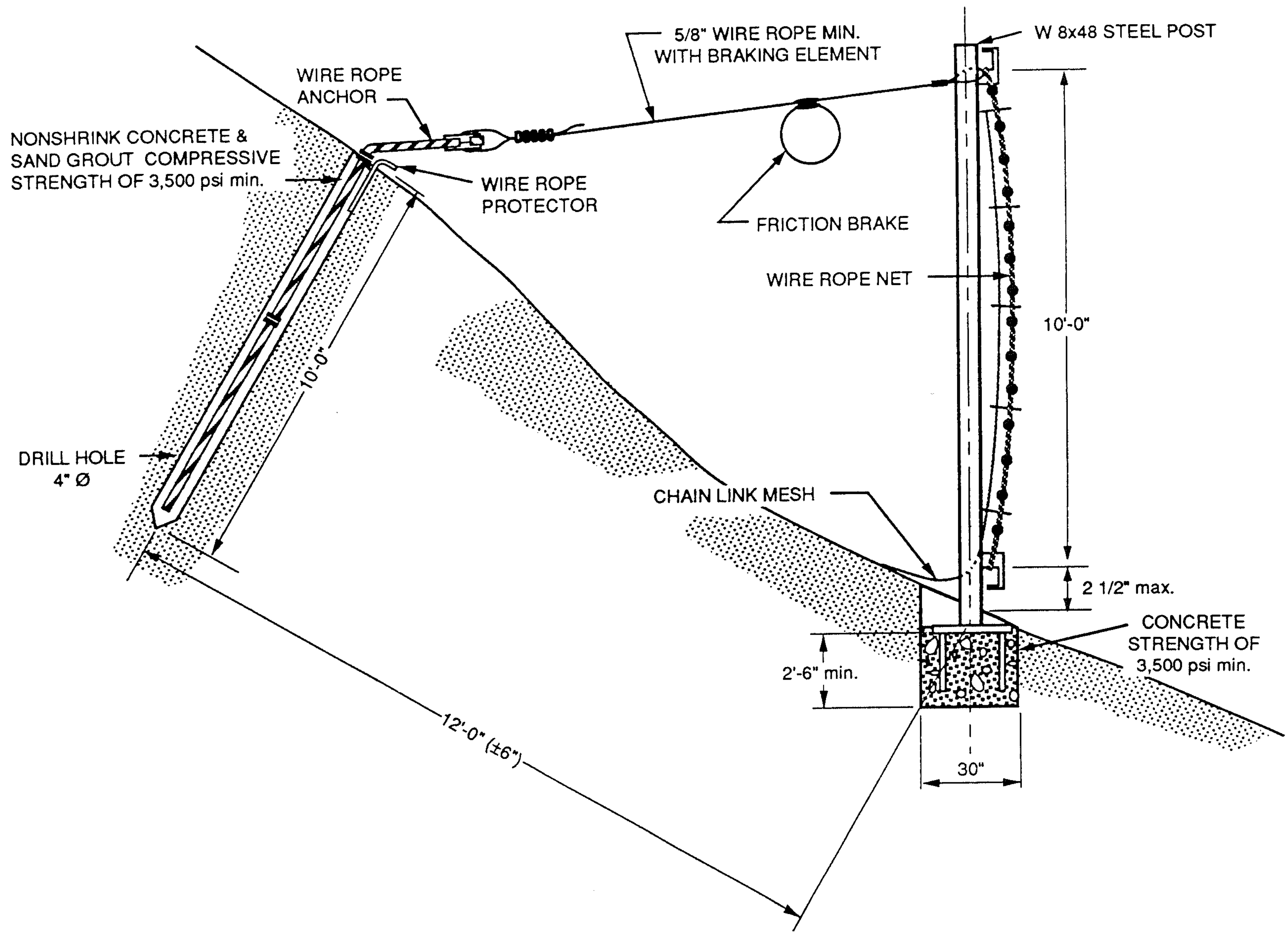


Figure 10. Side view of Brugg Cable Systems rock catch fence (California Department of Transportation).

5.4 Warning Fences

An inexpensive and effective method of protecting transportation routes from rockfalls is to use a system of fences and warning signals that are triggered by rockfalls. Figure 11 shows one such system in use on a railroad. The fence consists of a series of timber posts and cantilever cross-arms that support rows of wires spaced about 0.5 m (1.5 ft) apart. At least one wire will be broken by rocks either rolling down the face, or bouncing outwards from the face. The wires are connected to a signal system that shows a red light if a wire is broken; the signal light is located far enough from the rock slope that the traffic has time to stop before it reaches the rockfall location.

Warning fences are most often used by railways that normally operate under signaling systems, and where the traffic is light enough to accommodate occasional closures of the line. However, the use of warning fences as a protection measure has a number of disadvantages. First, the signal lights must be located a considerable distance from the slope, and falls may occur after the traffic has passed the light. Second, false alarms can be caused by minor falls of rock and ice, and by rocks that roll across the railroad or highway. In general, warning fences are best suited to low-traffic-density routes where rockfalls occur infrequently, and more expensive stabilization work cannot be justified.

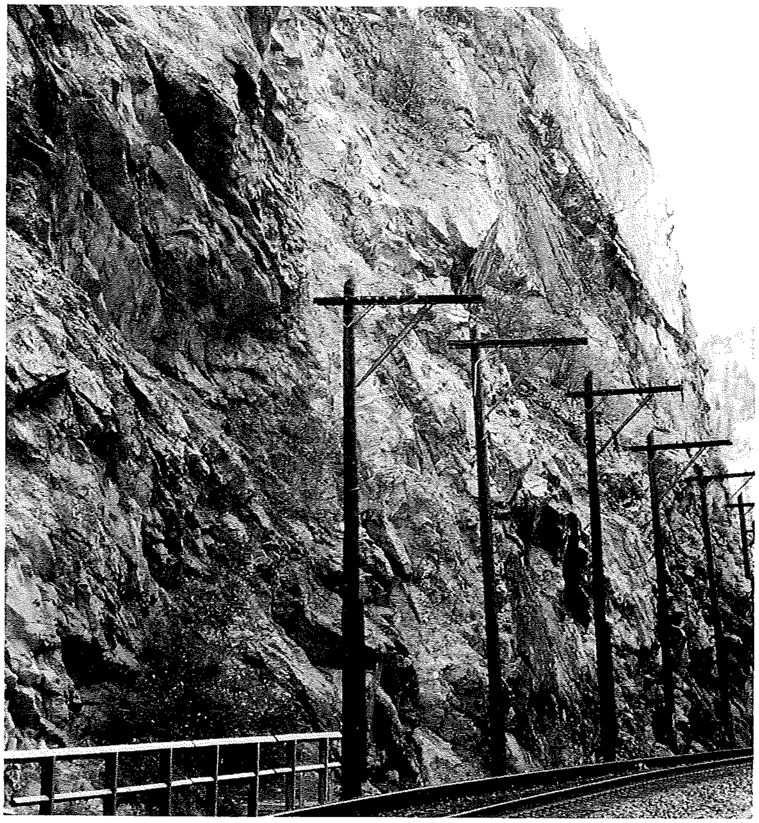
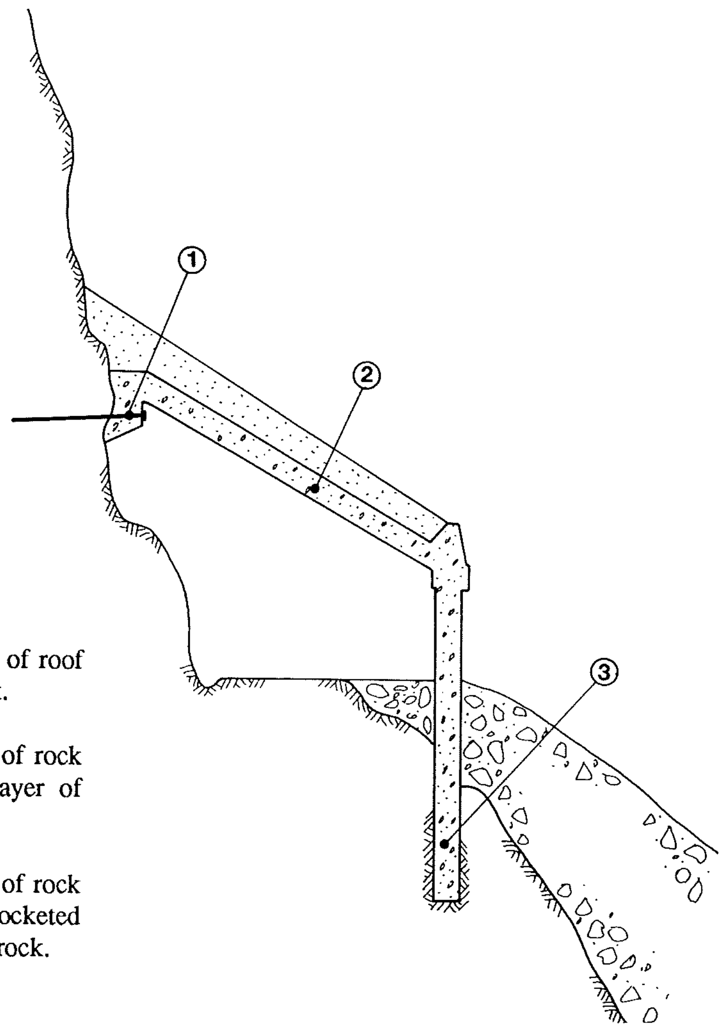


Figure 11. Typical warning fence at the toe of a steep rock slope to detect rock falls on a railway.

5.5 Rock Sheds and Tunnels

In areas of extreme rockfall hazard where stabilization work will be very costly, construction of a rock shed, or even relocation of the highway or railroad into a tunnel may be justified. If a shed can be constructed with the roof at close to the angle at which the rocks are rolling down the slope, then a lightweight roof can be constructed using timber for example. In this case, the roof will direct the rocks over the track, rather than withstand a direct impact.

Figure 12 shows a possible construction procedure for a rock shed where there are steep slopes above and below the highway. In this case, the roof will be subject to significant impact loads from rocks falling down the steep slope. The critical features of the design are the anchorage of the roof to the cliff face, the footings in the slope below the road, and the gravel on the roof to protect the concrete from rock fall damage.



1. Support for upper end of roof anchored to sound rock.
2. Sloping concrete roof of rock shed protected with layer of gravel.
3. Support for lower end of rock support with pier socketed through fill into sound rock.

Figure 12. Rock shed construction showing possible anchoring and foundation construction methods.

In locations where it is impractical to construct a rock shed, it may be necessary to drive a tunnel to by-pass the hazard zone. For example, a railway in British Columbia drove a 1200 m (3900 ft.) long tunnel to avoid a section of track located on a narrow bench between a 1000 m (3300 ft.) high unstable rock cliff and a 200 m (660 ft.) deep lake. Major rock falls were a hazard to train operations and had caused the track closures lasting as long as two weeks (Leighton 1990).

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