Flexible Wire Rope Rockfall Nets

JOHN D. DUFFY

The California Department of Transportation field tested and evaluated wire rope rockfall nets designed to absorb and dissipate rockfall impact energies as high as 200 kilojoules (70 ft-tons). The nets were supplied by Brugg Cable Products of Switzerland, and L'Entreprise Industrielle of France. Over 80 tests were conducted in which rocks weighing 136 to 5900 kg (300 to 13,000 lb) were rolled down a 76-m (250-ft) long, 34-degree slope. Rockfall impact energy was calculated by adding translational kinetic energy and rotational kinetic energy. Wire rope net energy dissipation was analyzed. The nets stopped rocks delivering impact energies up to 2.5 times design load with acceptable levels of maintenance. Maintenance and cleaning of the nets was easily accomplished by personnel using normal equipment and supplies. Damaged net components were repaired in a few minutes to 4 hr by maintenance crews. Wire rope rockfall catch nets will become a part of the rockfall mitigation measures available for use along California highways.

The purpose of this research project was to construct, test, and evaluate the effectiveness of flexible wire rope rockfall nets that will be used to mitigate rockfall. All aspects of the installation and performance, including field repair and cleaning, were evaluated.

Two manufacturers participated in this research: Brugg Cable Products of Switzerland and L'Entreprise Industrielle (EI) of France. Both manufacturers had tested their systems under controlled conditions (*1,2*), but no testing had been done under actual field conditions. Therefore, the California Department of Transportation (Caltrans) conducted tests and evaluations of these systems before the installation of a state project (*3*).

Brugg's system was constructed and tested by Caltrans personnel on August 8 through August 11, and again from November 13 through November 16, 1989. The EI system was constructed and tested on December 4 through December 7, 1989.

DEFINITION OF ROCKFALL NET

A rockfall net is a flexible barrier capable of catching and containing falling rocks (see Figure 1). This capability is a result of the net's design as a flexible system rather than as a standard, fixed-wire fence system. A properly designed barrier is flexible enough to absorb the anticipated energy with minimum damage to the system. Considerable flexibility is inherent in both the net material and the support wire rope infrastructure. Additional flexibility is added by using energy-dissipating friction brakes, which are attached to the wire rope support system and dissipate energy through friction as the wire ropes are pulled in tension. The two rockfall net systems tested by Caltrans consisted of rectangular panels of woven wire rope vertically supported by steel posts and designed with frictional brake elements. Both systems utilize woven wire rope with a fiber core. This construction provides greater flexibility than conventional steel-core cable.

California Department of Transportation, 50 Higuera Street, San Luis Obispo, Calif. 93401.

ROCKFALL NET DESIGNS

Both Brugg's and EI's woven wire rope net panels were 5 m (16.4 ft) wide and 3 m (9.84 ft) high. The panels were formed by weaving a single, continuous 9.5-mm (5/16-in.) wire rope into a 200-mm × 200-mm (8- × 8-in.) diagonal pattern around a wire rope border. Brugg net grid intersections were secured with machine-crimped fasteners fabricated from mild steel that had been coated with a corrosion-resistant zinc compound, whereas EI secured intersecting points with modified stainless steel cable clips. Both nets were covered on the impact side with chain-link mesh that was connected with wire ties on 0.6-m (2-ft) spacing. Chain-link mesh was used because of its flexibility.

Brugg's panels were connected to an 18-mm (3/4-in.) perimeter wire rope (minimum tensile strength, 24 tons) with 9.5-mm (5/16-in.) wire rope lacing (see Figure 2). Adjacent net panels were also connected together with lacing. The perimeter wire rope was fitted at the top and bottom of each panel with a single friction brake (minimum tensile strength, 22 tons).

Brugg friction brakes consisted of a loop in the wire rope secured with a heavy friction clamp and four bolts. The bolts were tightened to a specified torque to provide the desired tensile strength. When forces exceed this value, the brake is activated and the loop closes when the cable slips through the friction clamp. Brugg nets were suspended by wire ropes attached to 200-mm (8-in.) wide flange steel posts secured to the ground by concrete foundations and wire rope stanchions (see Figure 3). The upslope wire ropes were fitted with a friction brake (minimum tensile strength, 13.5 tons).

EI woven wire rope panels were not hung from a perimeter wire rope, but directly attached to the support posts (see Figure 4). Adjacent panels were joined together with steel bands. EI's friction brakes are four-bolt clamps shaped to accommodate two wire ropes that are sandwiched between them and tightened to a predetermined amount by applying a torque to the bolts. Each brake is preset to a minimum tensile strength of 2.75 tons. Instead of wire rope loops as used in the Brugg system, EI's brakes have excess wire rope exiting the brake. The excess wire rope is designed to slip through the braking device under tension. The length of this wire rope is predetermined and corresponds to anticipated

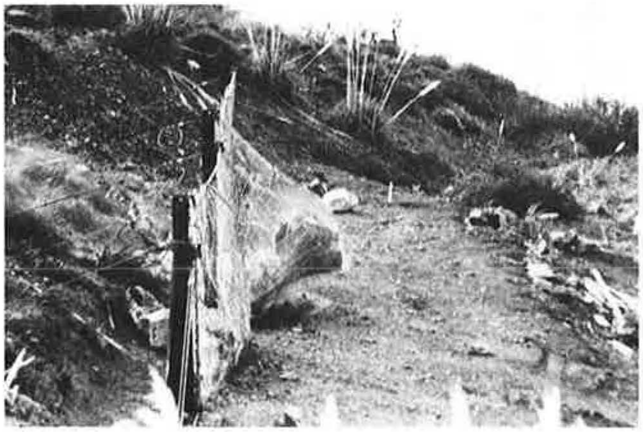

FIGURE 1 Brugg flexible rockfall net in action (rock weighs 3 tons) (Courtesy of John Walkinshaw, FHWA).

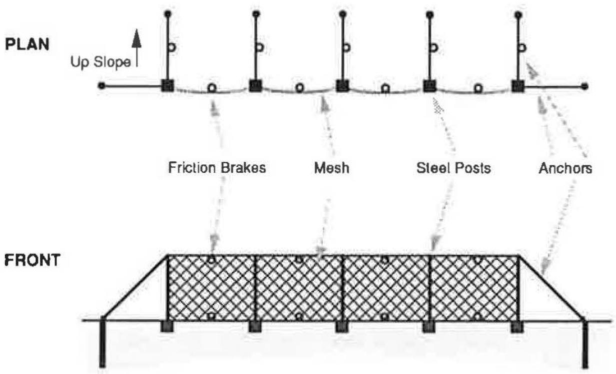

FIGURE 2 Typical plan view and front view of Brugg rockfall net.

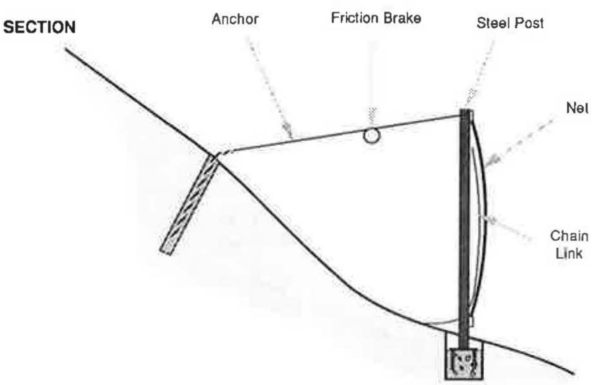

FIGURE 3 Typical side view of Brugg rockfall net.

energy dissipation. Short sections of chain, referred to as a fuse link, connect the friction brakes to fixed locations at each panel corner and ground anchor location.

EI nets were supported by four 140-mm (5½-in.), 4-mm (5/32-in.) galvanized steel box posts. A concrete foundation is not required for the EI rockfall net. Instead, the base of each steel post rests on the ground and is secured by 0.6-m (2-ft) long steel stakes driven through post baseplate holes into the ground. Each post was supported by three 12-mm (½-in.) guy wire ropes looped over the top (see Figure 5). The two end posts had a similar guy wire rope attached to lateral anchors. A single 6-mm (¼-in.) wire rope was attached to both the base of the posts and the upslope anchors to restrict the movement of the base of the post.

TEST PROCEDURE

In order to observe and analyze the flexible rockfall nets under field conditions, nets were constructed at the base of a slope and boulders of various sizes were rolled down the slope into the nets. Brugg's test section was 19.5 m (64 ft) long and 3 m (10 ft) high. EI's test section was 15 m (49 ft) long and 3 m (10 ft) high. The slope used for the tests was 40 m (130 ft) high and 65 m (215 ft) long with an overall slope angle of 34 degrees (see Figure 6). The slope measured along the ground surface was 76 m (250 ft) long. Relative to the rockfall diameters, the slope was smooth and did not greatly affect rockfall trajectories. There were, however, several gullies that affected rockfall trajectories of small, 0.3- to 0.6-m (1- to 2-ft) diameter boulders. Vegetation was sparse and had little, if any, effect on rockfall trajectories.

The slope material was composed of landslide debris consisting of 25- to 450-mm (1- to 18-in.) rock fragments in a matrix of clayey silt. This material was dry and hard during all three tests. However, in some areas, successive boulder rolls broke up the surface and created soft spots in the slope that seemed to decrease the velocity of some boulders. Test boulders were composed of hard, competent rock with a specific gravity ranging from 2.91 to 3.03. For test purposes, many of the rocks selected were round. Eighty boulders were rolled.

Before rock rolling, the three principal axes (x, y, and z) of each boulder were measured and the values were used to estimate rock weight and inertia. Fifteen boulders were accurately weighed with a load cell. Rock weights ranged from 136 kg (300 lb) to 5,900 kg (13,000 lb). Rock rolling was recorded on video and high-speed (16-mm) film from four locations along the slope. Four cameras captured two side, one oblique, and one front view.

Reference lines at 15-m (50-ft) intervals were placed on the slope perpendicular to the slope axis, which allowed detailed measurements of rockfall velocities. In addition, stadia rods 1 to 2 m (3 to 6 ft) high were randomly placed on the slope for bounce height analysis.

The nets were examined periodically during testing and net performance was recorded while repairs were made between rock rolls when necessary.

Rockfall Energy Analysis

Kinetic energy is the most common measurement used to describe rockfall for engineering design. According to Chasles' theorem, any general displacement of a rigid body (boulder) can be represented by a translation plus a rotation (*4*). On the basis of this theorem, the process of rockfall is made up of two components—translational motion and rotational motion—which can be quantified as energy in motion,

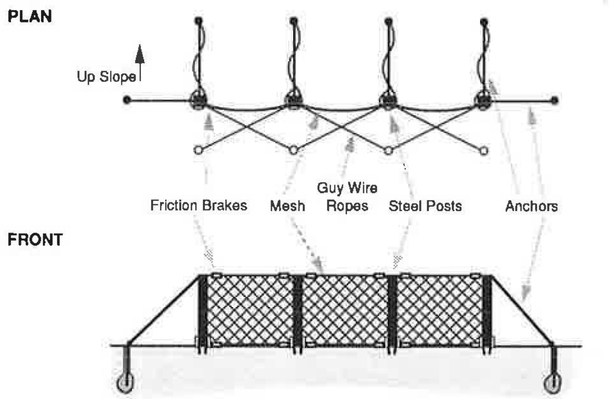

FIGURE 4 Typical plan view and front view of EI rock net.

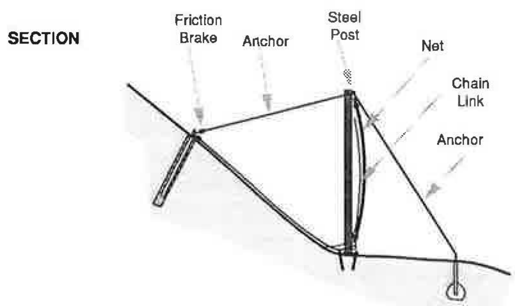

FIGURE 5 Typical side view of EI rockfall net.

or kinetic energy. Calculation of these kinetic energies (KE) is based on the assumption that the mass of the boulder is concentrated at the center of mass, and its motion revolves around the center of mass (*4*). Rockfall motion is therefore the sum of the translational kinetic energy (KE_T) and the angular kinetic energy (KE_A) (*5–7*). This sum, the total kinetic energy (KE), is expressed mathematically as

$$\text{Total } KE = KE_T + KE_A = 1/2mv^2 + 1/2I\omega^2 \quad (1)$$

where

m = mass of the boulder,
v = velocity of the boulder just before impact,
I = moment of inertia of the boulder as it spins, and
ω = angular velocity of the spinning boulder just before impact.

Rockfall kinetic energy is most commonly described in units of foot-tons, foot-pounds, or kilojoules.

Dynamic Load Path Analysis

The dynamic load path analysis was performed in an attempt to determine the forces occurring within individual net components. This information was used to study the net system and how the load is distributed. Because of the difficulties of analyzing dynamic loading, broad assumptions were made in this analysis. Therefore greater reliance should be placed on empirical field performance in the design of nets.

Rocks striking the net generate forces throughout the net system that are dissipated through the flexibility of the net. These forces emanate from the point of impact to the net system perimeter and apply loads that travel along a load path (Figures 7 and 8). The load path consists of several structural net components with various strengths and load-dissipation capabilities. When all components in the load path are in equilibrium, the net system is balanced. A balanced net system is the optimum design for load-carrying capacity.

Three rockfall impacts were analyzed dynamically to identify the load path and the loads within the load path. This was accomplished by analyzing the film footage of actual tests and using those data in the calculations.

Such events are analyzed using the vector quantities of impulse and momentum:

$$Ft = mv$$

$$\text{Impulse} = \text{momentum change} \quad (2)$$

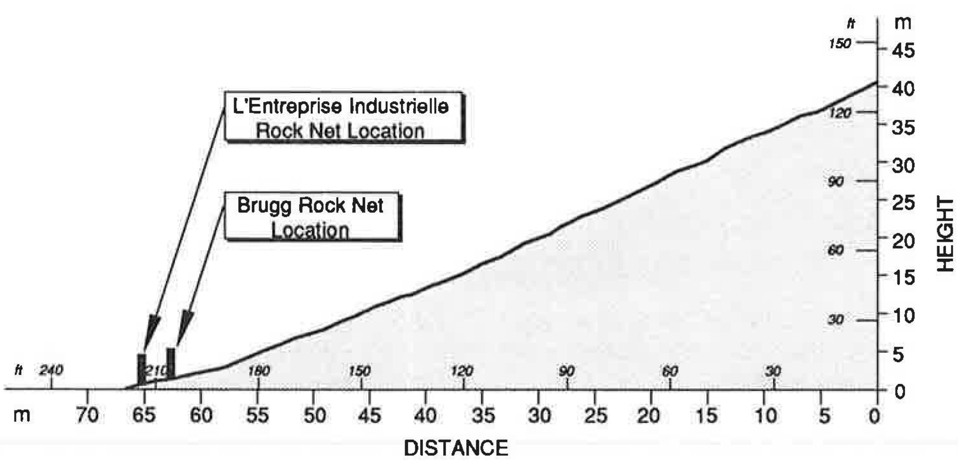

FIGURE 6 Cross section of test slope.

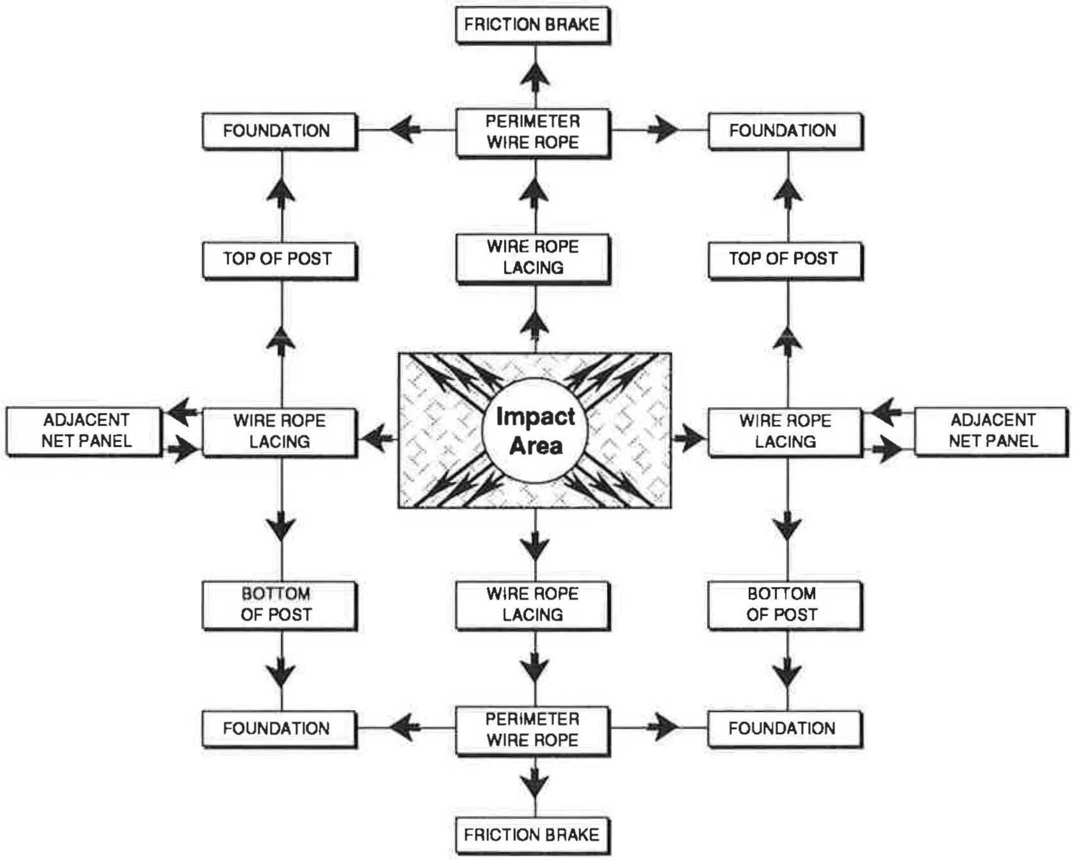

FIGURE 7 Flowchart of Brugg net system load path (arrows indicate direction of rock impact energy).

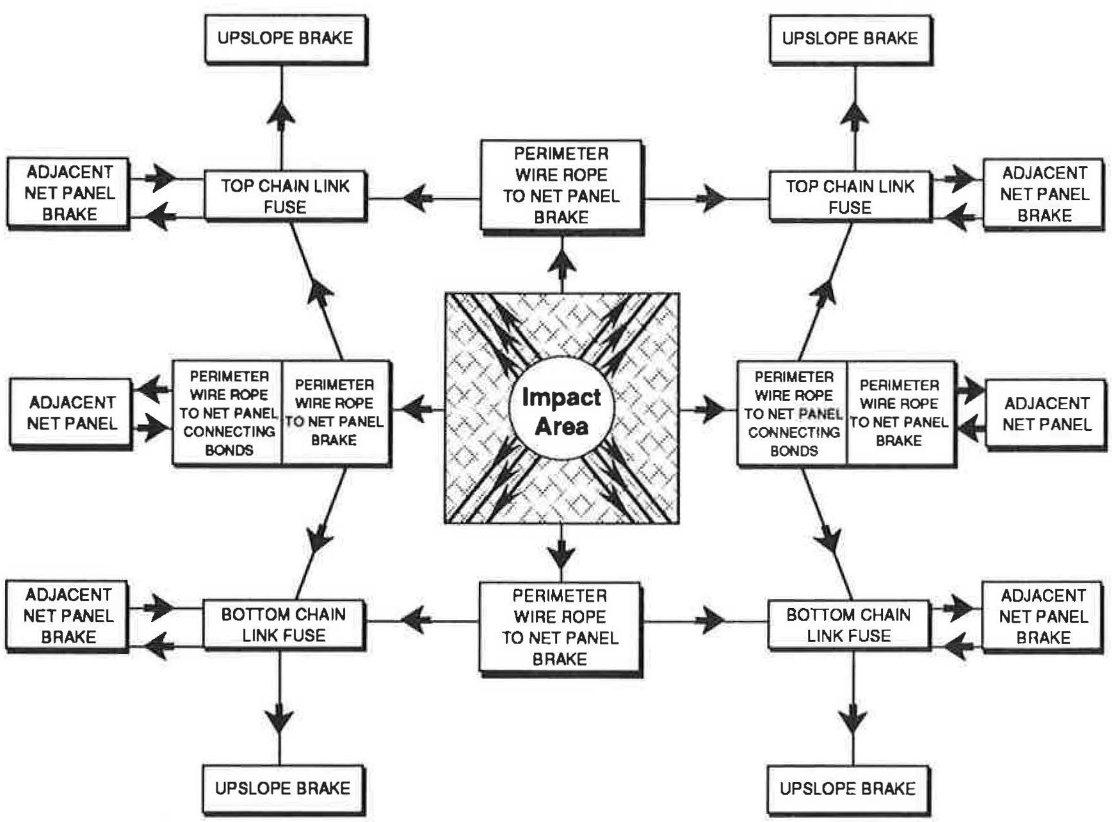

FIGURE 8 Flowchart of EI net system load path (arrows indicate direction of rock impact energy).

where

F = applied force,
t = time the boulder takes to decelerate to zero,
m = mass of the boulder, and
v = translational velocity at the initial point of impact (7).

An attempt was made to calculate the distribution of the impact loading. Because of the difficulty of mathematically predicting dynamic loading, an idealized net system was assumed. This system consisted of a 200-mm (8-in.) mesh attached to a 18-mm (¾-in.) perimeter cable. It was assumed that the rock struck the center of the net panel, although in actual testing the rocks hit all areas of the nets. This idealized analysis indicated that under the assumed conditions, the load per 100 percent loaded net strand is 2,024 kg (4,463 lb). The load in the top and bottom perimeter wire rope, where the load-dissipating friction brakes are located, was 11,984 kg (26,421 lb) in the outer third of the wire rope, 5,180 kg (11,425 lb) in the middle third of the wire rope, and 5,365 kg (11,829 lb) in the upslope anchor cable.

The values obtained in this analysis are based on broad assumptions. For detailed net design, empirical field test data should be used.

PERFORMANCE OF ROCKFALL NETS

The specified design load was 200 kJ (70 ft-tons) of impact energy. This value was intentionally exceeded to evaluate the maximum capacity of the nets. Throughout the tests, the nets were examined periodically. Typically, the nets were inspected when damage was observed. Net performance was recorded while necessary repairs or adjustments, or both, were made before the next rock-rolling sequence. Particular attention was given to maintenance of the nets.

Brugg Testing

Brugg's rockfall nets caught and contained rockfall impacts 2.5 times greater than the design load within acceptable levels of maintenance. Impacts 2 to 3.5 times greater than the design load were stopped, but maintenance was considerable. For impacts exceeding 3.5 times the design load, rock energy was attenuated but the rock passed through the net. Significant reductions in maintenance were achieved when 2.5-mm mild steel net-panel fasteners were used, when support cables were not fixed to the posts, and when chain-link mesh was used to cover the impact side of the net. Brugg's energy-absorbing friction brakes rarely activated, and weaker components in the energy path were consequently loaded to failure.

EI Testing

EI's rockfall nets caught and contained rockfall impacts 1.5 times above design load with acceptable levels of maintenance. One rock impact that was 2 times the design load was not stopped by the net. Significant reductions in maintenance could be achieved by increasing post strength to the equivalent of the posts used in the Brugg tests, and also by increasing net-panel connector strengths. EI's energy-absorbing friction brakes activated easily, even when rocks struck the net at less than the design load. As a result, net panels sagged considerably after only two rock impacts.

MAINTENANCE OF ROCKFALL NET SYSTEMS

Considerable interest has been expressed by maintenance personnel throughout California concerning the amount of repair and methods for cleaning rock-restraining nets. Because maintenance is an important consideration in the use of the nets, a significant effort was made during these tests to evaluate rock net maintenance.

Input was solicited from maintenance personnel during all phases of this study. It was concluded that rock nets could be maintained within acceptable limits using standard maintenance equipment and procedures. In most cases, repairs and cleaning were completed in 1 to 4 hr. It was determined during the study that rockfall accumulations behind a single panel could be removed easily and quickly while still providing maximum protection to workers and the traveling public. Access for clearing boulders and rockfall debris from the rock nets was gained by disconnecting the net panel along the top or bottom, and then raising or lowering the net panel.

In summary, cleaning and repair of a rock net restraining system can be accomplished by a typical maintenance crew using readily available tools such as ratchet wrenches and sockets, torque wrenches, come-alongs, pry bars, and, where possible, front-end loaders.

CONCLUSIONS

- Design load rockfalls were effectively stopped by both rock nets.
- Repair and cleaning are required and can be done quickly and safely with equipment that is readily available at all maintenance stations.
- Brugg net panels deflected downslope by as much as 2 m (6 ft) under the design load.
- EI's net panels deflected downslope by as much as 3 m (12 ft) under the design load.
- EI's net system requires more space than the Brugg system to accommodate downslope anchors and downslope deflection.
- Chain-link mesh is an integral part of the net design. The mesh prevents small rock fragments from passing through the net and reduces net damage.
- Brugg's friction brakes rarely activated. As a result, the energy that should have been dissipated by the brakes was transferred to other net components.
- EI's friction brakes were effective in dissipating energy, but activated so easily that the nets sagged considerably even after a single design load impact.
- EI's net posts were damaged by direct impacts below design load, requiring replacement or repair.
- Both foundation anchor designs provided adequate support to the net system.

• Proper selection of a rock net requires a detailed site investigation to determine rockfall trajectories and impact energies.

RECOMMENDATIONS

The following recommendations are intended to serve as a guide to reduce maintenance on rock nets designed to contain 200 kJ (70 ft-tons) of energy:

• Proper selection and design of rockfall mitigation measures should be based on a detailed site investigation. This includes, but is not limited to, determining slope geometry, rockfall size and frequency, and an analysis of rockfall trajectories and impact energies.

• The Brugg 2.5-mm mild steel net fasteners are recommended for use with their system.

• Attaching chain-link fencing to the net panels is recommended.

• All attachments of the Brugg net panels should be made exclusively to the perimeter wire rope and adjacent panels, rather than to the posts.

• When lacing is used to attach Brugg net panels, 8-mm (5/16-in.) wire rope lacing should be used to prevent net-panel failure.

• Brugg 18-m (3/4-in.) friction brake tensile strength should be reduced to balance the impact load distribution, which will reduce the need for repairs.

• EI 16-mm (5/8-in.) friction brake tensile strength should be increased to better balance the impact load distribution and reduce excessive net sag after impact.

• EI support post strength should be increased to that of a W8 × 48 steel post to eliminate the need for post replacement.

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