California Department Of Transportation
Transportation Materials And Research

FIELD TESTS AND EVALUATION OF ROCKFALL RESTRAINING NETS

Report No. CA/TL - 90/05

Final Report

June 1990 - Revised 9/90

Presented by
DUANE D. SMITH & JOHN D. DUFFY

State of California

DEPARTMENT OF TRANSPORTATION

Division of New Technology,
Materials and Research

Office of Transportation Materials and Research

FIELD TESTS AND EVALUATION OF ROCKFALL RESTRAINING NETS

Performed by..Engineering Geology Branch

Supervised by..Marvin L. McCauley

Principal Investigator..Duane D. Smith

Co-Principal investigator..John D. Duffy

Co-Investigator..Ralph Fitzpatrick

Report Prepared by ....Duane D. Smith
John D. Duffy

Duane D. Smith

EARL SHIRLEY, Chief
Office of Transportation Materials and Research

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. CA/TL-90/05	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Field Tests and Evaluation of Rockfall Restraining Nets		5. REPORT DATE June 1990 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Duane D. Smith and John D. Duffy		8. PERFORMING ORGANIZATION REPORT NO. 65322 - 642479
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Transportation Materials and Research California Department of Transportation Sacramento, California 95819		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. F90TL61
12. SPONSORING AGENCY NAME AND ADDRESS California Department of Transportation Sacramento, California 95807		13. TYPE OF REPORT & PERIOD COVERED Final July 1989 - June 1990 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted as a state-financed research project under the project entitled, "Field Test and Evaluation of a Rock Net Restraining System."

16. ABSTRACT

The California Department of Transportation field tested and evaluated rock restraining nets engineered to absorb and dissipate rockfall impact energies to a maximum of 70 ft-tons. The nets were supplied by Brugg Cable Products (Switzerland) and Industrial Enterprise (France) and constructed by Caltrans personnel. Rocks were rolled down a 250-foot-long, 34-degree slope into the nets. Test rocks weighed from 300 to 13,000 pounds. Rock rolls were recorded on video and slow motion cameras for analysis.

Rockfall impact energy (total kinetic energy) was calculated by adding translational kinetic energy and rotational kinetic energy. Over 80 tests were conducted and analyzed. Rock net energy dissipation characteristics were analyzed. Based on field performance and energy analysis, modifications and adjustments in net design were made to reduce net maintenance. These nets stopped rocks delivering impact energies 1.5 to 2.5 times above the design load with acceptable levels of maintenance.

Maintenance and cleaning of the nets was easily accomplished by Caltrans maintenance personnel using normal maintenance equipment and supplies. Removal of rockfall debris can be accomplished by raising or lowering the net to allow access. Nets at road level can be cleaned with typical maintenance equipment. Damaged net components can usually be reused or repaired in a few minutes to two hours by a maintenance crew.

These wire rope rock restraining nets will become an integral part of the rockfall mitigation measures available for use along California's highways.

17. KEY WORDS Rockfall mitigation, rockfall restraining nets, rock nets.	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the California Department of Transportation, Office of Transportation Materials and Research, Sacramento, California 95819.

19. SECURITY CLASSIF. (OF THIS REPORT)	20. SECURITY CLASSIF. (OF THIS PAGE)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified		

DS-TL-1242 (Rev. 6/76)

NOTICE

The contents of this report reflect the views of the Division of New Technology, Materials and Research which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

The State of California does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English Unit	Multiply By	To Get Metric Equivalent
Length	inches (in) or (")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft) or (')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic yards (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lb) kips (1000 lb)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lb) foot-pounds (ft-lb)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (°F)	$\frac{°F - 32}{1.8} = °C$	degrees celsius (°C)
Concentration	parts per million (ppm)	1	milligrams per kilogram (mg/kg)

ACKNOWLEDGMENTS

Special thanks to Robert Thommen and Bruno Haller of Brugg Cable Products and Alain Lazard, Patrick Nouvele and Roger Gateff of Industrial Enterprise for their generosity in providing their rock nets and their technical expertise in constructing them.

We greatly appreciate the time and effort of District 5 personnel and, in particular, the Willow Springs Maintenance crew, under the direction of Don "Robbie" Roberts, for their assistance in constructing and field testing the net systems.

Thanks are extended to Walt Richards of the Structural Materials Branch of the Office of Transportation Materials and Research for his technical expertise in testing friction brakes. Mark Seyed-Ranjbari of the Special Analysis Group, Office of Structure Design, is also thanked for his assistance in analysis of the dynamic load path.

We also thank the following individuals in Caltrans for their assistance in making this project possible.

Drilling	Max Sheaman David Johnson
Concrete Design	Don Roberts
Welding and Metallurgy	Paul Hartbower
Graphics	Ed Fong Irma Gamarra-Remmenn
Still Photography	Lynn Harrison
Motion Pictures	Gary Pund

The authors also thank Darla Bailey who good-naturedly typed this report and its many revisions.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF PHOTOS

LIST OF PHOTOS (Continued)

LIST OF PHOTOS (Continued)

LIST OF PHOTOS (Continued)

INTRODUCTION

The purpose of this research project was to construct, test, and evaluate the effectiveness of rock nets that will be used to mitigate rockfall hazards at selected sites in California. All aspects of the installation and performance, including field repair and cleaning, were evaluated and documented on video tape

Rockfall problem areas were identified along approximately 3000 miles of California highways in a rockfall mitigation study conducted by the Transportation Laboratory (4). It was concluded during the 1985 study that rolling rocks up to two feet in diameter may be restrained by wire mesh fence, commonly known as "chain link" fence. However, restraining devices of this type frequently suffer severe damage. It therefore became apparent during this initial study of rockfall mitigation that a "rock fence" or rock net designed to withstand much greater forces than the conventional chain link fence was needed to control large rockfall events. Such rock and snow structures designed to protect railroads, highways, mountain communities, and ski facilities have been in use for many years in Switzerland and France.

Brugg Cable Products, Inc., of Switzerland, developed high-impact wire rope net systems during the early 1950s for protection from snow avalanches and rockfall. A patented braking device, designed to dissipate high-impact energies, was developed and incorporated in their systems in 1975. The brake system dissipates energy through friction and can be adjusted to dissipate different levels of energy. Brugg tested the system by dropping a 2200-pound concrete block 65.6 feet onto a net secured horizontally to a heavy steel frame. Heierli (3) described these early efforts by Brugg and others in a paper presented at the 1st International Meeting about the dynamics of rockfalls and efficiency of protective systems at the Institute of Models and Structures in Bergamo, Italy.

The Industrial Enterprise Corporation developed a rock restraining system in the 1960s to protect facilities such as power plants and transmitter lines. Their patented braking devices were developed under the direction of the Technical Equipment Center of Bron. Initial testing used a 75-foot jib crane and a swinging one-ton concrete test block. More recent testing used a concrete block that slid down an inclined cable and was released prior to impacting the rock net.

Apparently little, if any, actual field testing has been done where large boulders were rolled down natural slopes into rock nets. Therefore, little is known about the effects of rotational energy on individual components. Because available detailed data on the construction, performance, repair, and general maintenance of rock nets is not available, the decision was made to conduct our own tests and evaluations prior to installation of an actual project.

An excellent test site was selected on Coastal Highway 1 in Monterey County between Big Sur and San Simeon. It consisted of a 250-foot, 34-degree, unbroken slope free of heavy vegetation, with a relatively flat area at the base for installation of the rock nets. The site is below the existing highway and free of foot and vehicular traffic. Local maintenance forces provided an ample supply of various sized boulders and personnel to assist in the construction and testing of the rock nets.

Robert Thommen, Vice President and General Manager of the Santa Fe, New Mexico office of Brugg Cable Products of Switzerland, provided a rock net for testing (less the structural posts) and the technical assistance necessary to construct their system. This system was constructed and tested by Caltrans personnel on August 8 through August 11, 1989.

During the testing, it was found that some components required excessive maintenance when less than design load rocks impacted the nets. Brugg subsequently provided additional nets with redesigned components to lessen maintenance. The newly designed rock net was constructed and tested on November 13 through November 16, 1989 at the same test site.

At this time, Alain Lazard, Director of Diversified Ski Services of Squaw Valley, and the United States representative of Industrial Enterprise of Paris, France, provided their complete rock net for testing at this site. Their system was constructed and tested on December 4, through December 7, 1989.

Definition of a Rock Restraining Net

For purposes of this report, a "rock restraining net" is defined as a rockfall protective device engineered to stop large rockfalls. The system consists of rectangular panels of woven wire rope vertically supported by steel posts and designed with frictional brake elements capable of absorbing and dissipating high energies. Both restraining systems utilize woven wire rope which has a fiber core providing greater flexibility than conventional steel core cable

CONCLUSIONS

- Design load rockfalls were effectively stopped by both rock nets.
- Repair and cleaning is required and can be done quickly and safely with equipment readily available at all maintenance stations.
- Modifications in design of both systems can be made to reduce repair.
- Brugg net panels deflected downslope as much as six feet under design load.
- EI net panels deflected downslope as much as 12 feet under design load.
- The EI net system requires more space than the Brugg system to accommodate downslope anchors.
- Chain link mesh is an integral part of the net design. The mesh prevents small rock fragments from passing through the net and reduces localized net damage.
- Wire twists work more effectively than hog rings for attachment of the chain link fencing to the net panels.
- Brugg's 2 mm mild steel net fasteners frequently failed below 70 ft-tons of energy with and without the fencing. Broken fasteners were replaced with wire rope clips.
- Brugg's 2.5 mm mild steel and spring steel net fasteners performed well up to design loads.
- EI's net fasteners did not fail but required some repositioning after impact.
- Partial connection of Brugg's net panel to the posts directed energy to the net panel corners.
- Brugg's 5/16-inch wire rope lacing occasionally failed at design load in the fixed corners where the lacing was triple twisted.

- Brugg's 3/8-inch-diameter lacing cable performed well, but its use resulted in failure at design load of the net strands in the corners.

- Failure of Brugg's net panel strands and wire rope lacing could have been reduced by attaching all the ends of the lacing cable to the 3/4-inch perimeter wire rope.

- Connection of EI's net panel to the 5/8-inch-diameter perimeter wire rope was efficient and worked well.

- EI's connection between adjacent net panels required replacement after design load impacts.

- All of the perimeter wire ropes, guy wire ropes, and anchor wire ropes were properly sized and worked well.

- Brugg's friction brakes rarely activated. As a result, the energy which should have been dissipated by the brakes was transferred to weaker components which failed or were damaged.

- Improving Brugg's friction brake energy dissipation and reducing net component damage and failure can be accomplished by reducing brake tensile strength by 50% (Appendix C).

- Heavily torqued friction brakes and minimal friction surface of the Brugg friction brakes caused permanent distortion of the wire rope upon brake activation, requiring replacement.

- Laboratory testing of Brugg friction brakes suggests that reducing torque and increasing friction surface area will reduce distortion to the degree that they can be reused.

- 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. Excessive sagging, because of the long friction brake tails, greatly reduced rock catchment area.

- Net sagging in EI's system could be greatly reduced by shortening brake tail length by 50% and increasing friction brake tensile strength by as much as 100%. Support for this estimate is provided by dynamic load analysis (Appendix C). This analysis predicts that an increase in brake tensile strength will not load the net strands to the point of failure.

- EI's support posts were damaged below design load impacts requiring repair and/or replacement.
- Both foundation anchor designs provided adequate support to the net system.
- EI's post base support cable required replacement below design load impacts.
- Anchor foundation locations can be offset two to three feet to accommodate difficult drilling conditions.
- Proper selection of a rock net requires a detailed site investigation.

RECOMMENDATIONS

The following recommendations are intended to serve as a guide to reduce maintenance on rock nets designed to contain 70 ft-tons of energy.

- Proper selection and design of rockfall mitigation measures should be based on a detailed site investigation.
- The Brugg 2.5 mm mild steel net fasteners are recommended for use with their system.
- Chain link fencing attached to the net panels with wire twists is recommended.
- All attachments of the Brugg net panels should be made exclusively to the perimeter wire rope and adjacent panels rather than partially to the posts.
- When lacing is used to attach Brugg net panels, 5/16-inch wire rope lacing should be used to mitigate net panel failure.
- Brugg 3/4-inch friction brake tensile strength should be reduced by approximately 50% to reduce repairs.
- Industrial Enterprise 5/8-inch friction brake tensile strength should be increased by approximately 100% to reduce excessive sag.
- Industrial Enterprise support post strength should be increased to that of an W8 x 48 steel post to eliminate the need for post replacement.
- Attachment between individual Industrial Enterprise net panels should be strengthened to reduce repair.

IMPLEMENTATION

Implementation of knowledge obtained during this project has already begun by reviewing rockfall sites in the districts where wire rope restraining systems might be a viable mitigation measure. The report will be distributed to all Caltrans Districts and to other agencies, states and countries that have indicated an interest. Consultation with personnel engaged in designing rockfall mitigation measures has occurred and is expected to increase. Specific sites have also been investigated at the request of district personnel engaged in the design of slopes in areas subject to rockfall.

The instructional video tape on the installation and maintenance of the rockfall restraining nets tested during this project will be shown to district maintenance and design personnel throughout the state.

Design procedures are being developed based on this research which will be used to develop standard special provisions for implementation statewide.

INSTALLATION OF ROCK RESTRAINING NETS

Construction Techniques, Problems, and Solutions - Brugg

Description of a Brugg Rock Restraining System

The Brugg rock net constructed for the initial field testing in August 1989 consisted of four woven wire rope panels supported by five steel posts (Figure 1 and Photos 1 and 2). Individual panels were hung from a heavy perimeter wire rope supported by steel posts. The posts were set on concrete foundations secured by upslope and lateral anchor wire ropes. The upslope anchors and perimeter ropes were fitted with energy absorbing friction brakes.

This system was designed by Brugg to withstand 74 ft-tons of total kinetic energy with a safety factor of 1.5.

Brugg woven wire rope panels, 16.4 feet (5 m) wide and 9.84 feet (3 m) high, are formed by weaving a single, continuous 5/16-inch wire rope into an 8- x 8-inch diagonal pattern within a 3/8-inch border wire rope (Figure 2 and Photo 3). Both wire ropes are galvanized and painted with a corrosion-resistant light green paint. Intersections of the 8- x 8-inch grid are secured with machine-crimped fasteners fabricated from 2 mm mild steel that has been coated with a corrosion-resistant zinc compound (Photo 4). Intersections of the 5/16-inch panel rope and the 3/8-inch border rope are secured by heavy galvanized stop sleeves that are crimped to hold the grid system in place.

Eleven-gage chain link fencing material was used to cover each panel on the upslope side of the net. The chain link was attached to the woven wire panels with hog rings at approximately one-foot intervals along the perimeter and two-foot intervals across the face of the panel (Photo 5).

Each panel is connected to the 3/4-inch perimeter wire rope (minimum tensile strength = 48,160 pounds) by 5/16-inch wire rope lacing (Photo 6) which passes through the post fittings and is secured by a single U-bolt wire rope clip. The perimeter wire rope is fitted at the top and bottom of each panel with a single friction brake which has a minimum tensile strength of 44,800 pounds.

Friction brakes consist of a 4.9 foot (1.5 m) loop in the cable secured with a heavy friction clamp and four bolts (Photo 7). The bolts are tightened to a specified torque to provide the desired tensile

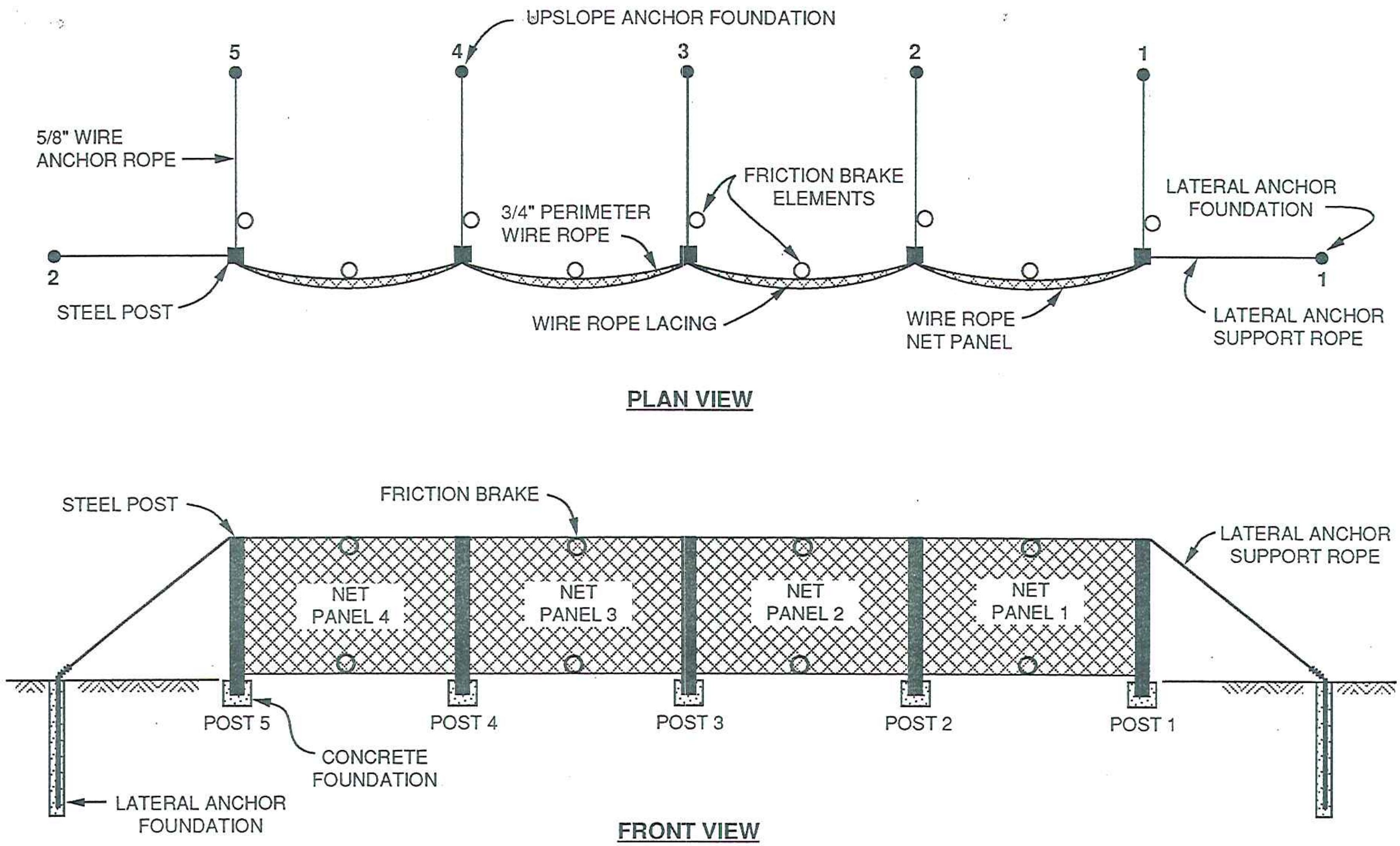


Figure 1. PLAN VIEW AND FRONT VIEW OF BRUGG ROCK NET CONSTRUCTED FOR THE INITIAL FIELD TESTING

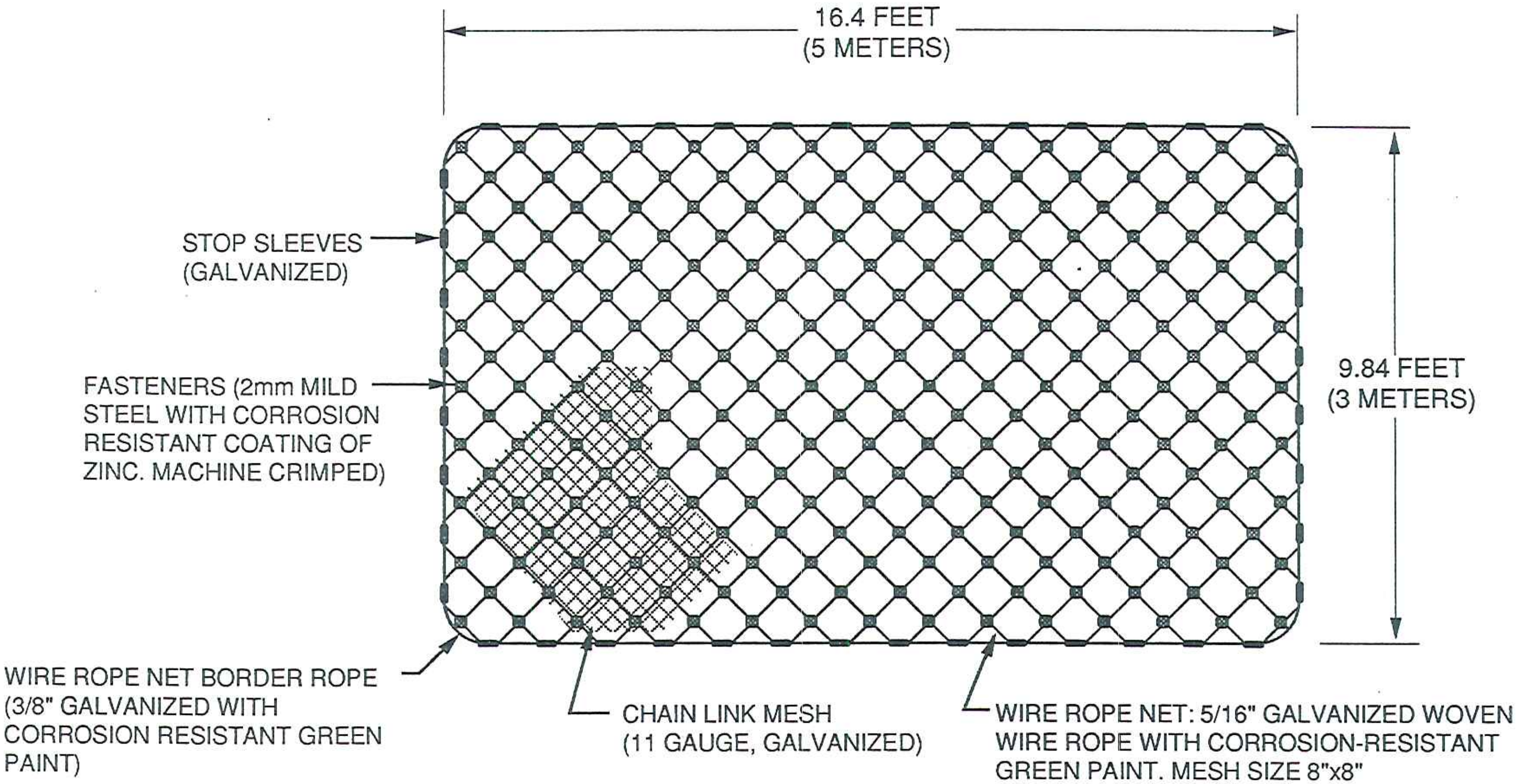


Figure 2. DETAIL OF THE BRUGG WOVEN WIRE ROPE PANEL USED IN THE INITIAL FIELD TESTING

Photo 1. VIEW OF BRUGG ROCK NET LOOKING 250 FEET DOWNSLOPE

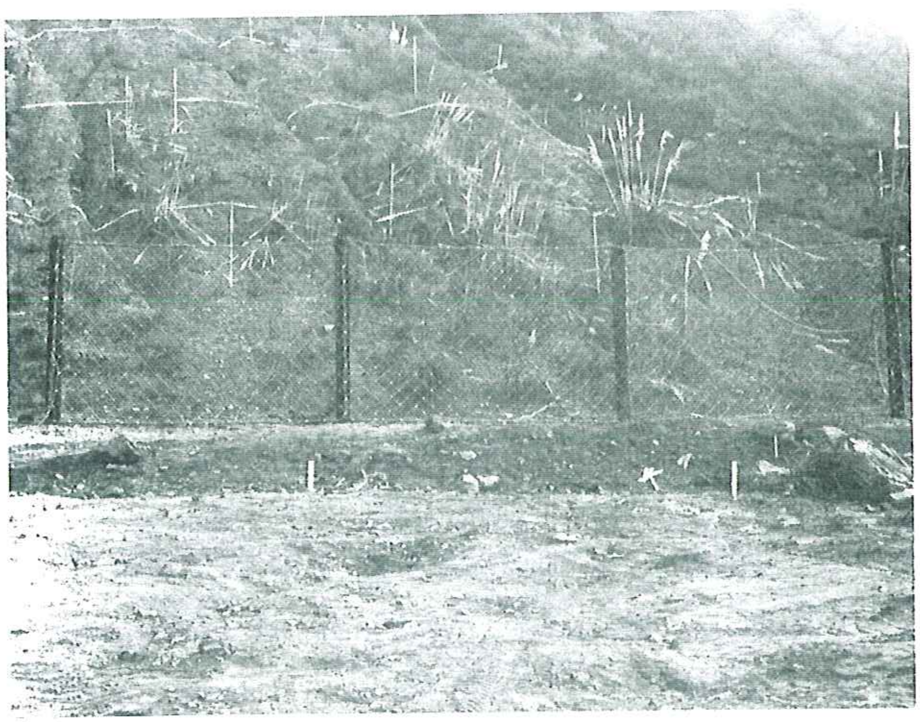


Photo 2. BRUGG ROCK NET AS IT APPEARS FROM ROADWAY GRADE

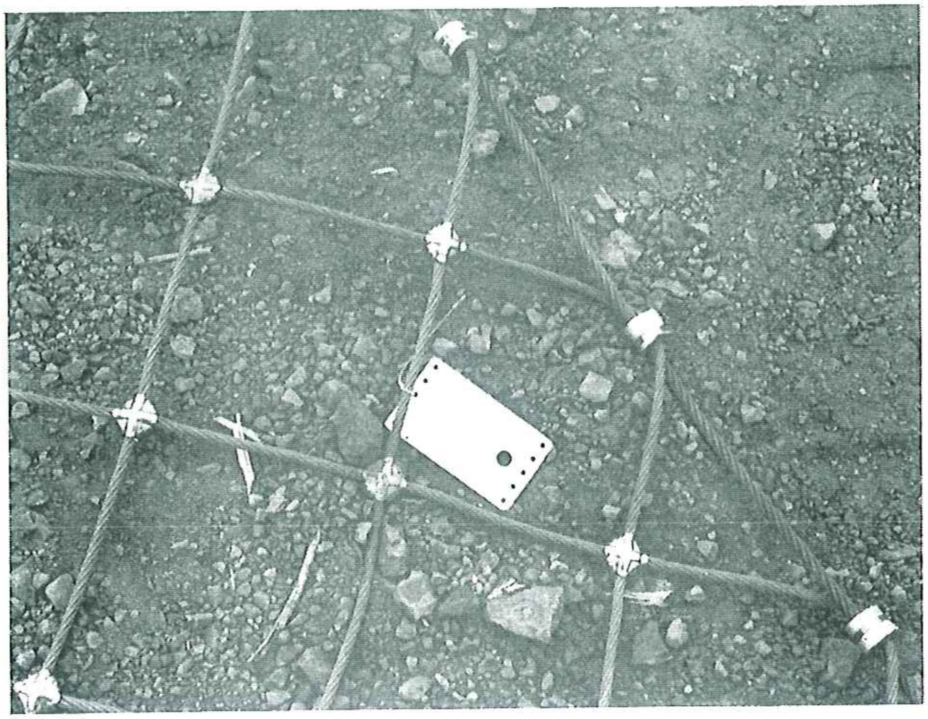


Photo 3. CLOSE-UP OF BRUG WOVEN WIRE ROPE NET SHOWING GRID SPACING, NET FASTENERS, AND BORDER ROPE

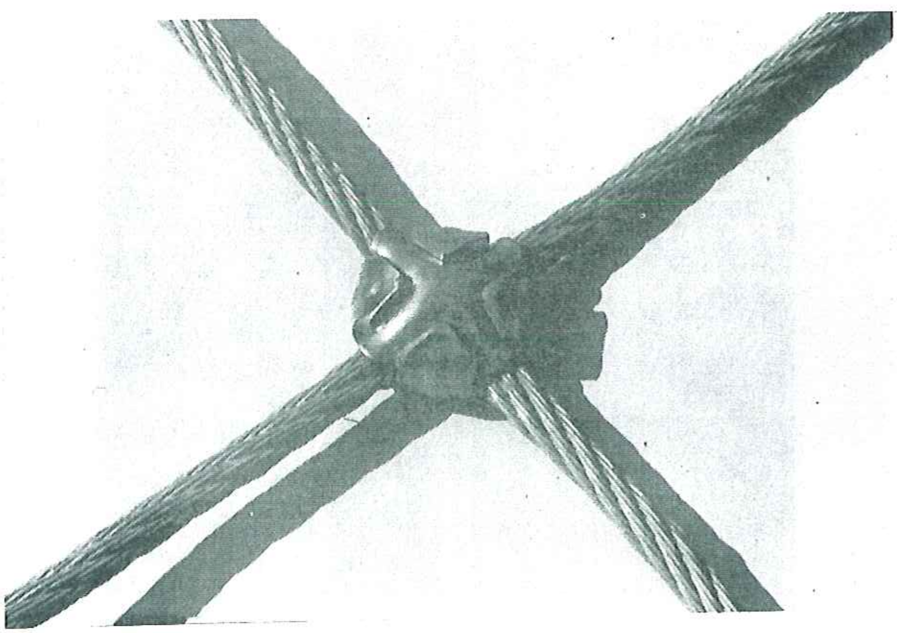


Photo 4. CLOSE-UP OF BRUGG MACHINE-CRIMPED NET FASTENER

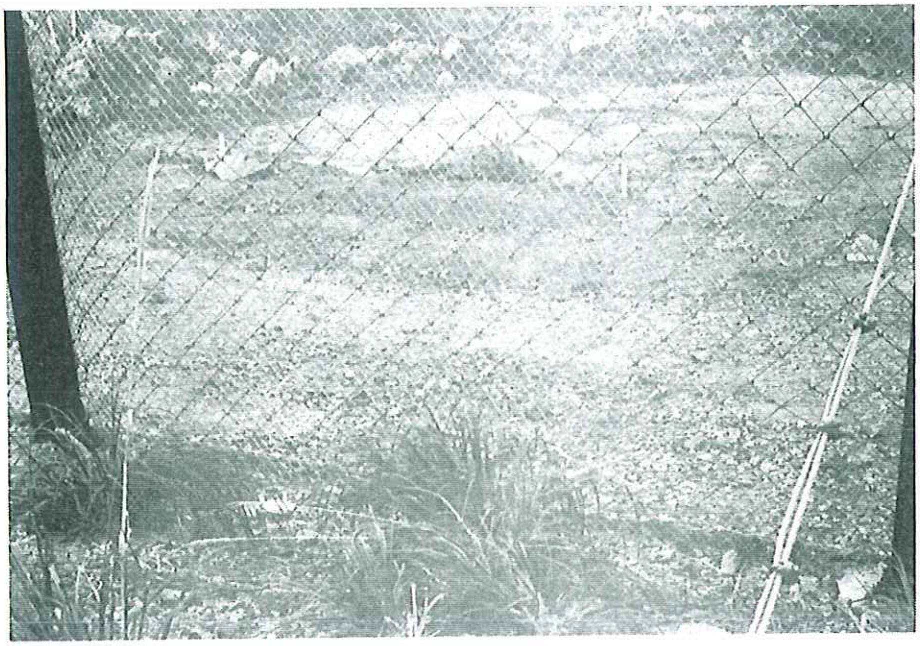


Photo 5. CHAIN LINK FENCING MATERIAL COVERING A BRUGG NET PANEL ON THE UPSLOPE SIDE. FENCING IS ATTACHED WITH HOG RINGS AND WIRE TWISTS

Photo 6. CONNECTING THE NET PANELS TO THE PERIMETER WIRE ROPE WITH WIRE ROPE LACING

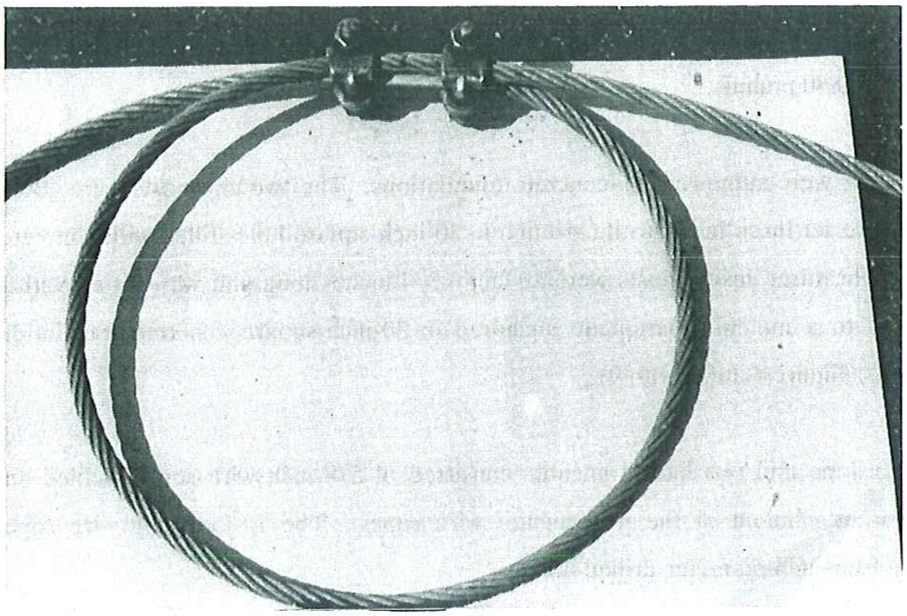


Photo 7. BRUGG FRICTION BRAKE WITH 4.9 FOOT ENERGY DISSIPATING LOOP AND HEAVY FRICTION CLAMP

strength. When forces exceed this value, the brake is activated and the loop is shortened by the cable slipping through the frictional clamp.

The net components are supported by five W8 x 48 steel posts. Stability of the wide flange posts and intervening panels is provided by 5/8-inch wire rope (minimum tensile strength of 37,632 pounds) anchored upslope. A similar support cable at each end of the net provided lateral support to the system. The upslope anchor wire ropes are fitted with one friction brake having a minimum tensile strength of 26,880 pounds.

All steel posts were supported by concrete foundations. The two end posts were 13 feet 5-3/4 inches long and were set three feet into the ground in 30-inch-square holes filled with concrete (Figure 3 and Photo 8). The three inside posts were 10 feet 5-3/4 inches long and were fitted with baseplates that were bolted to a matching baseplate anchored in 30-inch-square concrete foundations by steel "all thread" rods (Figure 4 and Photo 9).

The five upslope and two lateral anchors consisted of 5/8-inch wire rope doubled and fitted with a thimble for attachment of the post anchor wire ropes. The 10-foot-long wire rope anchors were grouted in four-inch-diameter drilled holes.

Drilling of Anchor and Post Foundation Holes

All anchor foundation holes were drilled to a depth of 10 feet with four-inch continuous flight augers by a hydraulically powered, truck-mounted articulated boom (Photo 10). Upslope and lateral anchor holes were drilled normal to the ground surface. Post foundation holes were drilled with a single 18-inch-diameter, four-foot-long auger flight similar to the type commonly used on spin auger drill rigs.

All borings were made in landslide debris consisting of 1- to 18-inch rocks in a clayey silt matrix. Drilling in the rocky, poorly consolidated material was very difficult. Inclined holes were more difficult than vertical ones because of the tendency for caving. Occasionally, large boulders were encountered and it was necessary to offset the anchor holes from their original location. Severe caving in two holes limited the depth of drilling to eight feet. These eight-foot anchors performed well.

The post foundation holes were constructed by drilling a hole with the 18-inch auger and finishing the excavation by hand.

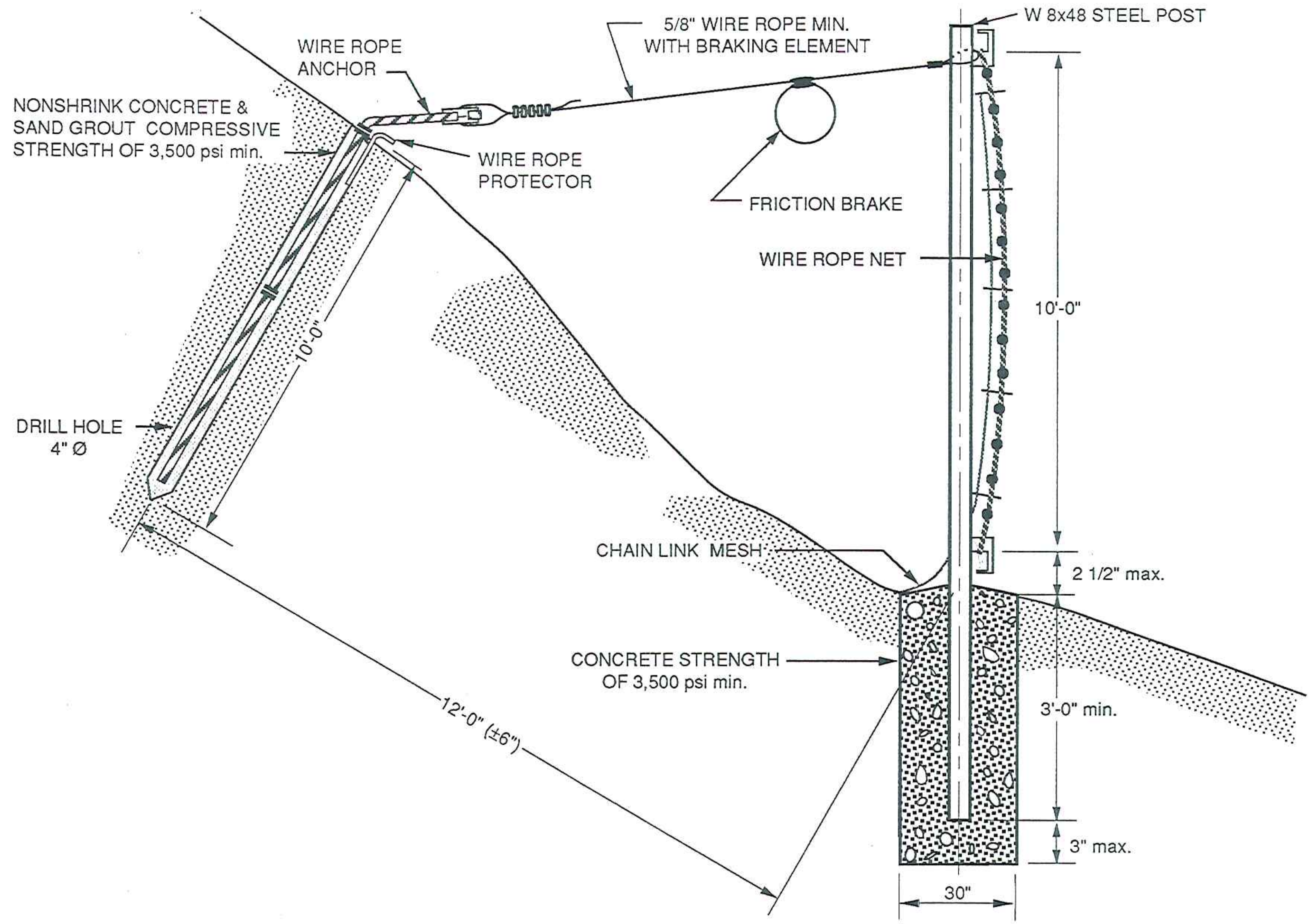


Figure 3. SIDE VIEW OF A BRUGG FULLY EMBEDDED POST FOUNDATION WITH UPSLOPE ANCHOR SUPPORT

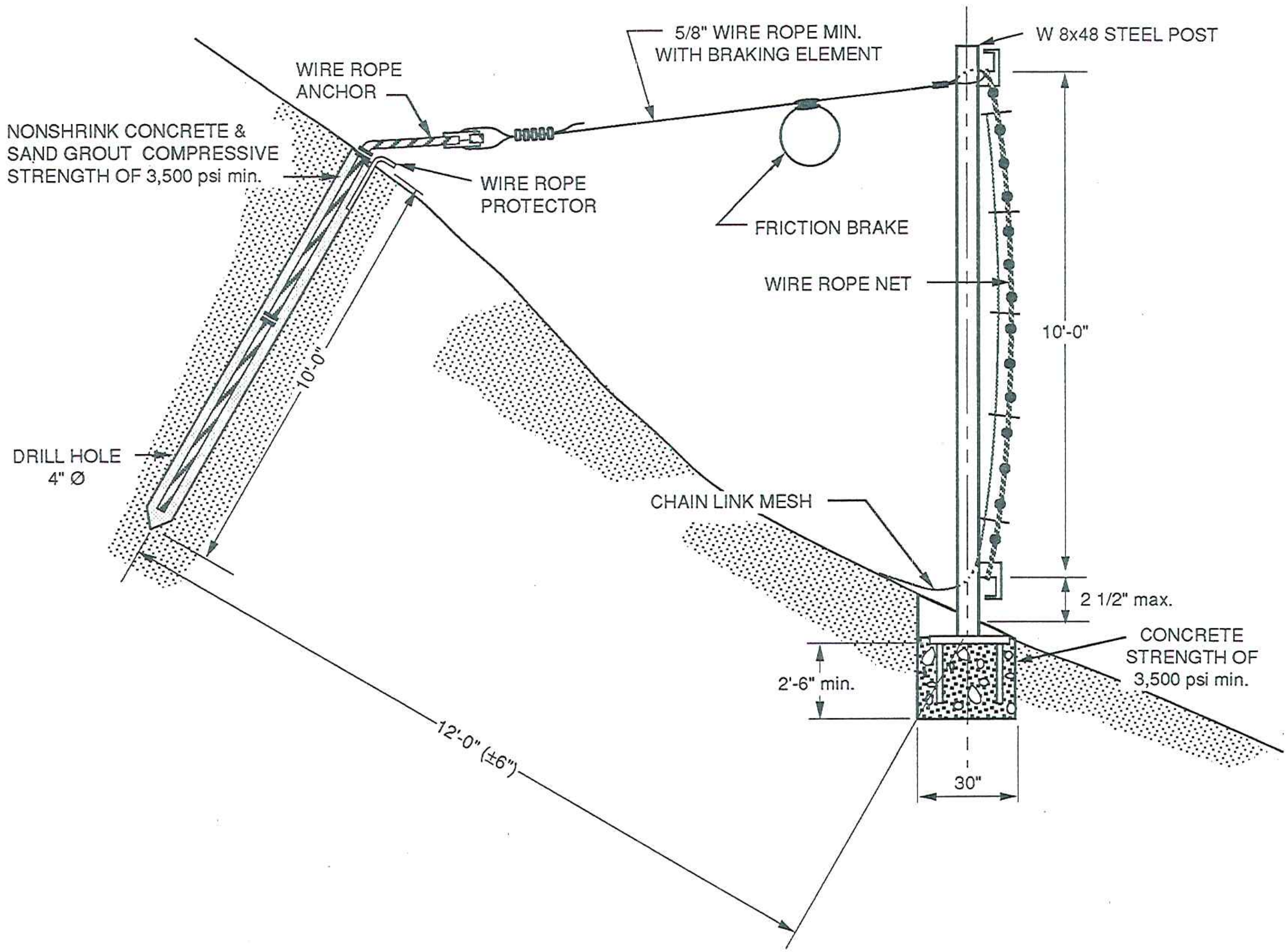


Figure 4. **SIDE VIEW OF A BRUGG BASEPLATE POST FOUNDATION WITH UPSLOPE ANCHOR SUPPORT**

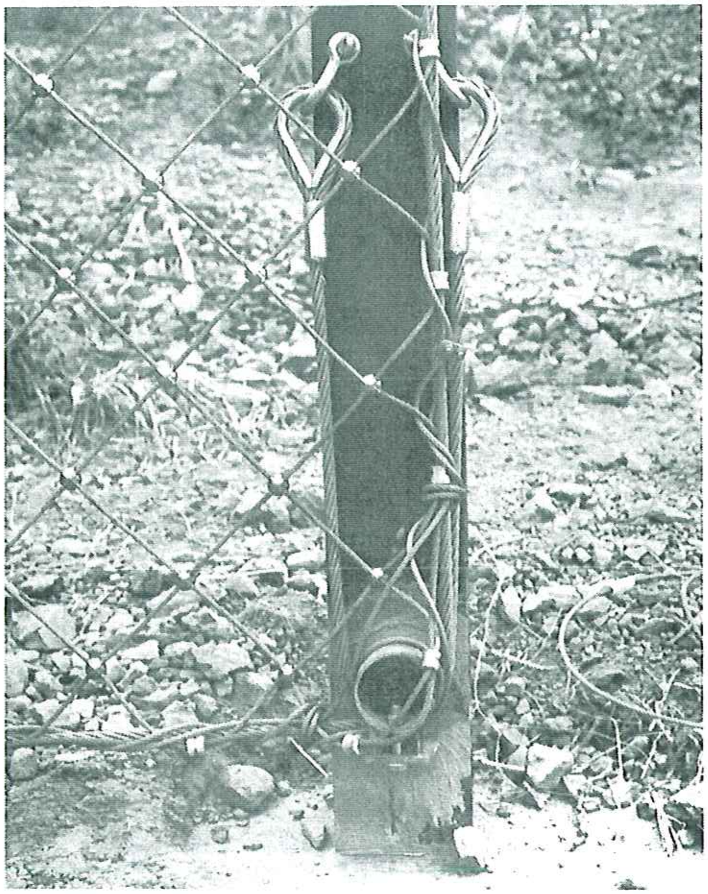


Photo 8. DETAIL OF BRUGG FULLY EMBEDDED POST. NOTE TRIPLE-TWISTED LACING CABLE ATTACHMENT AND SINGLE CABLE CLIP CONNECTION

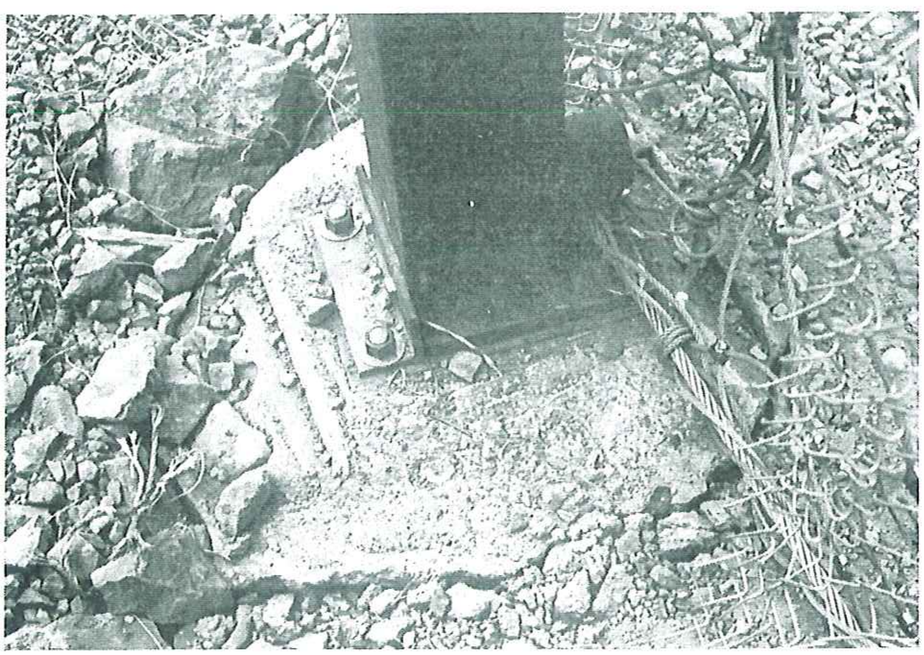


Photo 9. DETAIL OF BRUGG BASEPLATE POST ATTACHMENT

Photo 10. DRILLING ANCHOR FOUNDATION HOLES WITH 4-INCH CONTINUOUS FLIGHT AUGERS USING A HYDRAULICALLY POWERED TRUCK-MOUNTED ARTICULATED BOOM

Grouting of Anchor and Post Foundation Holes

Because of the remote location of the test site and the relatively small quantity of concrete required, it was not possible to have ready-mixed concrete delivered to the site. A 9-cubic foot concrete mixer was rented and taken to the site in an all-wheel-drive vehicle. Ninety-six 90-pound bags of 5-sack dry ready-mix were trucked to the site and mixed on location. Additional cement was added to produce a 7-sack mix.

Sufficient calcium chloride was added to the mix to obtain a strength of 3500 PSI within 24 hours; in addition, the concrete mix was modified with a plasticizer and vibrated to eliminate voids in concrete foundations. Use of calcium chloride in concrete will accelerate corrosion of steel in long-term installations and, therefore, would not be recommended.

The wet mix was transported from the mixer to the holes with a wheelbarrow where the terrain would permit and hand carried in five-gallon buckets to the upslope anchor holes. This system was labor-intensive and slow. A mini grout pump with a 10-foot tremie tube would have greatly reduced the time and effort involved in placing the concrete.

Installation of Perimeter and Anchor Wire Ropes

The 3/4-inch perimeter wire rope was attached to the machined fittings welded to the top and bottom of the posts (Photo 11) and tensioned with a "come-along". Wire rope clips were used at the terminus of each wire rope (Photo 12). The 5/8-inch wire ropes that tie the top of posts to the upslope and lateral anchors were installed in a similar fashion. Over 50 wire rope clips were used on the installation.

No difficulties were experienced in installing either the perimeter or anchor wire ropes.

Installation of Wire Rope Panels

The four wire rope panels were raised into position with the help of the boom truck, but could have been put in place manually. The panels were temporarily attached to the perimeter rope with wire ties. Final adjustment and attachment was made by lacing each panel to the 3/4-inch perimeter wire rope with 5/16-inch wire rope. Adjacent panels were also laced together. The ends of the top and bottom

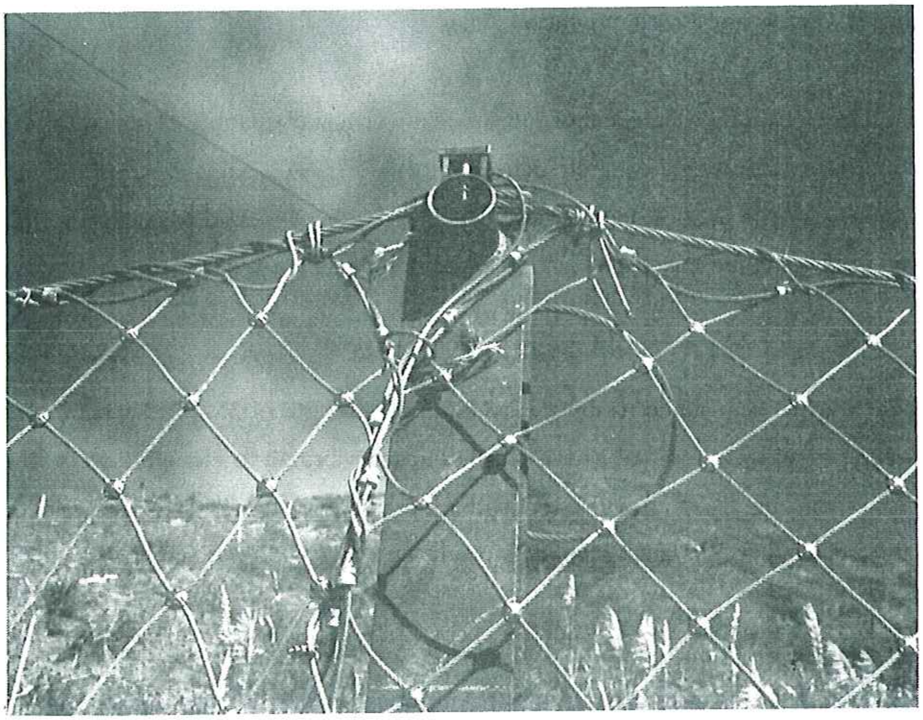


Photo 11. DETAIL OF A BRUGG POST WITH MACHINED FITTINGS SUPPORTING THE PERIMETER WIRE ROPE

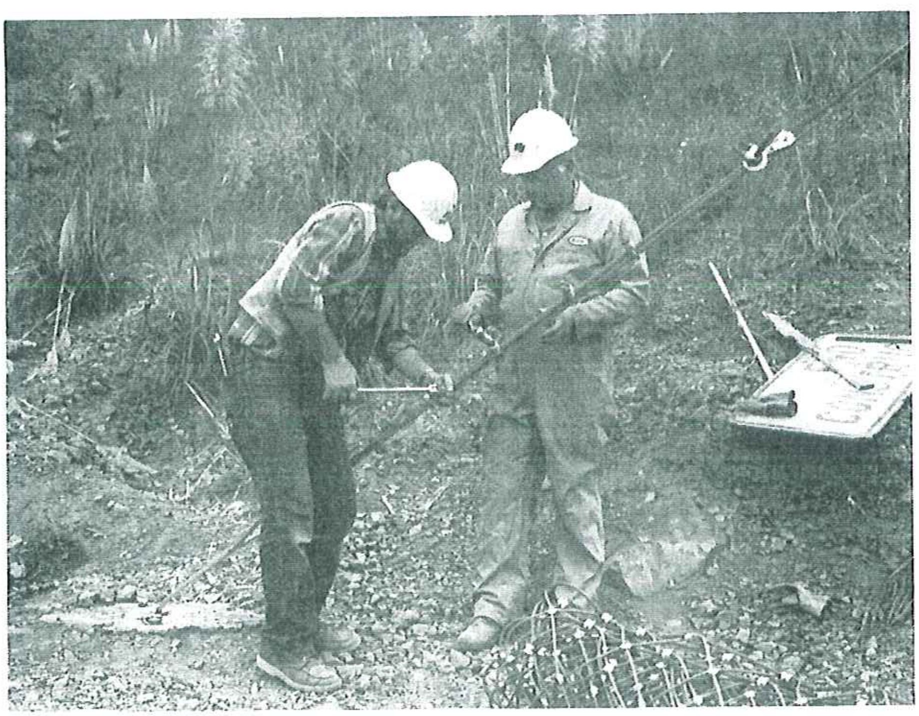


Photo 12. WIRE ROPE CLIP ATTACHMENT AT THE TERMINUS OF A LATERAL SUPPORT CABLE

lacing cable were wrapped three times around the 3/4-inch perimeter cable and fixed with a wire rope clip. The ends of the side lacing cables were wrapped three times around the net border cable and once around the machined fitting on the post and fixed with a wire rope clip (Photo 13).

No difficulties were experienced in installing the wire rope panels. Lacing the panels in place was labor-intensive, however.

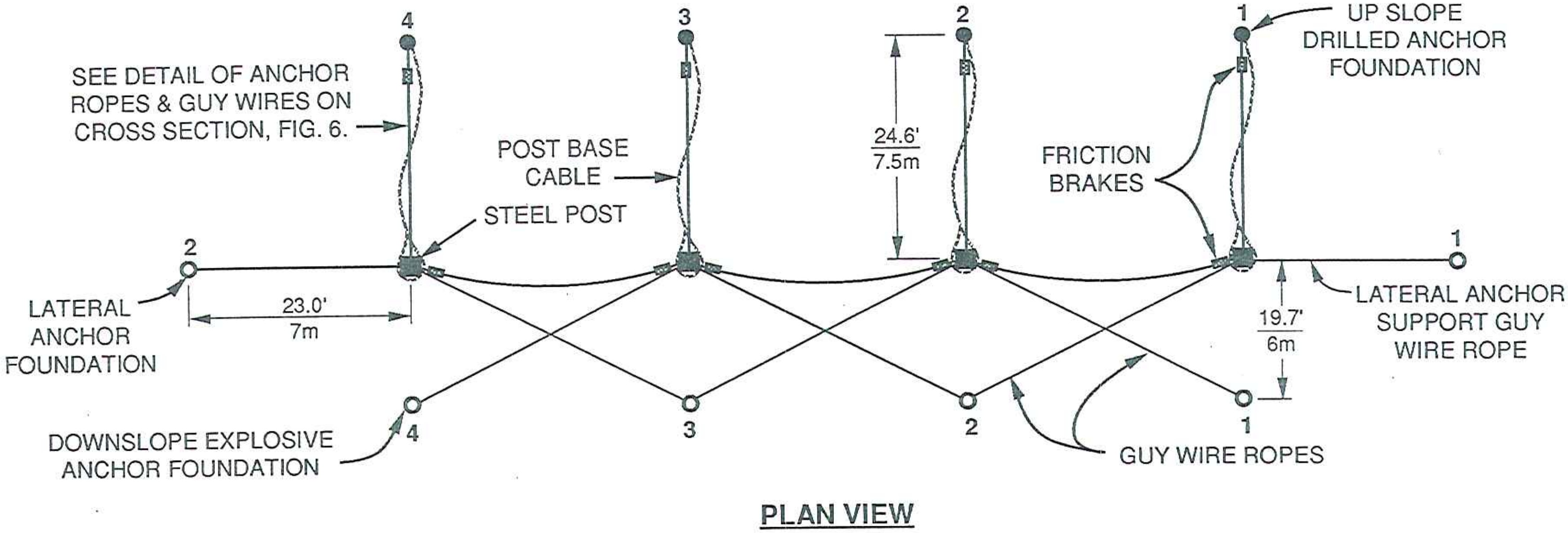
Construction Techniques, Problems, and Solutions - Industrial Enterprise

Description of The Industrial Enterprise Rock Net

The Industrial Enterprise (EI) rock net constructed for field testing in December 1989 consisted of three woven wire panels suspended from four box steel posts (Figures 5 and 6 and Photo 14). Net panels were joined together on their common sides and linked together at their corners with chain (Figure 7 and Photo 15). Wire rope attached to the chain passed through the top of the box posts to the friction brakes attached to the uphill anchors (Photo 16). Friction braking elements were also attached to each corner of the individual panels. Three guy wire ropes were attached to the top of each steel post for support. One was secured to an upslope anchor and the other two to downslope anchors. Guy wires also extend from the end posts to the lateral anchors located at each end of the rock restraining system.

A 70 ft-ton rock restraining system was requested from EI for testing.

EI woven wire panels are 16.4 feet (5 m) wide by 9.84 feet (3 m) high and consist of a continuous unpainted, galvanized 5/16-inch wire rope woven into an 8- x 8-inch diagonal pattern within a 5/8-inch perimeter rope (Figure 8). The woven panel is attached to the perimeter cable with simple one-bolt clamps. The intersecting wire rope panel strands are secured with wire rope clips that utilize a single nut and washer (Photo 17). Adjacent panels are joined together with steel bands attached with a banding machine similar to that used at a shipping dock to package freight (Figure 7 and Photo 18).



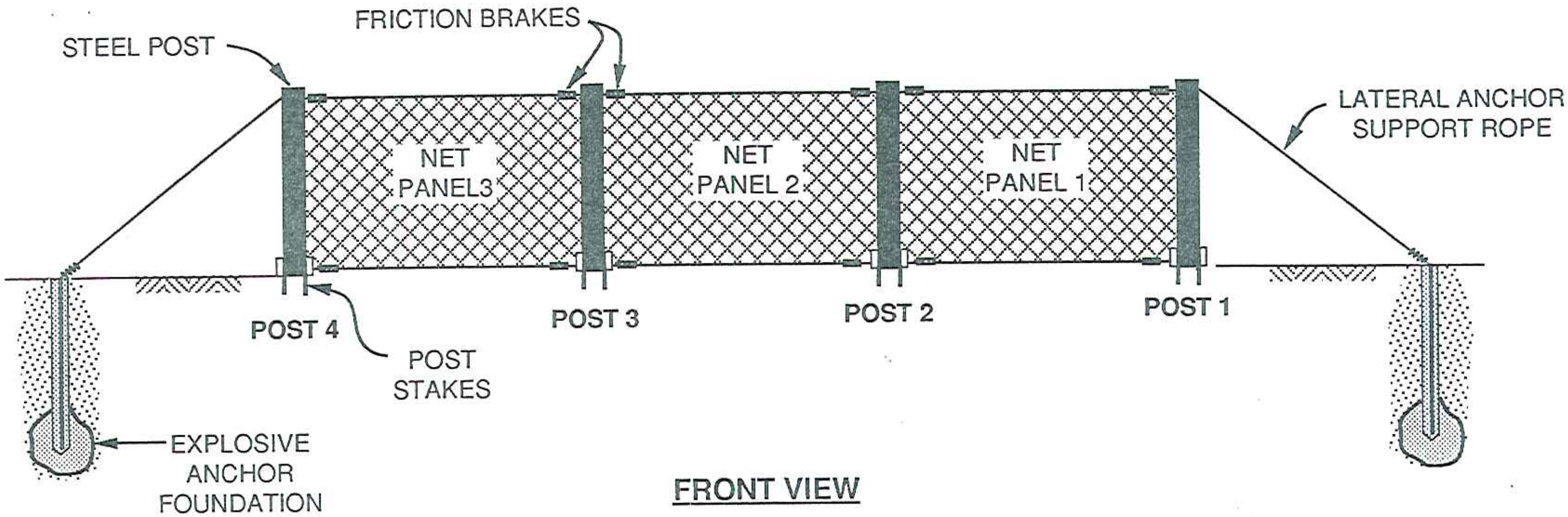


Figure 5. FRONT AND PLAN VIEW OF THE INDUSTRIAL ENTERPRISE ROCK NET CONSTRUCTED FOR FIELD TESTING

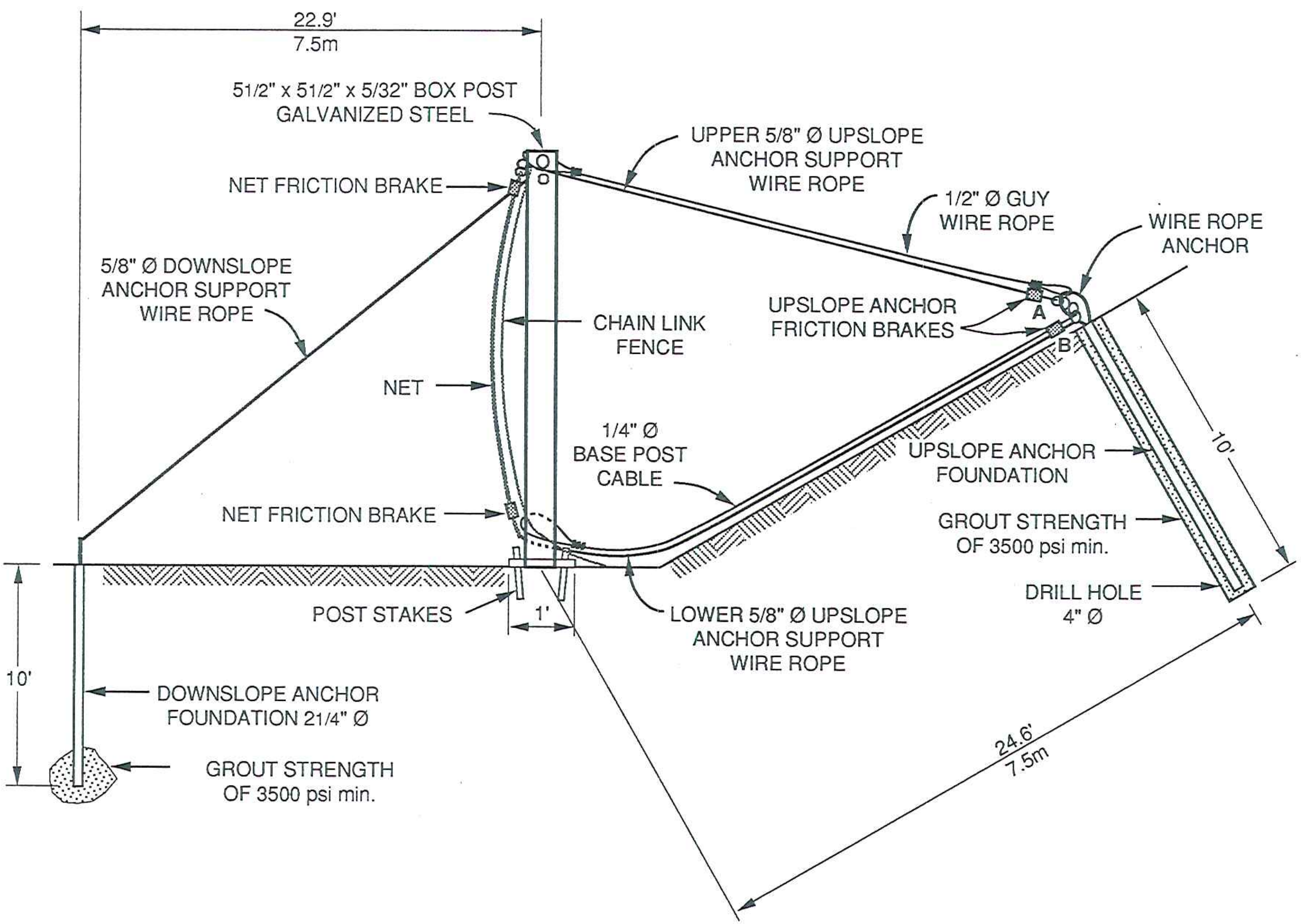


Figure 6. SIDE VIEW OF THE INDUSTRIAL ENTERPRISE ROCK NET

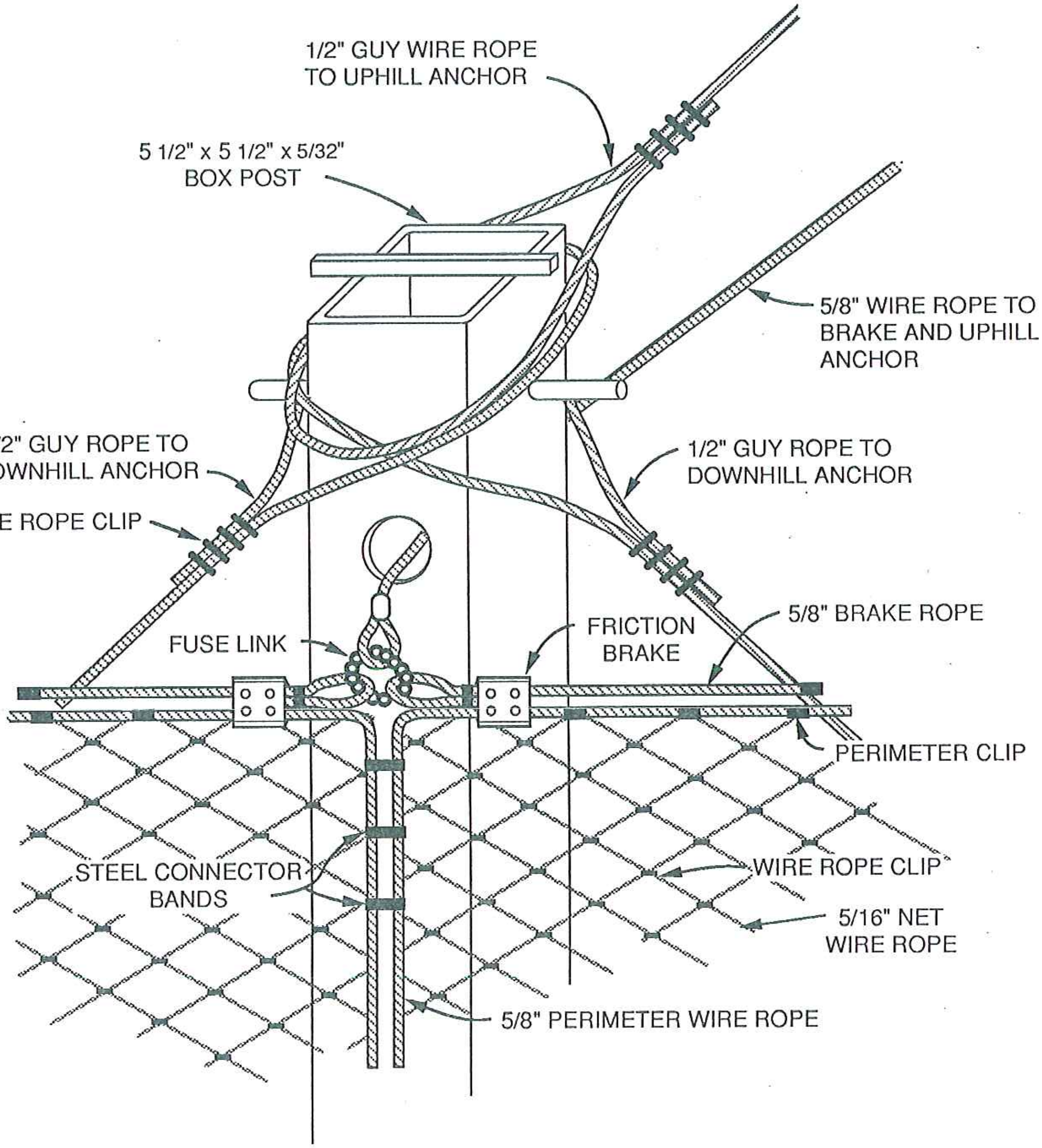


Figure 7. DETAIL OF INDUSTRIAL ENTERPRISE TOP POST ASSEMBLY

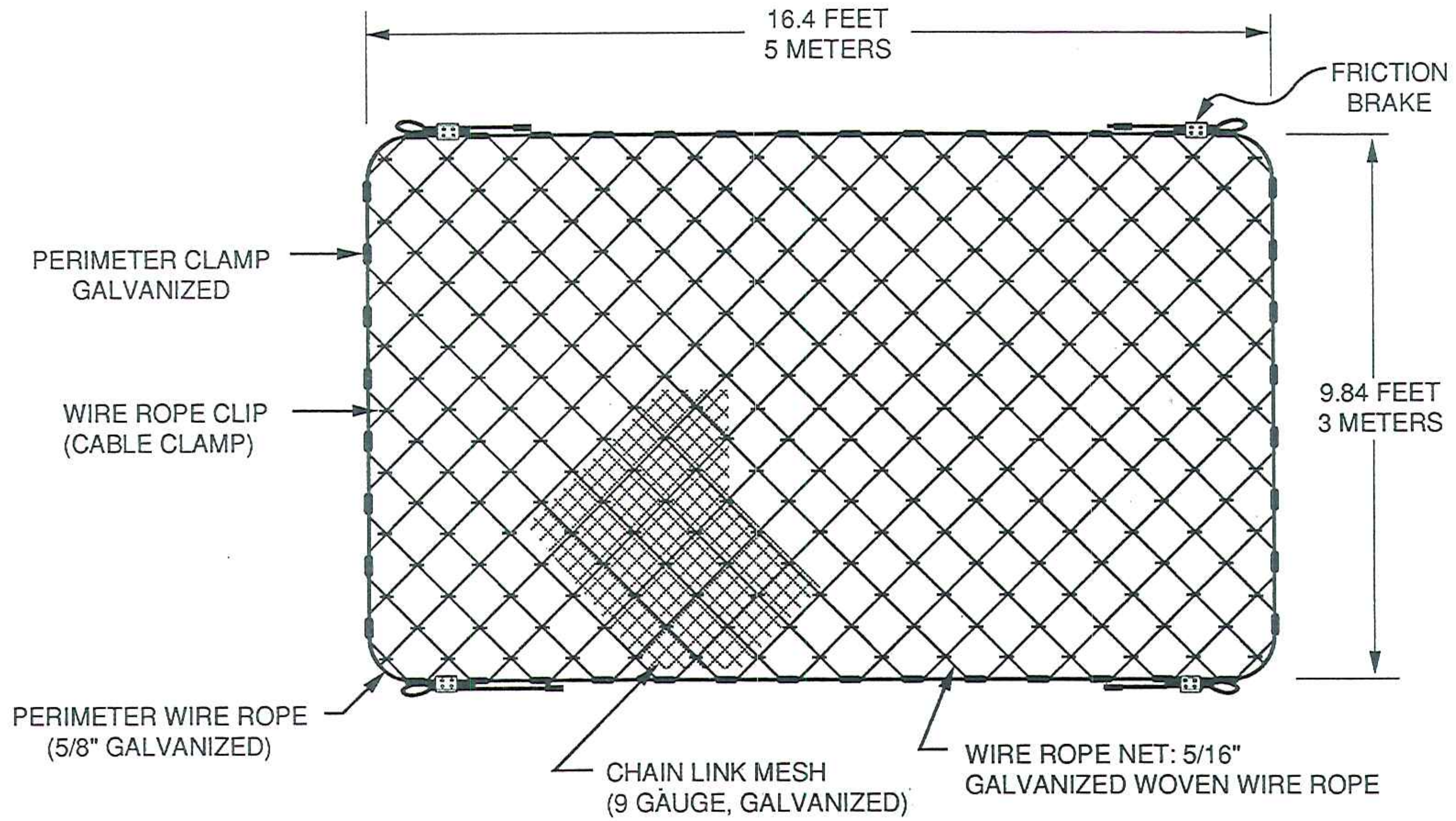


Figure 8. DETAIL OF THE INDUSTRIAL ENTERPRISE WOVEN WIRE ROPE PANEL

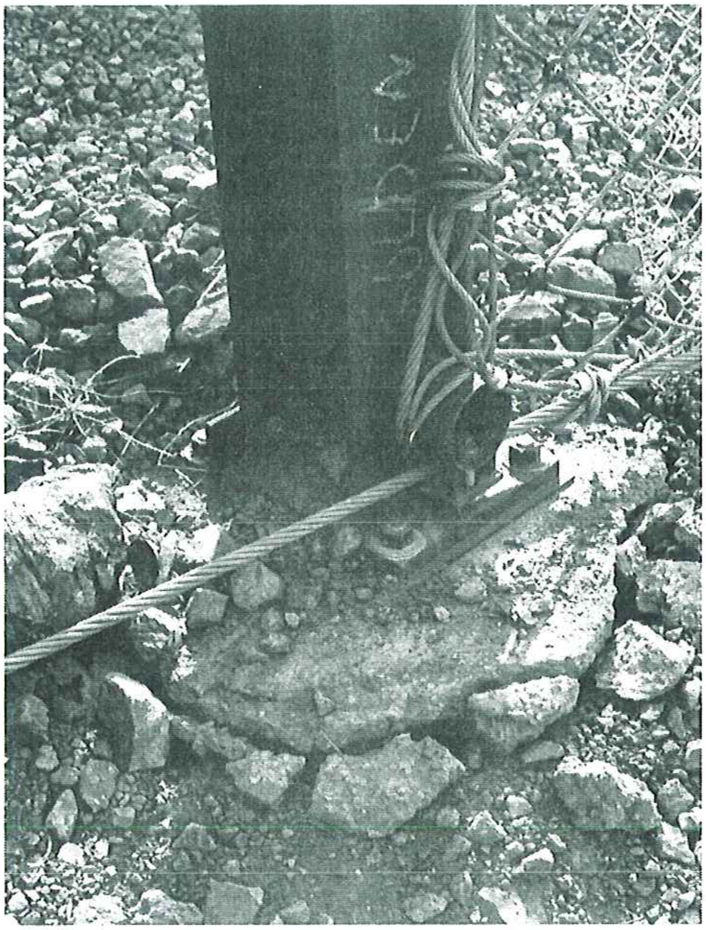


Photo 13. ATTACHMENT OF LACING CABLE TO PERIMETER WIRE ROPE SHOWING TRIPLE WRAP AROUND THE BORDER ROPE AND ONCE AROUND THE MACHINED FITTING

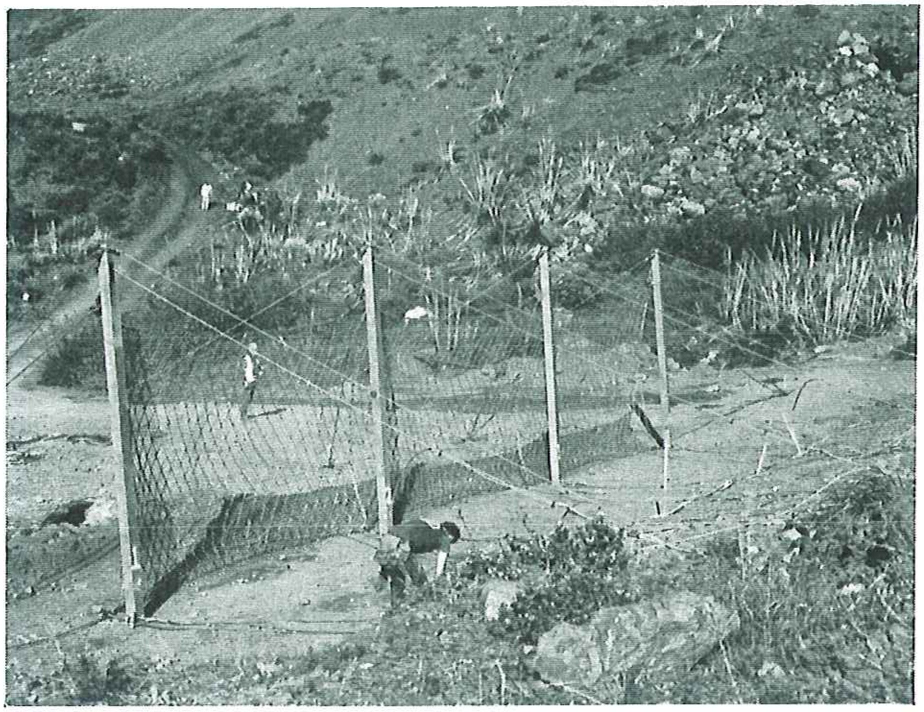


Photo 14. DOWNSLOPE VIEW OF THE INDUSTRIAL ENTERPRISE ROCK NET

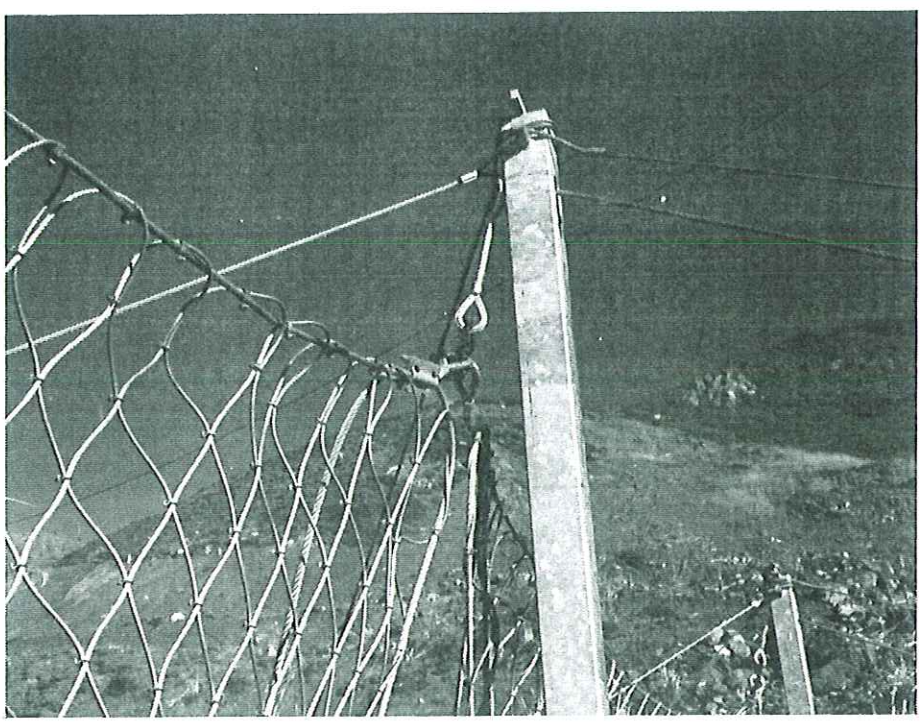


Photo 15. INDUSTRIAL ENTERPRISE TOP POST ASSEMBLY

Photo 16. INDUSTRIAL ENTERPRISE UPSLOPE ANCHOR FUSE LINK ATTACHMENT

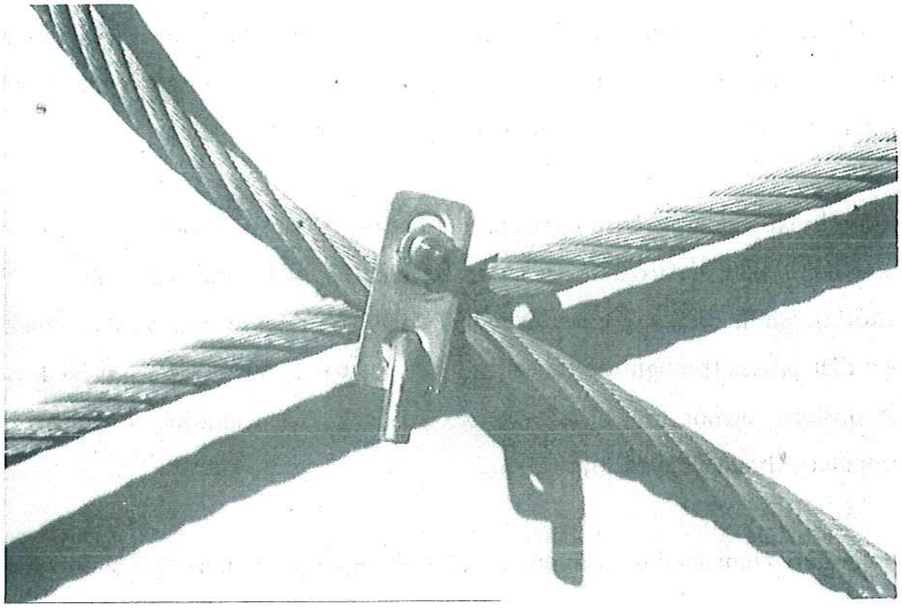


Photo 17. CLOSE-UP OF INDUSTRIAL ENTERPRISE WIRE ROPE NET CLIP

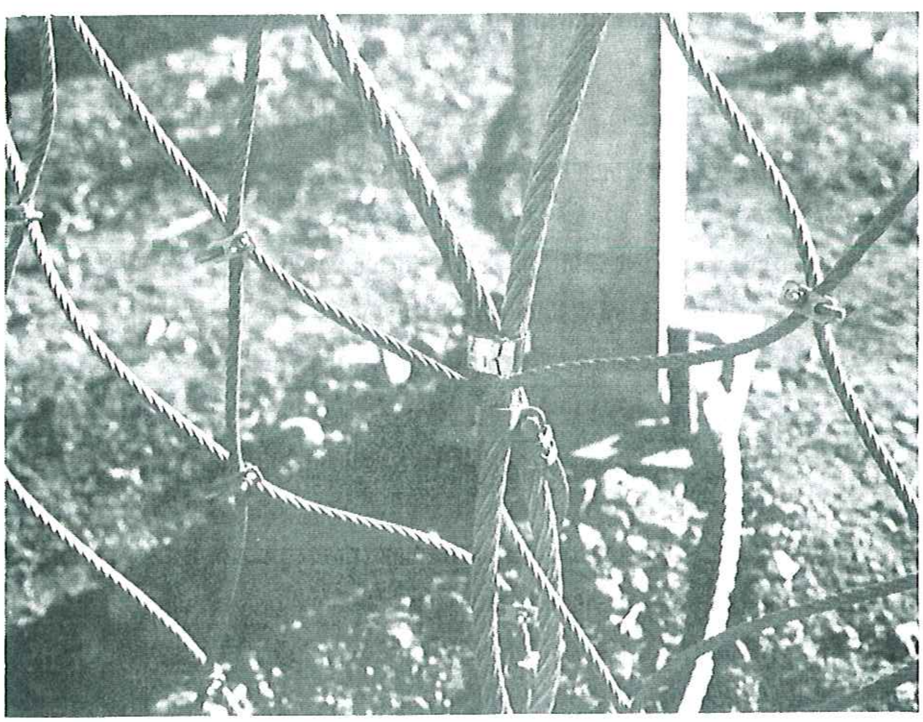


Photo 18. INDUSTRIAL ENTERPRISE STEEL BANDS USED TO JOIN ADJACENT NET PANELS

EI's friction brakes are four-bolt clamps that are shaped to accommodate two wire ropes that can be sandwiched between them and squeezed to a predetermined amount by applying a torque to the bolts (Photo 19). Each brake is preset to a minimum tensile strength of 5500 pounds. Two opposing ends of the wire ropes are attached to a net corner and an upslope anchor leaving two free ends or "tails". The tails have a specified length that corresponds to anticipated energy dissipation.

Net panel friction brake elements have only one tail because they are attached to each corner of the panels by bolting the braking device to the perimeter cable. The tail of the brake allows 5.9 feet of wire rope movement through the brake when activated. Two adjacent net brakes are then connected with a third wire rope that passes through the top of the steel post to a third brake attached to an upslope anchor. This upslope anchor brake has two 10.6-foot-long tails allowing a total of 21.2 feet of movement through the brake (Photo 20).

The friction brakes are connected to each other and to the upslope anchors by a short section of chain, referred to as a fuse link (Figure 7 and Photo 16). Impacts exceeding ultimate design load will cause the chain to break allowing the panel to lay down, permitting the boulder to pass through the installation without causing damage to the net. Single and doubled fuse links are used which will fail under 10 to 20 tons of loading, respectively.

Individual net panels were covered on the upslope side with nine-gage chain link fencing material. The chain link mesh was attached to the woven wire panels by using short pieces of 11-gage wire twisted securely in place by hand (Photo 21). These wire ties were spaced at about one-foot intervals around the perimeter and roughly two-foot spacing across the upslope side of each panel.

The nets were supported by four 5 1/2-inch by 5 1/2-inch box posts that were 13 feet 2 3/4 inches long and made of 5/32-inch galvanized steel (Photo 22). The posts were fitted with pins, bars, and holes at the appropriate positions to accommodate the various wire ropes and fittings.

A concrete foundation is not required for the EI rock restraining system. Instead, the base of each steel post sits on the surface of the construction pad which had been roughly graded to provide a level surface. Two-foot-long steel stakes were driven through the baseplate holes and into the underlying soil to hold the base of the post in position (Photo 23). The function of the posts is to hold the panels in position. In theory, if a direct hit is made by a boulder on a post, the base of the post will be able to move outward and downslope thereby preventing damage to the post. Maintenance forces would then be able to reposition the post and reset the steel pins or spikes.

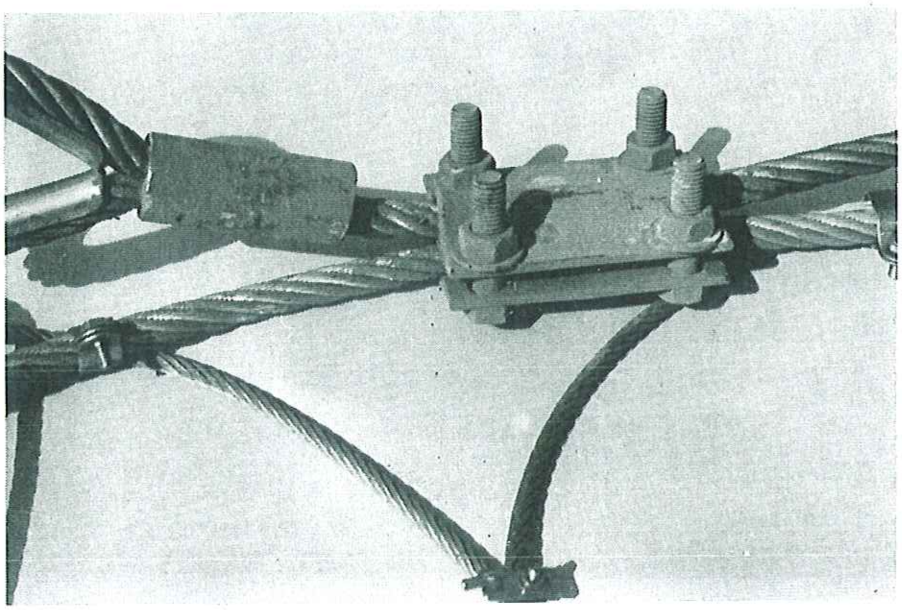


Photo 19. INDUSTRIAL ENTERPRISE NET PANEL FRICTION BRAKE

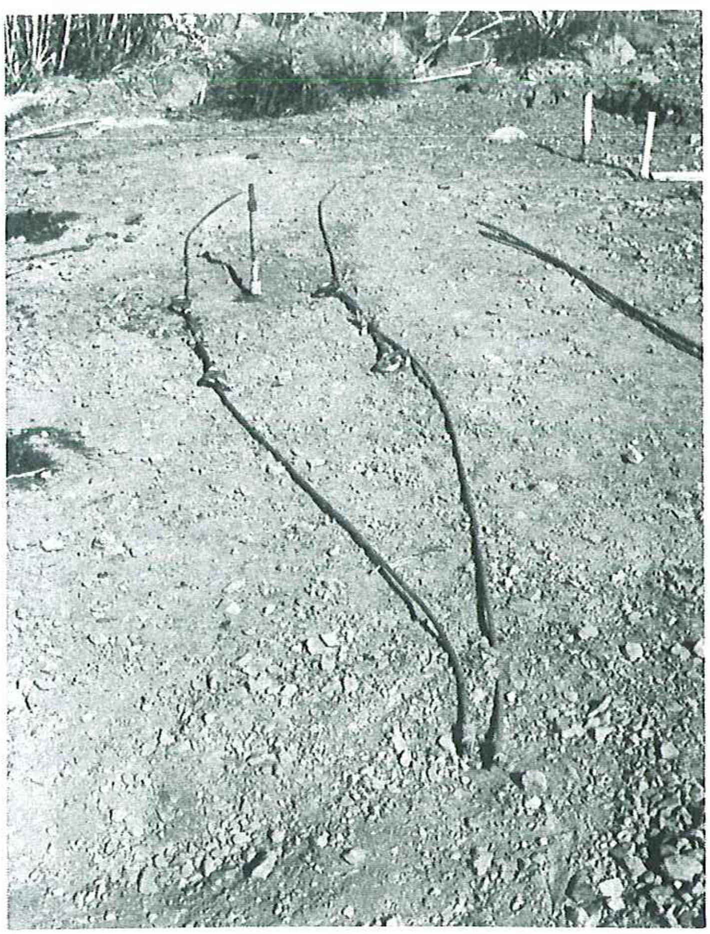


Photo 20. INDUSTRIAL ENTERPRISE 10.6-FOOT ENERGY-DISSIPATING FRICTION BRAKE TAILS

Photo 21. ATTACHING CHAIN LINK FENCING TO INDUSTRIAL ENTERPRISE WIRE ROPE NET WITH WIRE TWISTS

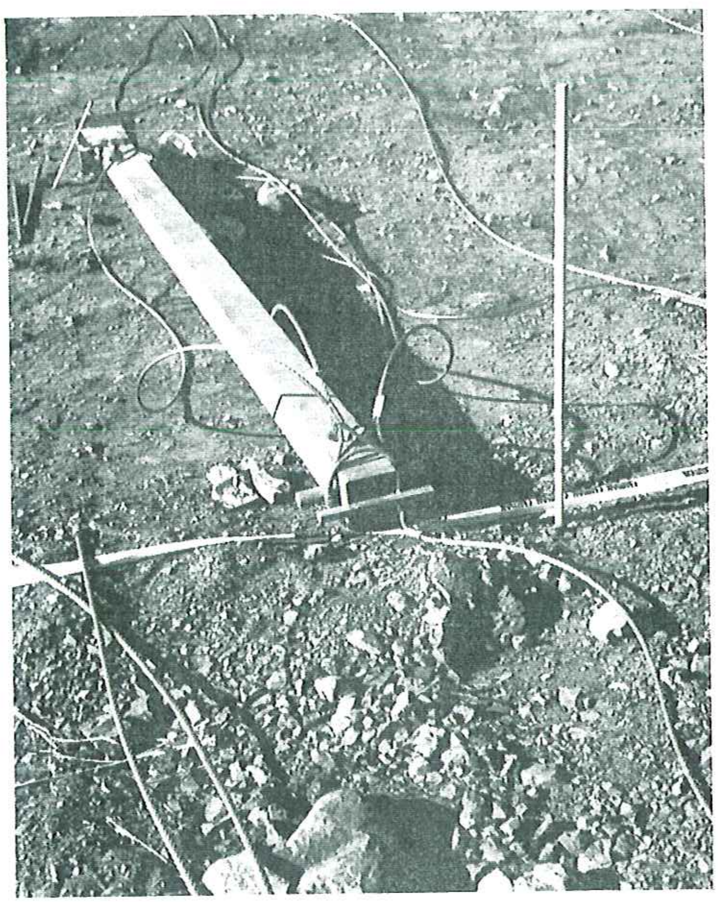


Photo 22. INDUSTRIAL ENTERPRISE 51/2-x51/2 -INCH GALVANIZED STEEL BOX POST WITH GUY WIRES

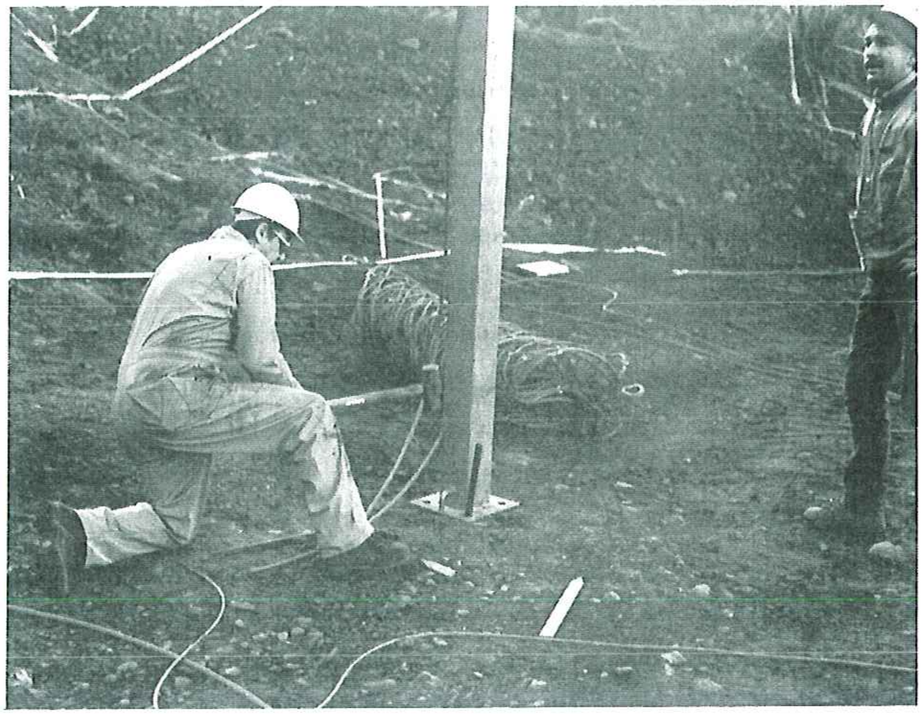


Photo 23. INSTALLATION OF INDUSTRIAL ENTERPRISE STEEL STAKES TO SECURE THE POST BASE

Each post was supported by three 1/2-inch guy wire ropes looped over the top. One guy wire was attached to the upslope anchor, while the other two were attached to downslope anchors (Figure 5 and Photo 24). The two end posts had a similar guy wire rope attached to lateral anchors. All guy wire ropes were secured with four wire rope clips at the anchor ends.

A single 1/4-inch cable was attached to the base of the posts and to the upslope anchors with wire rope clips. The purpose of this cable is to restrict movement of the base of the post if it should be struck with a boulder.

Previously installed upslope anchors used for the Brugg tests were utilized for the EI tests. Because of angle requirements for the upslope wire ropes attached to the panels, the rock net was shifted down-slope approximately 10 feet requiring relocation of the two lateral anchors. Four downslope anchors were required for the EI system, each anchor being located 19.7 feet (6 m) downslope from the box posts. Upslope anchors were 24.6 feet (7.5 m) upslope from the posts, while lateral anchors were 23 feet (7 m) from the end posts (Figure 5 and Photo 24).

The additional anchors were constructed by drilling a 2 1/4-inch hole to a depth of 10 feet using a trailer-mounted McKiernan-Terry air hammer with "AW" drill rod. A two-inch-diameter steel pipe with a machined point was then pushed to the bottom of the hole. Four grooves had been machined into the wall of the lower one foot of the steel pipe so that the detonation of a small explosive charge would rupture the wall of the pipe and create a cavity for filling with grout (Photo 25).

Each hole was filled with grout consisting of three to five 50-pound bags of grout mix enriched with additional cement to produce a 7-sack mix. Calcium chloride was added to accelerate curing time to obtain 3500 psi within 24 hours. Plasticizer was added to make the mix more liquid ensuring that all subsurface voids in the cavity area were filled with grout.

A No. 8 (1 inch) rebar, 11.5 feet long was then placed in each grouted hole to complete the anchor. A 7- by 8-inch steel plate was later placed on the rebar and secured with a nut to hold wire ropes and fuse links in place and prevent them from slipping off the rebar rod (Photos 26 and 27).

Minerite 2 (formerly Tovex 220) was used as the explosive agent. This Class A, cap-sensitive explosive is a water-resistant gel encased in soft plastic tubes 1 1/8 x 16 inches that weigh 2/3 lb. The gel consists of nitroglycerine, trinitroglycerine, dinitroglycerine, ammonium nitrate and aluminum powder.

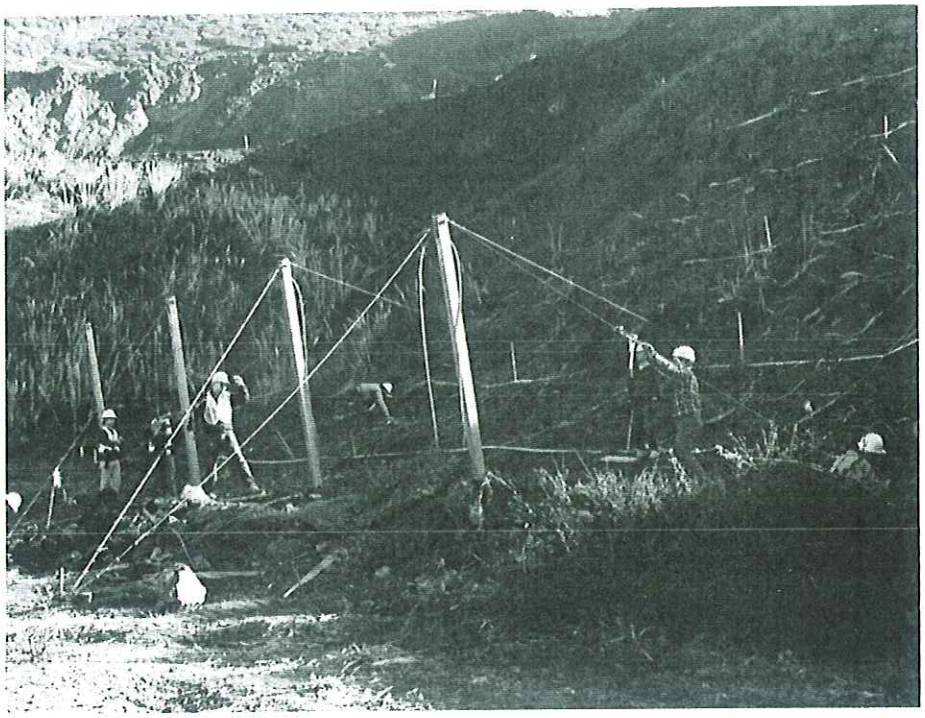


Photo 24. INDUSTRIAL ENTERPRISE UPSLOPE ANCHOR AND GUY WIRE ASSEMBLY

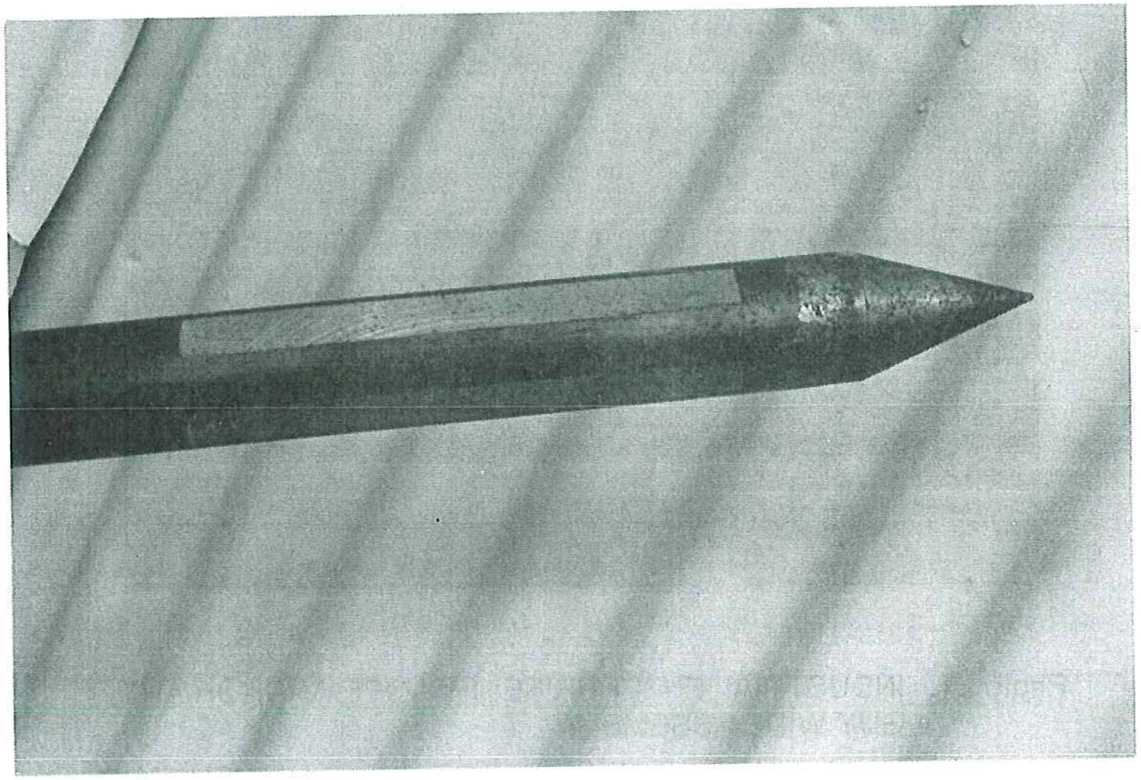


Photo 25. CLOSE-UP OF THE 2-INCH-DIAMETER MACHINE-GROOVED STEEL PIPE USED TO INSTALL THE INDUSTRIAL ENTERPRISE ANCHORS. (Photo Courtesy of Alain Lazard)

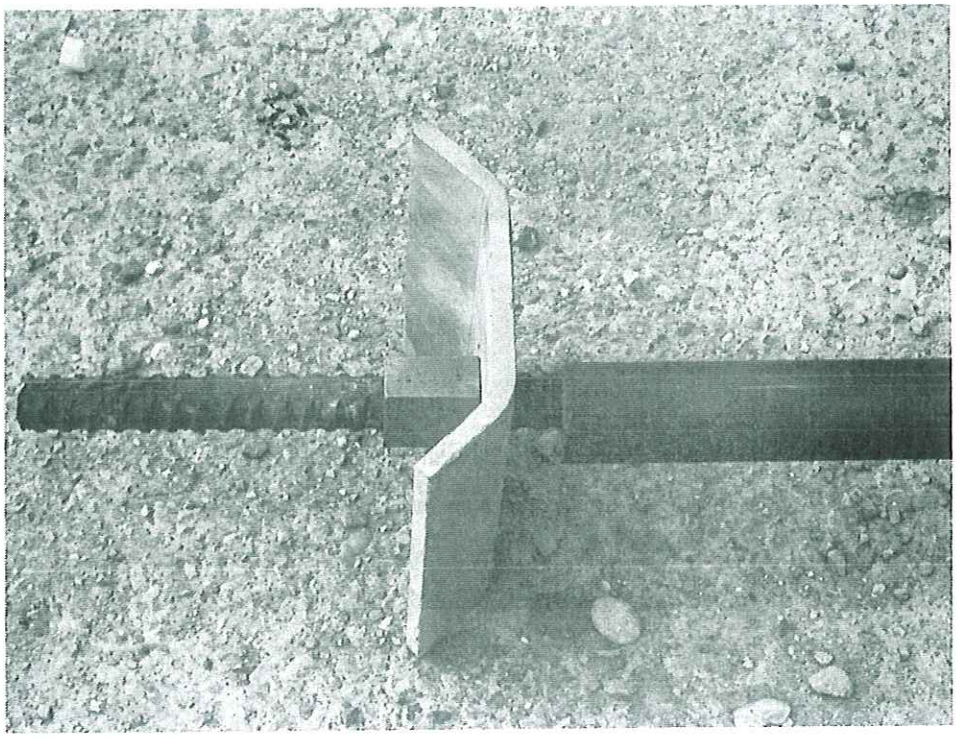


Photo 26. INDUSTRIAL ENTERPRISE FOUNDATION ANCHOR ASSEMBLY. (Photo Courtesy of Alain Lazard)

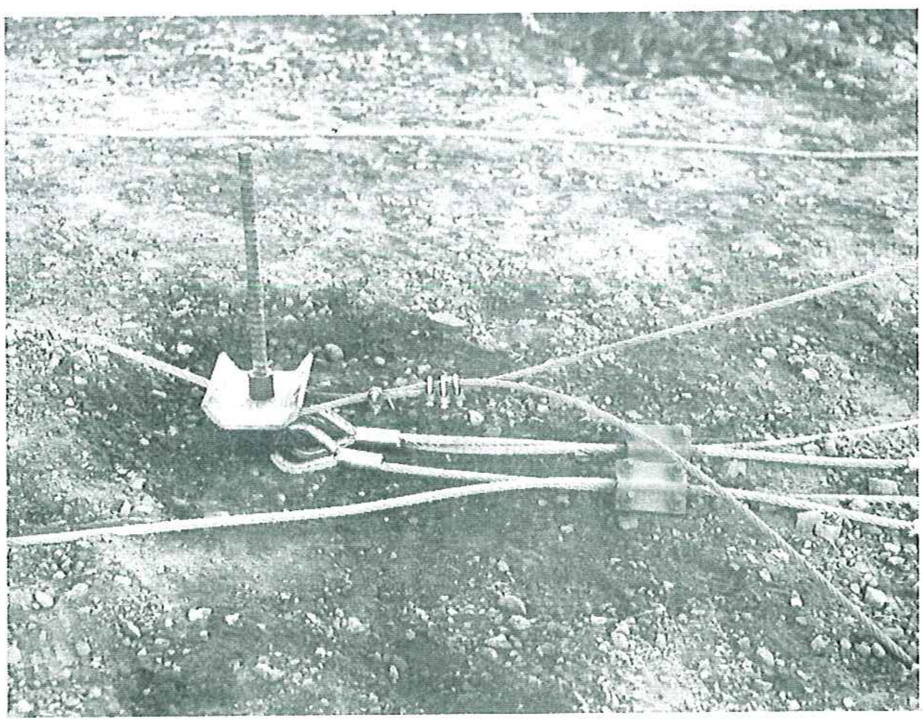


Photo 27. INDUSTRIAL ENTERPRISE FOUNDATION ANCHOR ASSEMBLY WITH GUY WIRE ROPES AND FRICTION BRAKES ATTACHED

Blasting procedures consisted of stemming the bottom of the steel pipe with about one pint of sand, placing a 1/3 stick of Minerite 2 with an electric nondelay blasting cap in contact with the sand and then filling the rest of the pipe with water. Detonation of the charge was barely noticeable at the surface and was expressed as a slight "bump" with a small shower of water emanating from the pipe.

Installation of Anchors

The McKiernan-Terry air hammer worked very well in driving the pilot holes for the two-inch pipes. Anchor locations had to be offset on two occasions because large boulders were present that could not be penetrated. This driving technique was much faster and more efficient than augering holes for anchors and required considerably less grout. Enlarging the bottom of the hole with explosives was easy, but requires the purchase, transportation, and storage of Class A explosives as well as requiring the services of a licensed blaster.

Grout was poured with a funnel into the two-inch steel pipe extending out of the hole. Air pockets constantly developed, making the grouting process very slow and laborious. A tremie pipe sufficiently long to reach the bottom of the hole should be used in conjunction with a small grout pump. Filling the holes from the bottom up would eliminate air pockets in the grout.

Installation of Posts, Anchor Ropes, Fuse Links, Brake Elements and Guy Wires

Raising the four steel posts into position and securing them with steel pins at the base and guy wire ropes at the top was a simple process that required about 1 1/2 hours. This process requires a minimum of four people and six would be preferable (Photos 28 and 29). Guy wire loops were slipped over the top of each post while the opposite end of the guy wire was wrapped around the upslope and downslope anchors and secured with four wire rope clips (Photo 30). The guy wire ropes were tensioned in a hopscotch fashion using two come-alongs at a time.

Two frictional brakes were attached to each upslope anchor by a doubled fuse link. The ends of the chain were joined by using a "D"-shaped link with a tapered pin and sleeve that was hammered in place (Photo 31). After the woven wire panels were raised in place, the end of the wire ropes were attached to the corner of each panel and secured to the frictional brake elements with four wire rope clips.

Photo 28. POSITIONING OF THE INDUSTRIAL ENTERPRISE POST

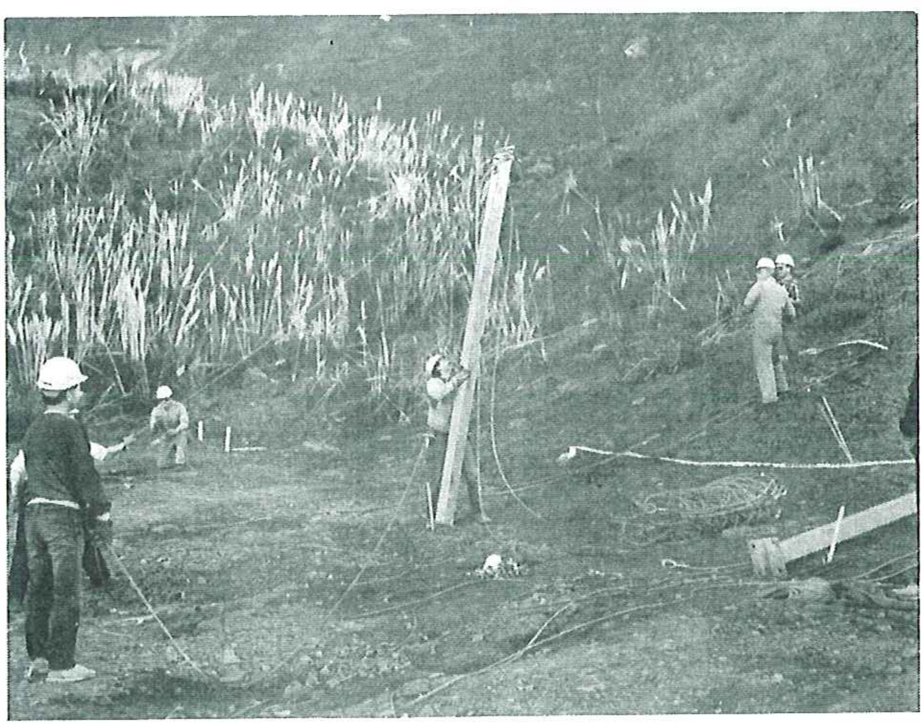


Photo 29. RAISING AN INDUSTRIAL ENTERPRISE POST

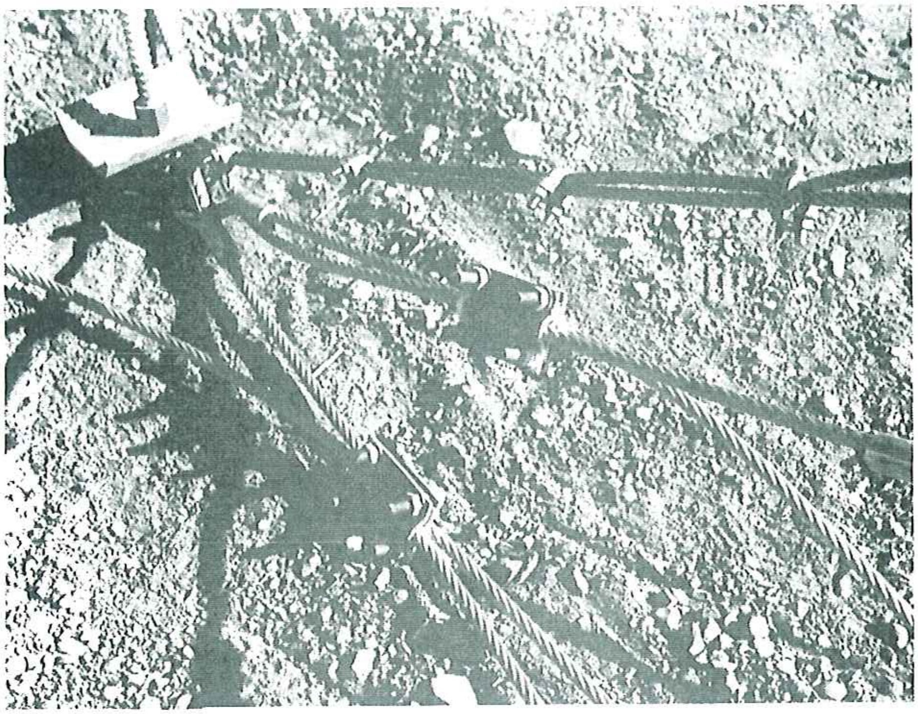


Photo 30. COMPLETED ASSEMBLY OF INDUSTRIAL ENTERPRISE GUY WIRE ROPES AND FRICTION BRAKES TO THE FOUNDATION ANCHOR

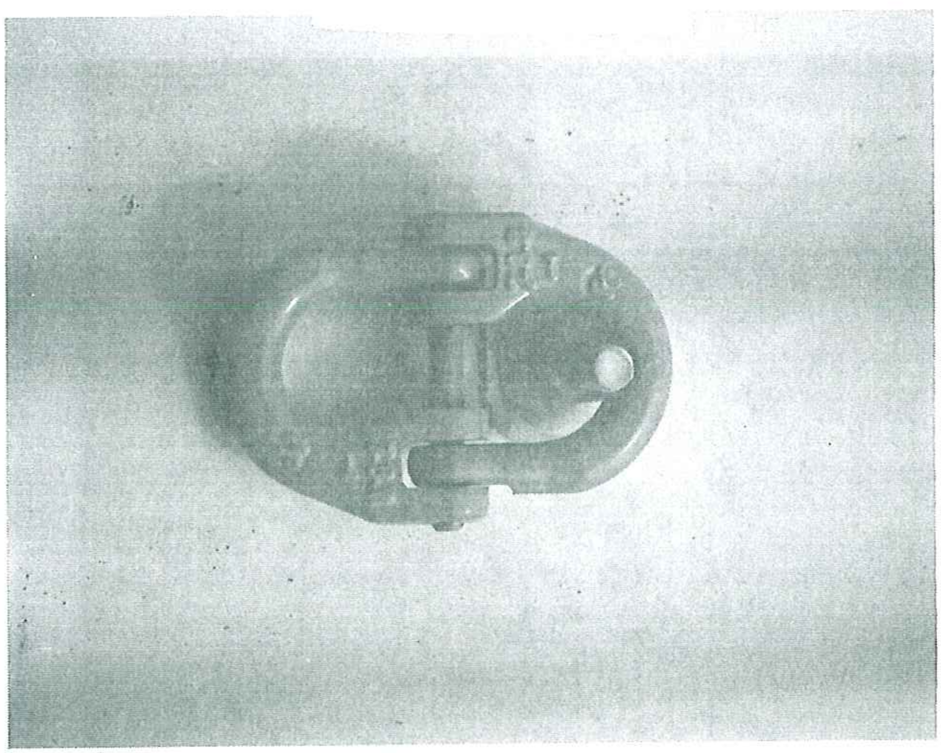


Photo 31. INDUSTRIAL ENTERPRISE "D"-SHAPED LINK FOR ATTACHMENT OF FUSE. (Photo Courtesy of Alain Lazard)

Positioning and securing the fairly large number of wire ropes, frictional brakes, and fuse links is labor-intensive. Over 100 wire rope clips were required in this installation.

Installation of Woven Wire Panels

The panels were put into position by pulling the wire rope through the post with come-alongs and securing them to the friction brakes attached to the upslope anchors (Figure 6). Since the net panels at this point were all joined at the corners, raising them concurrently was required (Photo 32). After the panels were raised into position, the common sides were joined using steel strapping bands.

The final step in constructing the EI rock net restraining system was to attach the 9-gage chain link mesh to the upslope face of the panels. Ten-foot-wide rolls of the mesh were used so that there would be no seams on the panels. The mesh was attached by twisting short pieces of 11-gage wire ties in place. Ties were placed on roughly one-foot-centers around the perimeter of each panel and on roughly two-foot-centers for the rest of the net.

TEST PROCEDURE

The test slope is 130 feet high and 100 feet wide with an overall slope angle of 34 degrees (1 1/2:1). The slope measured along the ground surface, is 250 feet long (Photo 33). A contour map and cross-sections were developed from a detailed survey of the slope (Figures 9 and 10). Survey points were located two to five feet apart. Relative to the rockfall diameters, the slope is smooth and did not greatly affect rockfall trajectories. There are, however, several gullies which affected rockfall trajectories of small (one to two feet in diameter) boulders. Vegetation is sparse and had little, if any, effect on rockfall trajectories.

The slope material is composed of landslide debris consisting of 1- to 18-inch 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 creating soft spots which slowed some boulders.

Test boulders were obtained from a local stockpile of rockfall and rockslide material (Photo 34). These boulders are dense greenstone with a specific gravity ranging from 2.91 to 3.03. For test

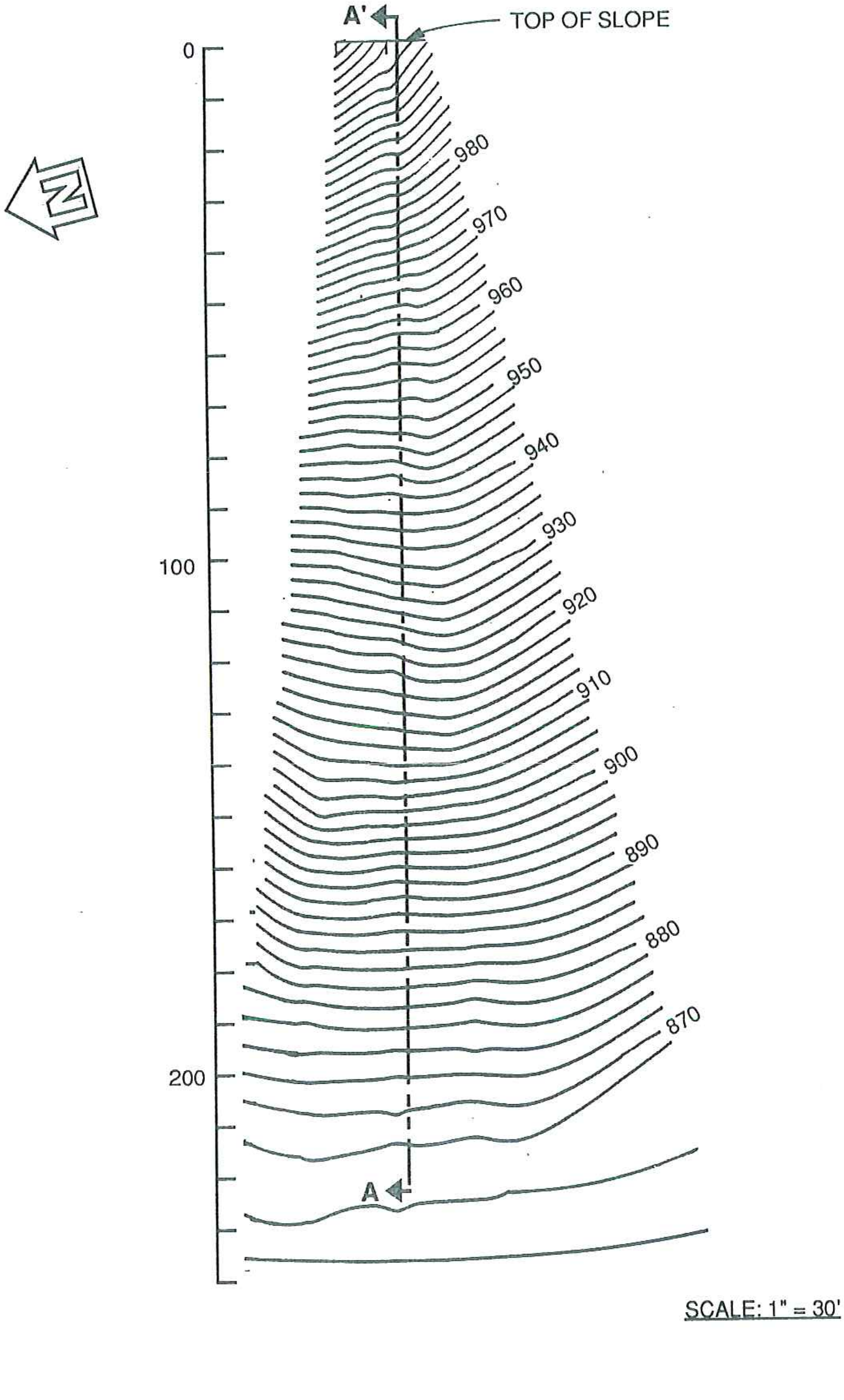


Figure 9. TEST SLOPE PLAN VIEW

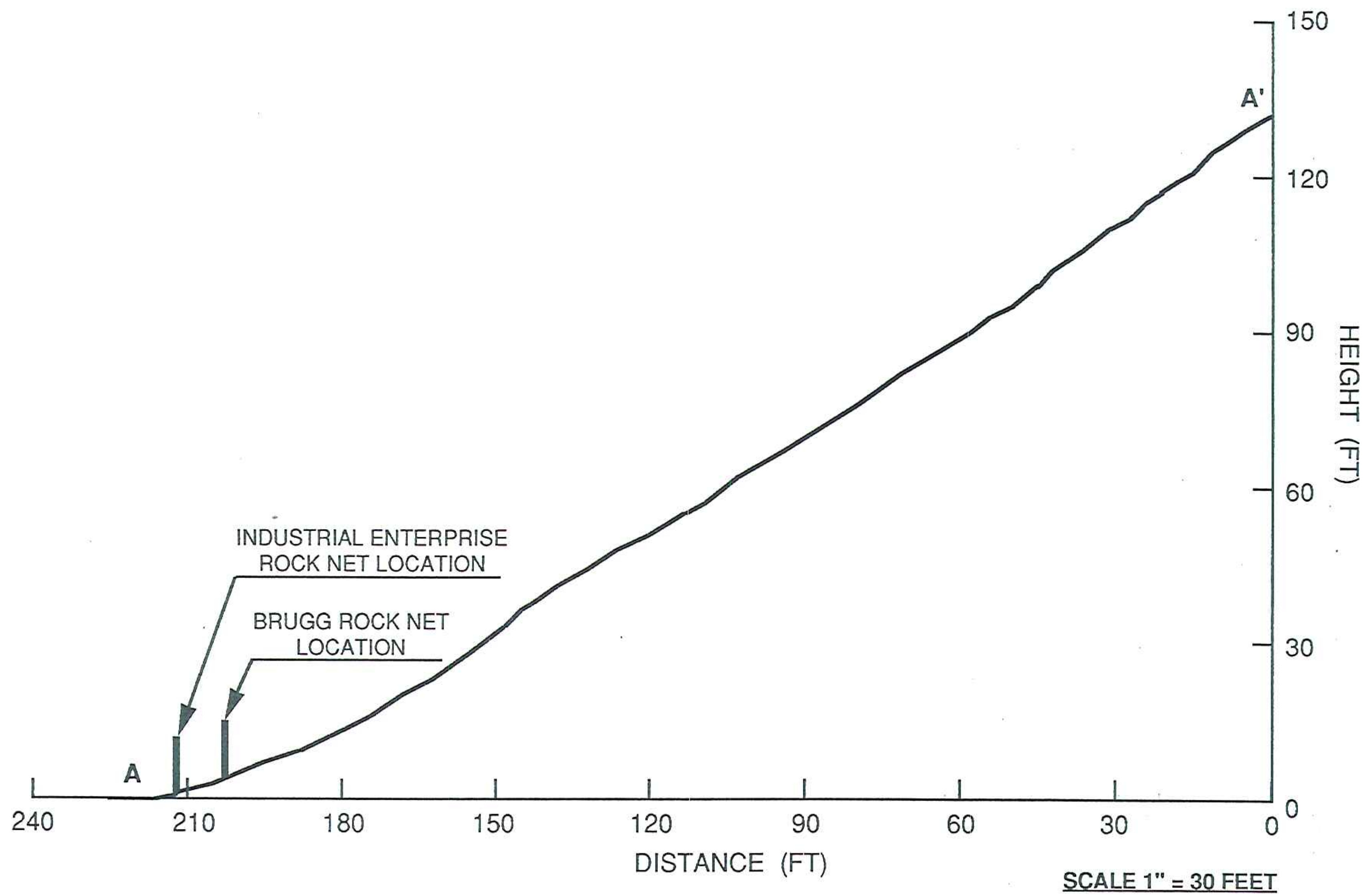


Figure 10. CROSS SECTION A-A'

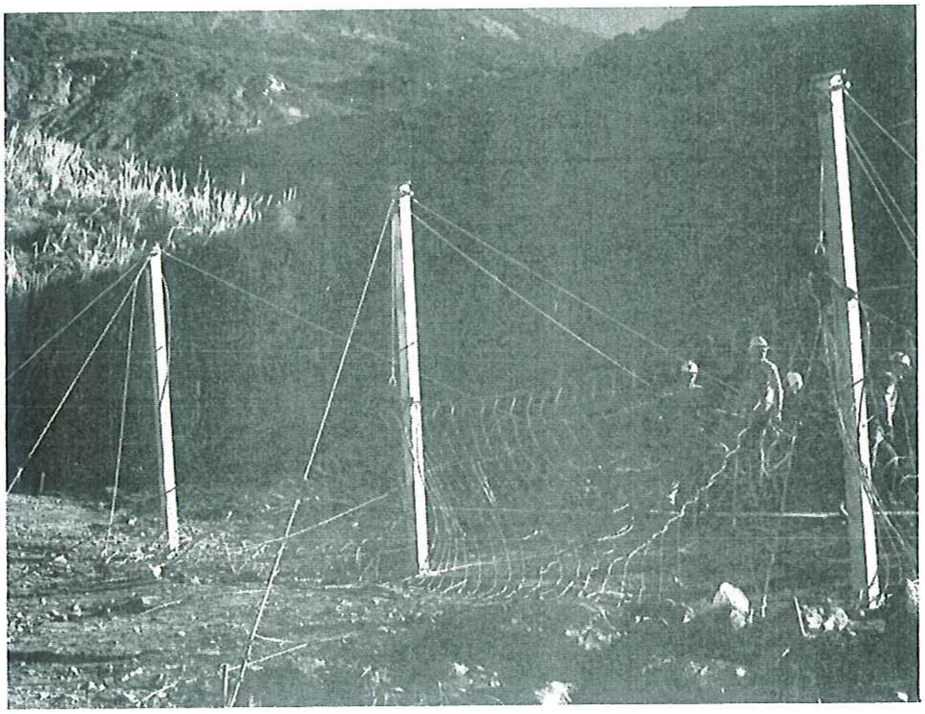


Photo 32. RAISING THE INDUSTRIAL ENTERPRISE NET PANELS

Photo 33. OBLIQUE VIEW OF TEST SITE SHOWING REFERENCE LINES AND WORKING AREA

Photo 34. FIVE-TON BOULDER USED IN THE TESTS

purposes, many of the rocks selected were equant in shape. However, with so many rock rolls, the stockpile of round rocks was depleted and other rock shapes were rolled. Eighty boulders were rolled and identified by a name or number.

Prior to rock rolling, the three principle axes (x, y, and z) of each boulder were measured. These values were used to estimate rock weight and inertia. Fifteen boulders were accurately weighed with a load cell (Photo 35). Actual weights were compared to estimated weights to evaluate estimated weight accuracy.

Rock rolling was recorded on video and high-speed (16 mm) film from four different locations along the slope. Real time was recorded on video (30 frames per second) and slow motion coverage was recorded on high-speed film (60 to 80 frames per second). The four cameras captured two side views, one oblique, and one frontal (Figure 11).

In order to fully utilize the film and video footage, reference lines on 50-foot intervals were placed on the slope perpendicular to the slope axis (Photos 35 and 36). During the Industrial Enterprise test (Test 3), the spacing of reference lines on the lower portion of the slope was modified (Figures 12 and 13). This allowed detailed measurements of boulder travel time over a known distance. The information was used to calculate rockfall velocities. Yellow, three-inch-wide "caution" tape was used for the reference lines because of its high visibility. In addition, stadia rods, three feet to six feet high, were randomly placed on the slope for bounce height analysis.

Rocks were dropped from a height of 10 feet over the edge of the slope with a front end loader. Extremely large boulders (Test 2, Rolls No. 37 and 38; Test 3, Rolls No. 10 and 12) and the simulated rockslide (Test 3, Roll No. 19) were pushed off the edge of the slope with a front end loader.

The nets were examined periodically during testing. Typically, the nets were inspected when noteworthy damage was observed by Engineering Geologists stationed at two of the four camera locations. Net performance was recorded and necessary repairs were made before the next rock was rolled. Particular attention was given to maintenance of the nets, such as ease of repair, feasibility of repair, and replacement parts required for repairs. Caltrans maintenance personnel were on site providing input on practical use and maintenance of the nets in the field.

All data were recorded for each rock roll on a data sheet developed by TM&R staff (Appendix A). Recorded data included impact locations, net damage, and net repairs. With over 80 rock rolls, this system was essential for recording and organizing the large amount of data obtained.

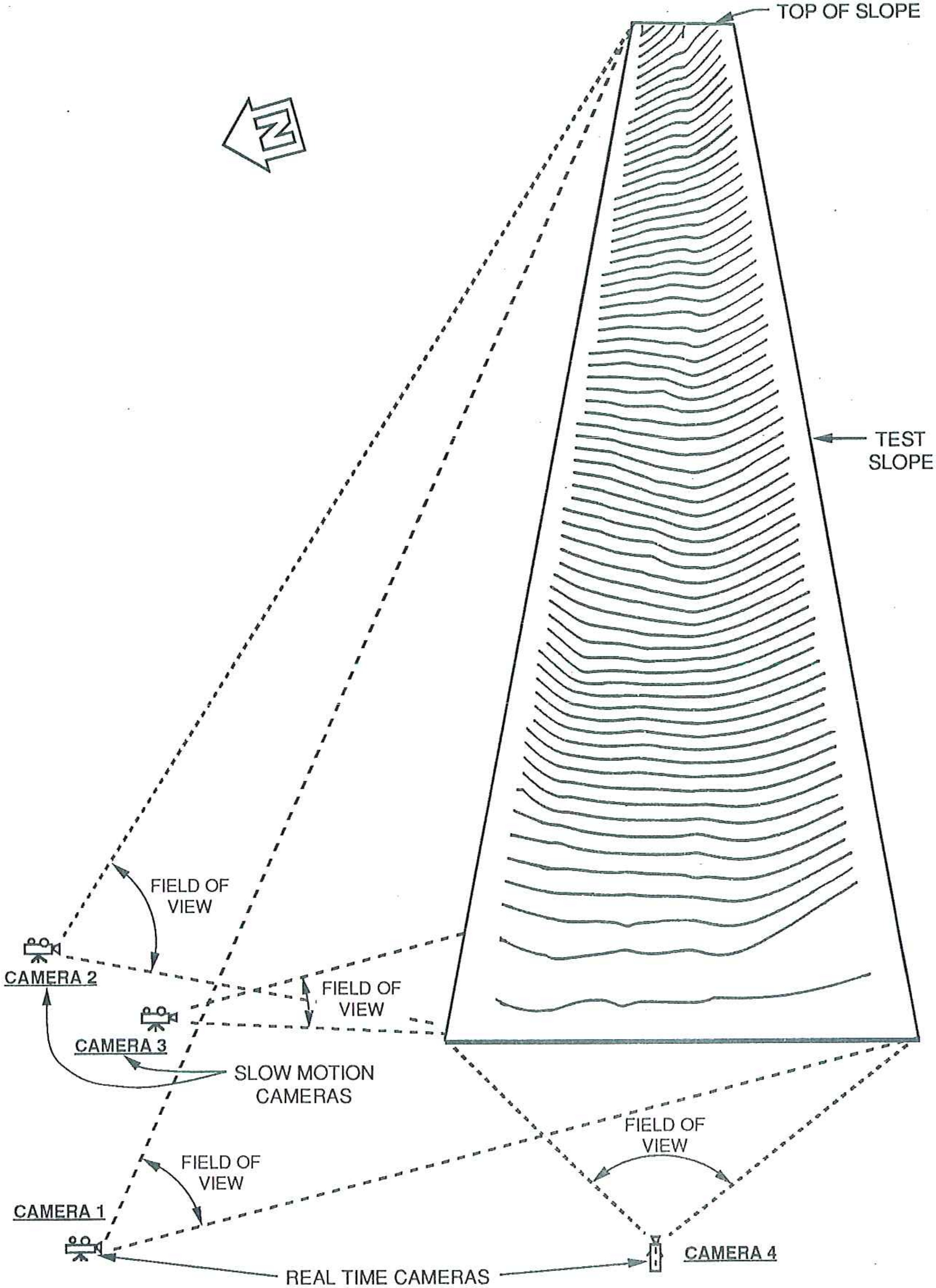


Figure 11. APPROXIMATE CAMERA LOCATIONS FOR FILMING EACH ROCK ROLL

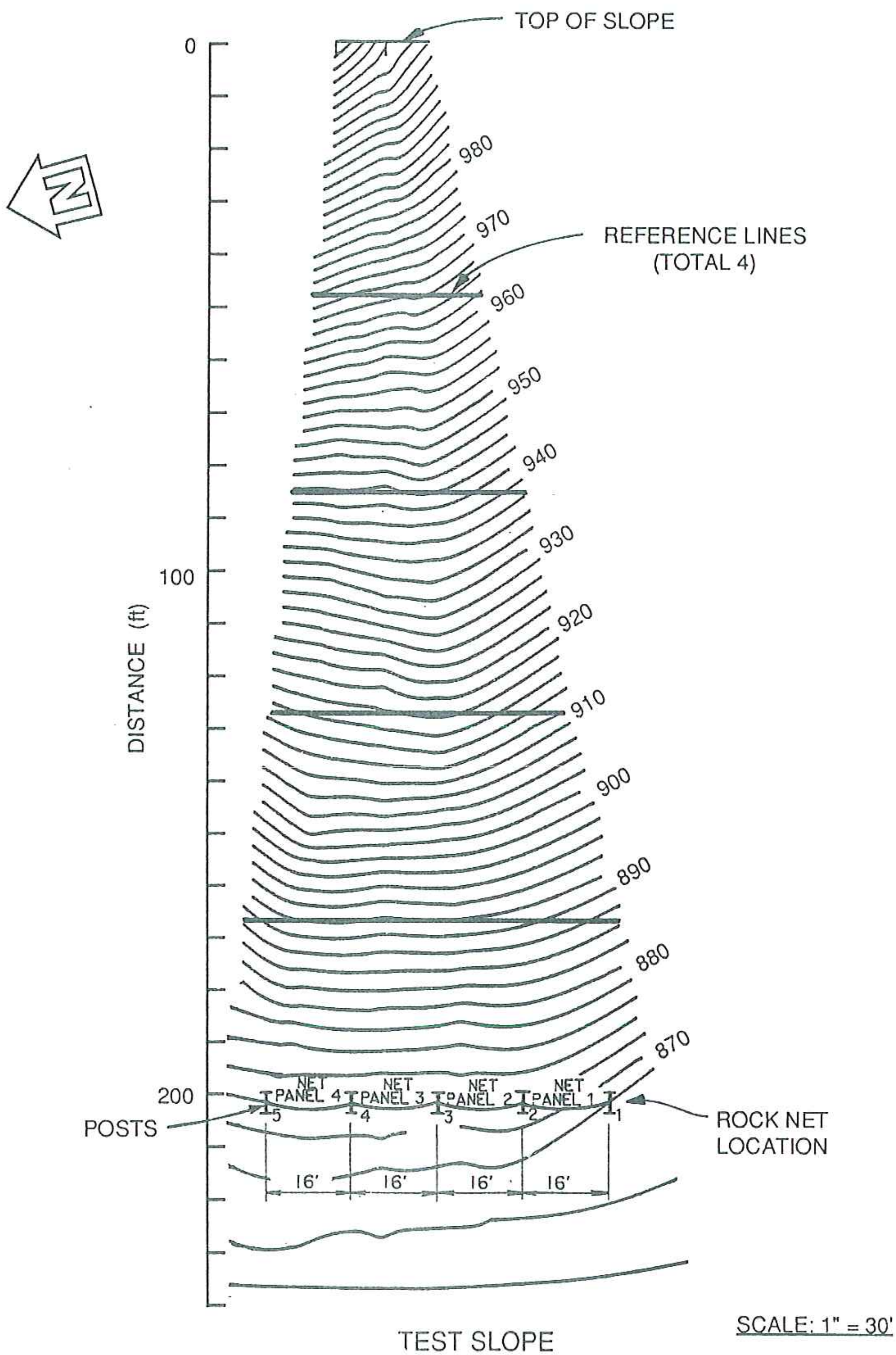


Figure 12. REFERENCE LINE LOCATIONS USED TO ANALYZE IMPACT VELOCITIES DURING TESTS 1 AND 2

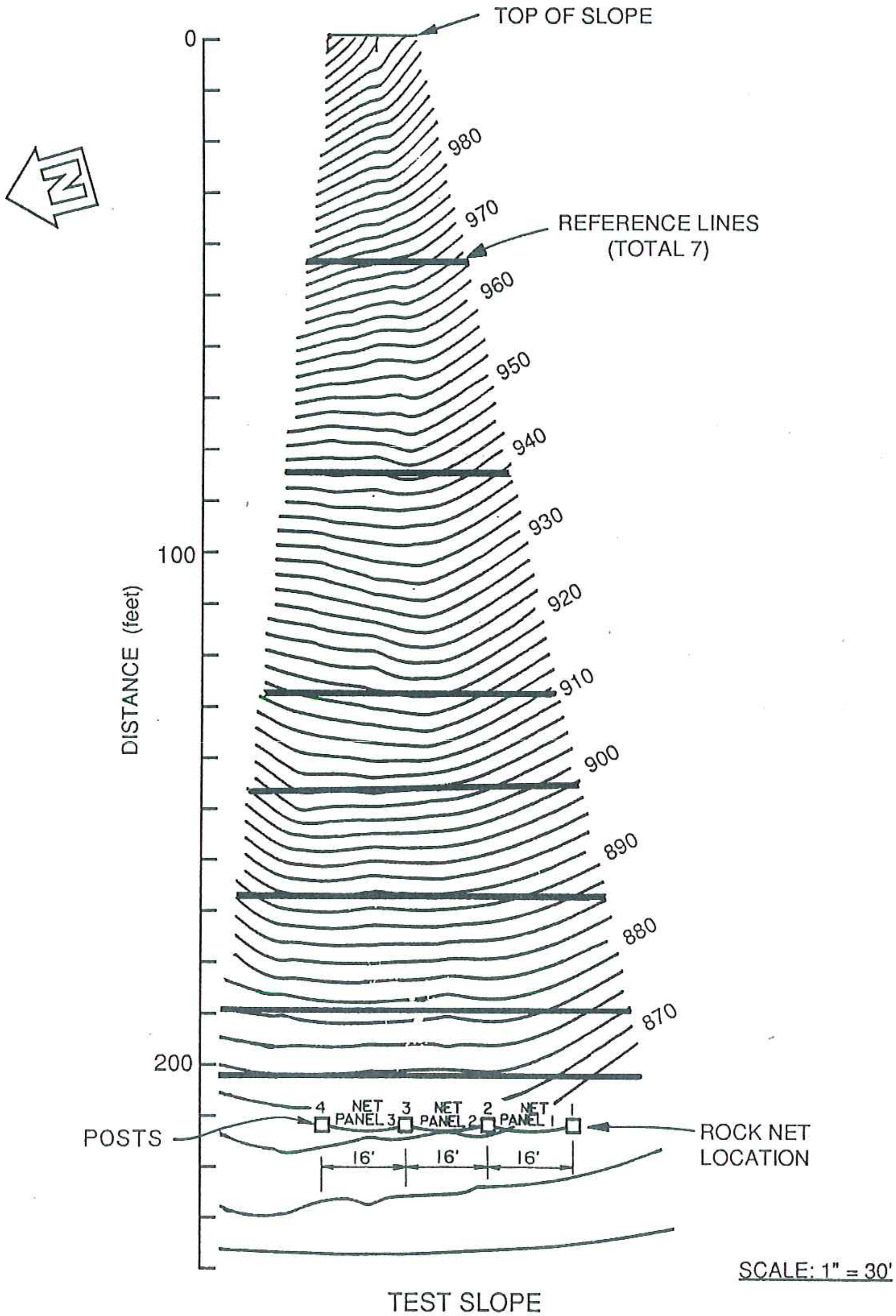


Figure 13. REFERENCE LINE LOCATIONS USED TO ANALYZE IMPACT VELOCITIES DURING TEST 3

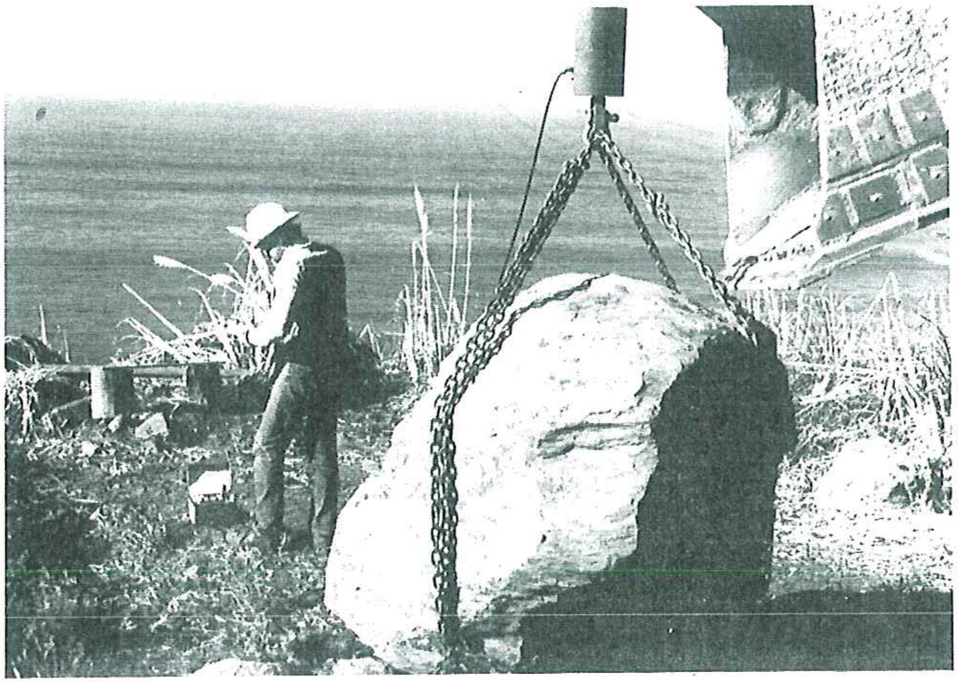


Photo 35. WEIGHING A 5-TON BOULDER USING A LOAD CELL ATTACHED TO THE BUCKET OF A FRONT END LOADER

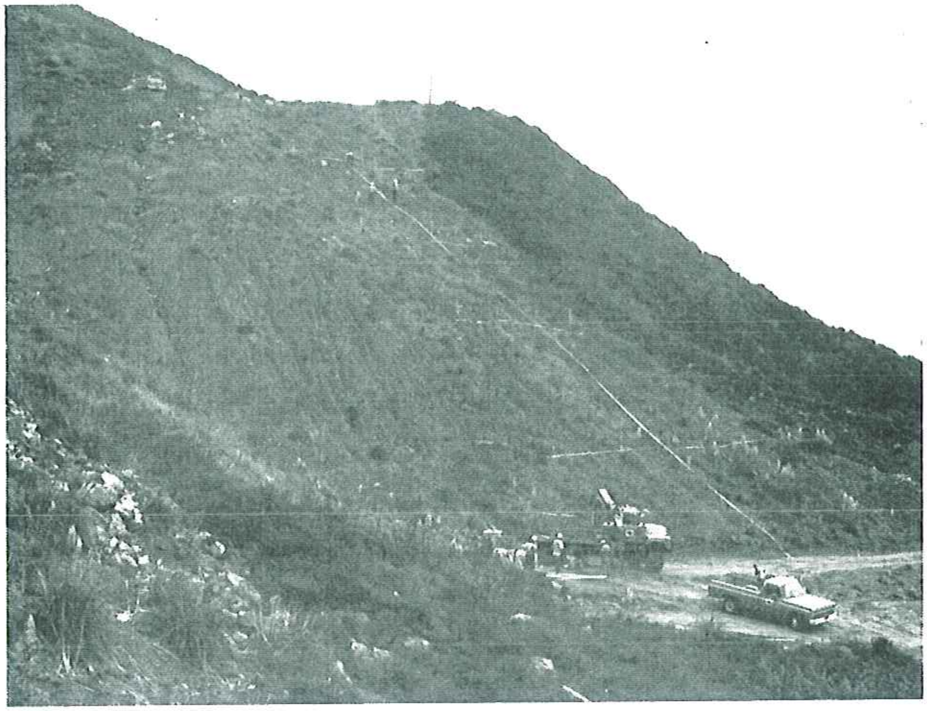


Photo 36a. INSTALLATION OF REFERENCE LINES USED DURING BRUGG TESTS FOR ROCK VELOCITY ANALYSIS

Photo 36b. REFERENCE LINE SPACING USED DURING INDUSTRIAL ENTERPRISE TESTS FOR ROCK VELOCITY ANALYSIS

Rockfall Energy Analysis

Kinetic Energy

Kinetic energy is the most common measurement used to describe rockfall for engineering design. Throughout the energy analysis, each rockfall was treated as a rigid body in motion. According to Chasles' theorem, any general displacement of a rigid body can be represented by a translation plus a rotation (2). Based on this theorem, the process of rockfall is made up of two components: translational motion and rotational motion. These two components can both be quantified as energy in motion, 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 (2). Rockfall motion is therefore the sum of the translational kinetic energy (KE_T) and the angular kinetic energy (KE_A) (1, 2, 6, and 7). This sum, the total kinetic energy (KE), is expressed mathematically as:

$$\text{Total KE} = KE_T + KE_A = 1/2\, mv^2 + 1/2\, I\omega^2 \qquad \text{Eq. 1.1}$$

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

Mass and Weight

The weight (W) of a body is the gravitational force with which the earth attracts the body (1). Mass (m) is the property a body has of resisting any change in its state of rest and is a measure of inertia of the rock body (1). The mass (m) of the boulder is calculated by dividing the boulder's weight (W) by the acceleration of gravity (g). The value for the acceleration of gravity used was 32.2 ft/sec.

$$m = W/g \qquad \text{Eq. 1.2}$$

As stated earlier, an estimate of the weight of the boulder was made by measuring the three principle axes (x, y, and z) of the rock. These values are used to calculate a representative volume (V) of the boulder. The weight of the boulder equals boulder volume (V) multiplied by the unit weight of the rock. The unit weight of the rock was determined from two field samples tested in the TM&R

laboratory for specific gravity (SG) which, when multiplied by the unit weight of water equals the unit weight of the rock.

$$(SG_{rock})\text{ (Unit Weight of Water)} = \text{Unit Weight of Rock} \qquad \text{Eq. 1.3}$$

A unit weight of 190 pounds per cubic foot was used in the boulder weight calculations. Some boulders were weighed after they were rolled to accurately determine their weight. Although it was not possible to weigh all boulders in this manner, it was determined from random rock weighing that the estimated weight was within ± 10% of the actual weights. Therefore, estimated weights in the energy calculations use a maximum and minimum value of ± 10% of the estimated boulder weight.

Velocity

Two velocities are required to determine total kinetic energy (KE_T): translational velocity and angular velocity. Translational velocity (v) is the velocity of the rock mass concentrated at the center of the rock body. This velocity was determined by measuring the time (t) it took the boulder to travel from the last reference line to the net. This distance (d) was 40 feet in the Brugg tests and 10 feet in the EI test.

$$v = \text{distance} \div \text{time} = \text{ft/sec} \qquad \text{Eq. 1.4}$$

Angular velocity (ω) is the velocity of the rock mass spinning around the center of the rock body. Angular velocity (ω) was determined by measuring the time it took the boulder to complete one revolution (360 degrees) before hitting the net.

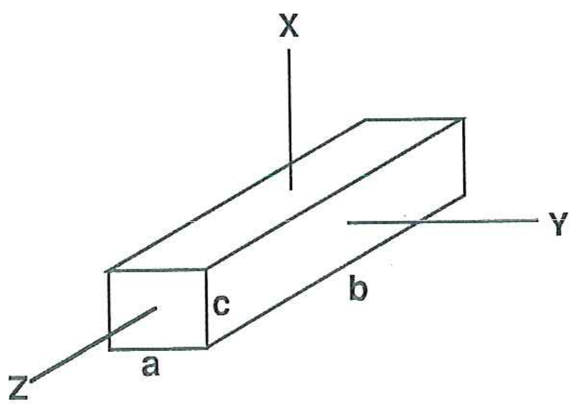
$$\omega = \text{radians} \div \text{time} = \text{seconds}^{-1} \qquad \text{Eq. 1.5}$$

This information was obtained from the video tapes and slow motion film footage. With the visible reference lines on the slope and film editing equipment capable of achieving frame-by-frame control, accurate measurements were obtained of the time (t) the boulders traveled between reference lines, and the time it took the boulder to spin one revolution.

Moment of Inertia

The moment of inertia depends on the mass distribution relative to the axis of rotation of the rock body (7). The value of the moment of inertia (I) of a rock body about a particular axis of rotation not only depends upon the body's mass, but also upon how the mass is distributed about the axis (7). In this analysis, the axes are assumed to be centered about the center of mass of the rock body. The same principle axes (x, y, and z) used to estimate boulder weight are used in the inertia calculations. For the moment of inertia (I) calculations, equations representing rectangular bodies and spherical bodies were selected and the boulders were assumed to be homogeneous solids.

The motion of rectangular bodies is a function of the axis about which they rotate. In this analysis, rotation was assumed to occur around only one of the three principle axes (x, y, or z) and is described by three equations.



$$I_{xx} = 1/12\, m\, (a^2 + b^2) \quad \text{Eq. 1.6a}$$

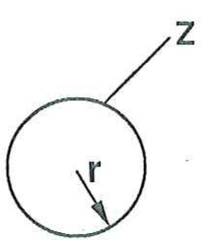
$$I_{yy} = 1/12\, m\, (c^2 + b^2) \quad \text{Eq. 1.6b}$$

$$I_{zz} = 1/12\, m\, (a^2 + c^2) \quad \text{Eq. 1.6c}$$

where m = mass

Rectangular
Parallelepiped

The motion of spherical bodies is a function of the radius of the bodies and is described by the equation



$$I_{zz} = 2/5\, mr^2 \quad \text{Eq. 1.7}$$

where m = mass

Sphere

The axes of rotation were determined from the videos and slow motion films. It was observed during the 80 rock rolls that, in most cases, rocks revolved around the shortest axis for the first 150 feet. As rock velocity increased, rocks then revolved around their longest axis. Under similar conditions, the long axis should be used in angular KE calculations. Detailed analysis of this occurrence is beyond the scope of this report, but will be investigated in future reports.

Calculations

Each rockfall impact is measured in terms of foot-tons of total kinetic energy. Maximum value calculations use 110% of the estimated weight and minimum value calculations use 90% of the estimated weight. A computer spread sheet was developed by TM&R staff to calculate the total kinetic energy. The results of these calculations are in Appendix B.

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 is used to balance the net system so that each component will function without failure.

Rocks impacting the net generate forces throughout the net system which 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". The load path consists of several structural net components with different strengths and load-dissipation capabilities. When all of the 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 momentum, and impulse:

$$F\,t = m\,v \qquad \text{Eq. 1.8}$$

Impulse = momentum change

where F is the applied force, t is the time it takes the boulder to stop, m is the mass of the boulder, and v is the translational velocity at the initial point of impact. The procedure by which these values were obtained, the calculations, and the results of this analysis are presented in Appendix C.

Friction Brake Analysis

Several laboratory tests were conducted on the friction brakes to evaluate their performance. Tests were performed on new brakes, retorqued brakes, and two brakes in tandem. An MTS electro hydraulic machine with a one million pound capacity was used to load the brakes until they activated. Test results are presented in Appendix D.

PERFORMANCE OF THE ROCK RESTRAINING NETS

The performance of the Brugg and Industrial Enterprise rock net systems are presented in the following tables. Each table represents a series of rock rolls between inspections. Reported in the tables are net condition before testing, rock roll identification, rock impact energy, rock impact zones, performance of the nets, and maintenance.

The opening paragraph of each table describes the rock net that was tested. Three different net conditions are possible; a new installation, a repaired installation, and a modified installation. Where there is no description, no changes have been made from the previous test series.

Rock roll identification numbers correlate with the tables in Appendix B. Appendix B tables list each rock roll with rock weight, velocity, translational kinetic energy, angular kinetic energy, and total kinetic energy. Rocks that missed the net system are not recorded causing a gap in the number sequence.

Energy is presented in foot-tons as this is the most common unit to describe rockfall impacts. The energies are presented as minimum-maximum based on estimated rock weights. In some cases, rocks were weighed and a single "true" energy is given.

The rock impact zone column identifies what net panel or support post was impacted. The performance column describes, in detail, the condition of the net system and damage after the rock rolling series. Maintenance requirements and solutions are described at the end of each table.

Table 1: Energy, Impact Locations, and Performance for Brugg Test No. 1

The Brugg net was tested on August 10 and 11, 1989

Rock No.	Energy (ft-tons) Min.	Energy (ft-tons) Max.	Impact Zone
2	3.7	4.6	Panel 2
3	4.5	5.5	Panel 1
4	8.1	9.8	Panel 2
5	14.4	19.3	Panel 2
6	5.2	6.3	Panel 2
8	37.8	46.2	Panel 2
10	31.0	37.9	Panel 3

Performance

All the rocks were stopped by the nets. Rocks #4, #5, and #6 were stopped by the net but hit in approximately the same location, causing considerable damage to the 2 mm mild steel fasteners. Subsequent rocks were stopped on initial impact but upon rebounding, hit stationary rocks, pushing them through the loosened net grid. These rocks stopped two feet beyond the net.

Rock #8 broke into several fragments, many of which went over the net. The largest fragment hit the net and rolled through the loose mesh, stopping three feet downslope (Photos 37 and 38).

Chain link mesh was not used during this portion of the testing.

At the conclusion of this test sequence, many fasteners in the impact zone failed or were loosened. The 5/16-inch lacing cable did not fail but the single wire rope clips holding the ends in place slipped at two locations in Panel 2. None of the friction brakes were activated. All other net components were intact.

Maintenance of the net required replacing missing fasteners with wire rope clips and refitting the wire rope clips on the wire rope lacing.

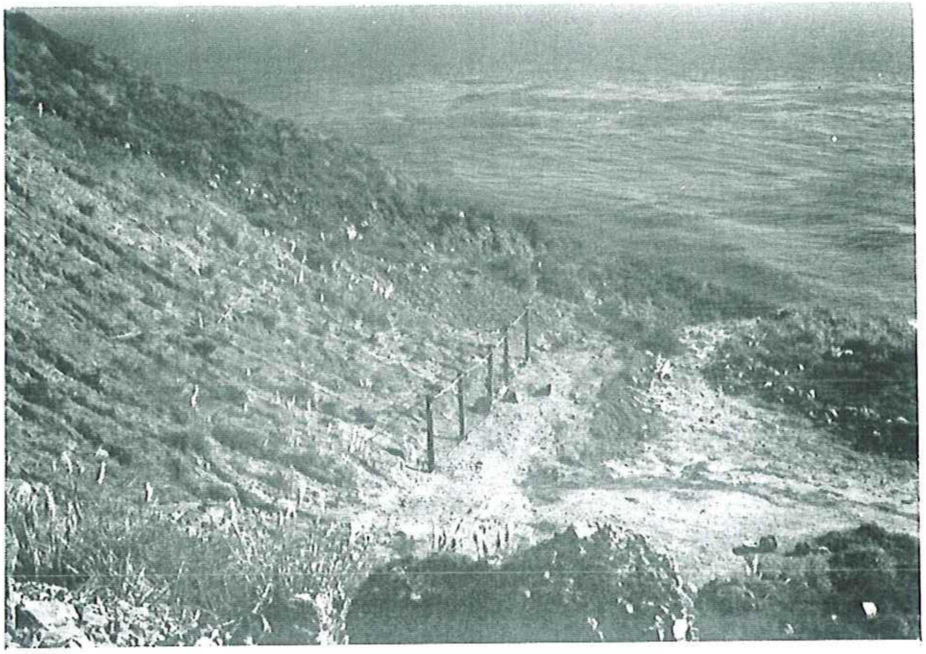


Photo 37. PENETRATION OF THE BRUGG NET BY ROCKS #6 AND #8 AFTER LOOSENING OF THE NET FASTENERS BY PREVIOUS ROCK IMPACTS

Photo 38. CLOSE-UP VIEW OF BRUGG NET AND ROCKS AFTER ROCK ROLLS 1-10. NOTE ROCK #6 IN CENTER OF PHOTO

Table 2: Energy, Impact Locations, and Performance for Brugg Test No. 1

Panels 2 and 3 were replaced with new panels, 5/16-inch wire rope lacing cables, and a second wire rope clip was added to the lacing cable connections. In addition, 11-gage chain link mesh was attached to the net on the upslope side of Panels 2, 3, and 4. Panel 1 remained as originally constructed.

Rock No.	Energy (ft-tons) Min.	Max.	Impact Zone	Performance
12	5.0	6.1	Panel 3	All rocks were stopped by the nets. The chain link fencing greatly reduced the damage to the fasteners and prevented small rock fragments from going through the net. Smaller rocks did more damage to the fasteners than larger rocks. The 5/16-inch wire rope lacing failed where it was wrapped three times when rock energies exceeded 35 ft-tons. Most of the foundations were loosened but remained intact except where the foundation for lateral wire rope Anchor 2 moved two inches. During impact of rock #19, the net deflected downslope approximately six feet and the boulder stopped in the net four feet downslope.
13	6.0	7.3	Panel 1	
15	35.4		Panel 2	
16	13.8		Panel 2	
18	18.8	23.0	Panel 1	
19	134.5	164.4	Panel 3	

Panel 1: Four fasteners failed and 24 fasteners were loose within the impact zones. No friction brakes were activated.

Panel 2: Six fasteners failed and 15 fasteners were loose in the impact zones. The 5/16-inch wire rope lacing cable was intact and there was no slippage of the double wire rope clips. The bottom friction brake activated and moved 1/2 inch.

Panel 3: Twelve fasteners failed and 30 were loose in the impact zones. The lacing cable failed where it was triple wrapped but the double wire rope clips held. The top friction brake activated and moved 1/4 inch. Few of the hog rings held and, as a result, the chain link mesh separated from the net. The upslope friction brake on Post 3 activated and moved 1/2 inch (Photos 39 and 40).

Maintenance consisted of replacing several lacing wire ropes, replacing missing fasteners with wire rope clips, and completely replacing Panel 3.

Photo 39. THREE-TON ROCK #19 AFTER IMPACTING THE BRUGG ROCK NET

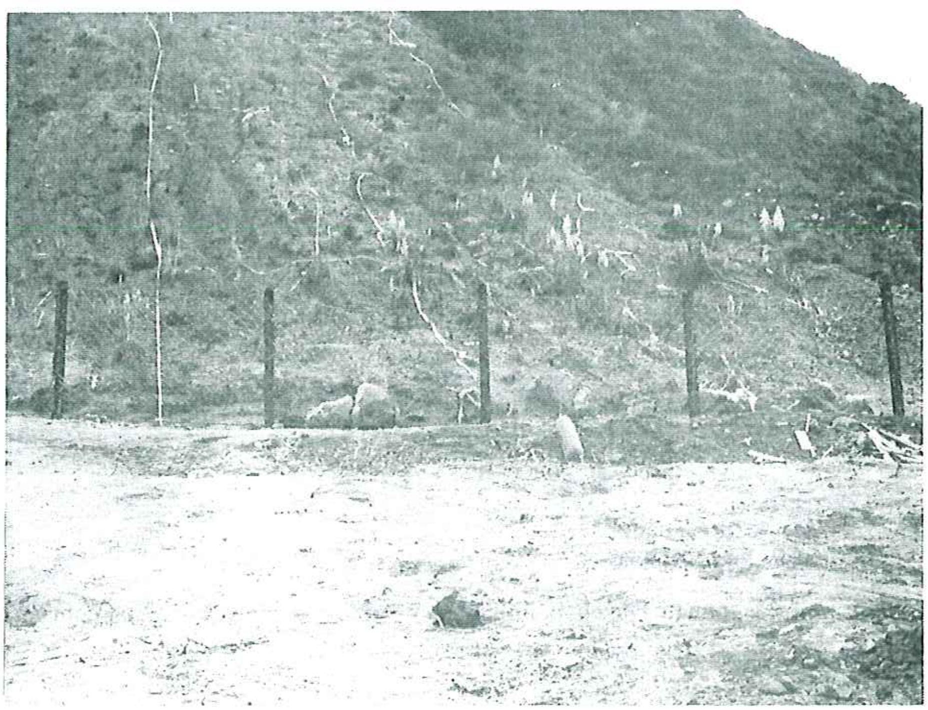


Photo 40. ROAD LEVEL VIEW OF BRUGG ROCK NET AFTER ROCK ROLLS 12-19. NOTE SLIGHT SAG IN NET PANEL 3

Table 3: Energy, Impact Locations, and Performance for Brugg Test No. 2

This test was conducted on November 14 and 15, 1989.

Only Panels 1, 2, and 3 were installed for this test. In this sequence, Panel 1 was constructed with the 2.5 mm spring steel fasteners and Panels 2 and 3 were constructed with the 2.5 mm low strength steel fasteners. The lacing wire rope was replaced with stronger 3/8-inch-diameter cable and all three panels were covered on the upslope side with 9-gage wire mesh fastened with hog rings. Lateral anchor foundation Number 2 was replaced. All the other net components are the same as in Test 1, described in an earlier section.

Rock No.	Energy (ft-tons) Min.	Energy (ft-tons) Max.	Impact Zone
2	1.6	1.9	Panel 1
3a	1.2	1.4	Panel 3
3b	1.8	2.2	Panel 3
4	9.4	11.5	Panel 1
5	17.4	21.3	Panel 2
6	3.2	4.0	Panel 3
7	3.8	4.6	Panel 3
9	2.8	3.4	Panel 1
11	8.2		Panel 2
12a	2.9		Panel 3
12b	14.9		Panel 2
13	24.7		Panel 3

Performance

All the rocks were stopped by the nets. The chain link mesh loosened and separated from the net after Rock Rolls #2 to #6.

Panel 3: The top friction brake activated and moved 1/2 inch. In the upper right hand corner, several wire rope net strands failed (Photo 41).

The rest of the system was intact. The chain link mesh was rehung and rock rolling continued.

Photo 41. FIVE 1000-TO 1600-POUND ROCKS IN THE BRUGG NET REPRESENTING ROCK ROLLS 9-13. NET PANEL 1 IS SEEN IN THE FOREGROUND. NOTE CHAIN LINK MESH SEPARATING FROM ROCK NET

Table 4: Energy, Impact Locations, and Performance for Brugg Test No. 2

Rock No.	Energy (ft-tons)		Impact Zone	Performance
	Min.	Max.		All the rocks were stopped by the rock nets.
14	21.7		Panel 3	Panel 2: No fasteners failed but 12 fasteners were loose in the impact zone. Two strands of the wire rope net failed in the lower left corner.
15	34.8	- 42.5	Panel 2	
16	21.8	- 26.6	Panel 2	Panel 3: Three fasteners failed and two fasteners were loose in the impact zone. The lacing cable appeared stressed in the lower left and right hand corners (Photo 42).

The rest of the system was intact. No repairs were made and the rock rolling continued.

Table 5: Energy, Impact Locations, and Performance for Brugg Test No. 2

Rock No.	Energy (ft-tons)	Impact Zone	Performance
18	17.8	Panel 3	The rock was stopped by the rock net. No fasteners failed but eight fasteners were loose in the impact zone. The wire rope nets appeared stressed in the upper right and left corners (Photo 42).

Maintenance of the nets required replacing missing fasteners with wire rope clips, replacing some of the lacing cable, and repairing the wire rope net strands at the corners.

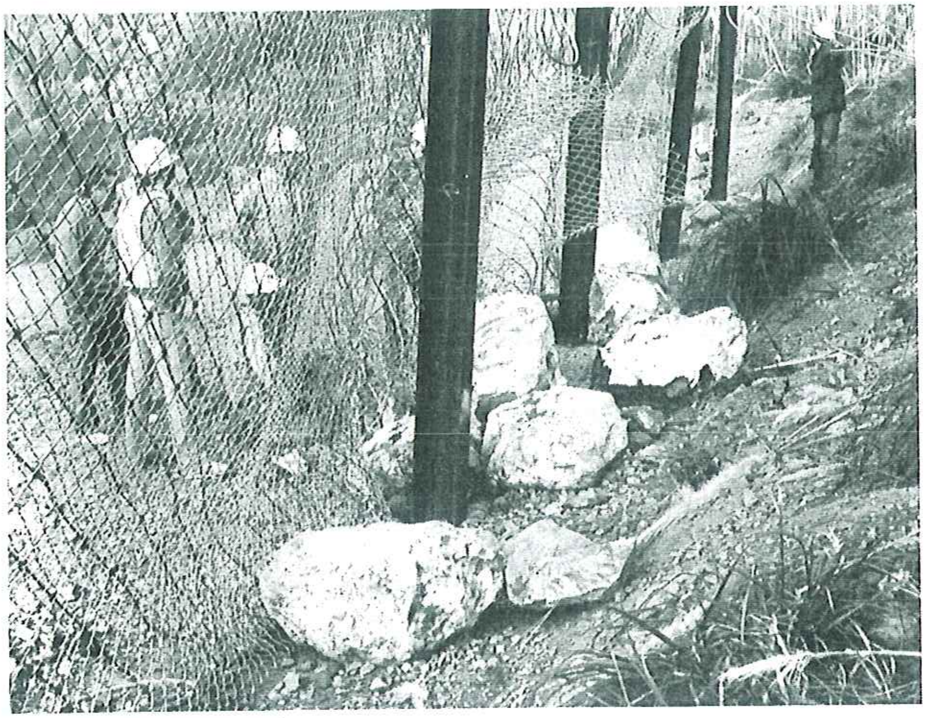


Photo 42. BRUGG ROCK NET AFTER ROCK ROLLS 9-18. NOTE CHAIN LINK MESH SEPARATING FROM THE ROCK NET. NET PANEL 1 IS IN THE FOREGROUND.

Table 6: Energy, Impact Locations, and Performance for Brugg Test No. 2

Panels 1, 2, and 3 were replaced with new panels and all of the lacing cable was replaced. Panels 1 and 3 were constructed with 2.5 mm low strength steel fasteners and Panel 2 was constructed with 2.5 mm spring steel fasteners. The net lacing was 3/8-inch cable. All of the chain link mesh was replaced, but in this test, wire twists and hog rings were used to connect the chain link mesh to the wire rope net.

Rock No.	Energy (ft-tons) Min.		Energy (ft-tons) Max.	Impact Zone
19	5.9	-	7.3	Panel 2
20	1.0	-	1.3	Panel 1
22	0.8	-	0.8	Panel 2
23	3.7	-	4.5	Panel 3
24	1.0	-	1.2	Panel 2

Performance

All the rocks were stopped by the rock net. Damage was minimal to the net system.

Panel 3: One fastener split, nine fasteners slid and four fasteners were loose. The rest of the net system was intact.

Table 7: Energy, Impact Locations, and Performance for Brugg Test No. 2

Rock No.	Energy (ft-tons) Min.		Energy (ft-tons) Max.	Impact Zone	Performance
30	13.7	-	16.8	Panel 2	All the rocks were stopped by the rock nets. Post #5 took a direct impact (Photo 58). The rock hit the post 5.2 feet above ground level. The flanges were bent, the foundation loosened, and the upslope anchor brake was fully activated and irreparably damaged. The post was still functional and the rest of the net system was intact.
31a	14.3	-	17.4	Panel 3	
31b	8.9	-	10.9	Panel 3	
32	70.0			Post 5	

Post 5 was reused, the anchor brake was replaced, and rock rolling continued.

Table 8: Energy, Impact Locations, and Performance for Brugg Test No. 2

Rock No.	Energy (ft-tons) Min.	Max.	Impact Zone	Performance
				Rock Roll #36 was 1.7 times the design load.
34	6.9	8.4	Panel 3	All the rocks were stopped by the nets (Photo 43). The net performed well.
35	57.5	70.3	Panel 1	Panel 1: Two fasteners failed and 15 fasteners were loose. The top and bottom perimeter cable brakes activated and moved 1/8 inch. The upslope anchor cable brake on Post 2 activated and moved 1/2 inch. The net sagged approximately four inches.
36	125.4		Panel 2	Panel 2: Six fasteners failed and nine fasteners were loose. One wire rope net strand broke in the impact zone and in the upper right corner. In the lower left corner, the lacing cable pulled through one of the two wire rope clips holding it in place. The upslope anchor cable brake on Post 3 was activated and moved 1/2 inch. The net sagged approximately one foot.
				Panel 3: One fastener was loose. The rest of the net system was intact (Photos 44 and 45).

Details of the dynamic energy distribution in the net during Rock #36 impact are described in Appendix C.

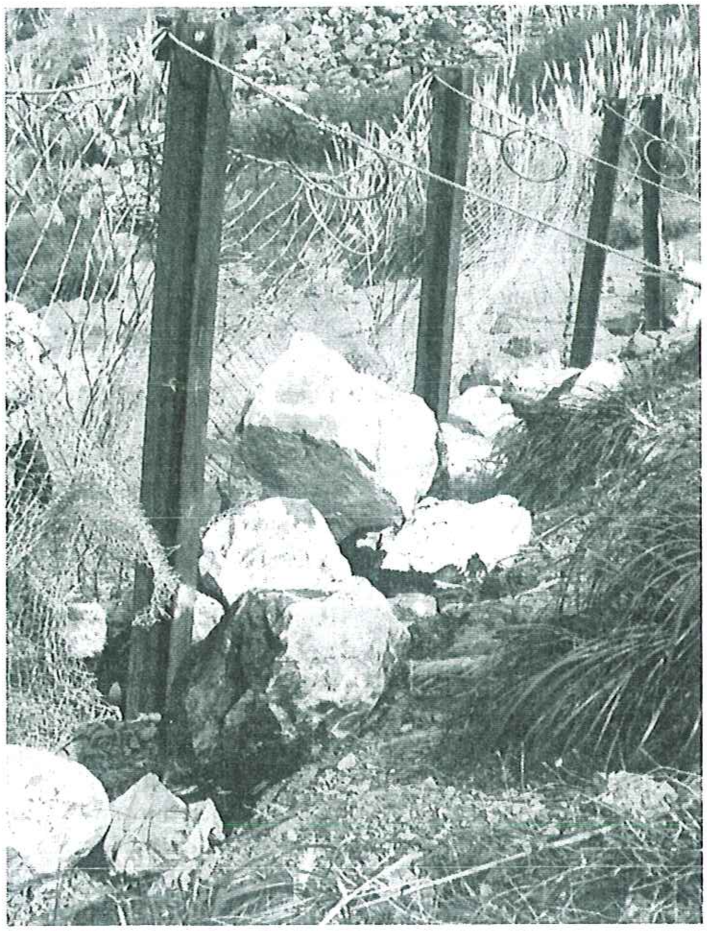


Photo 43. BRUGG ROCK NET AFTER ROCK ROLLS 9-36. NOTE THE CHAIN LINK MESH SEPARATING FROM THE ROCK NET AND THE SLIGHT SAG IN NET PANEL 2 IN THE MIDDLE OF THE PHOTO. ROCK IN CENTER OF PHOTO IS ROCK #36 WHICH WEIGHS 5,500 POUNDS

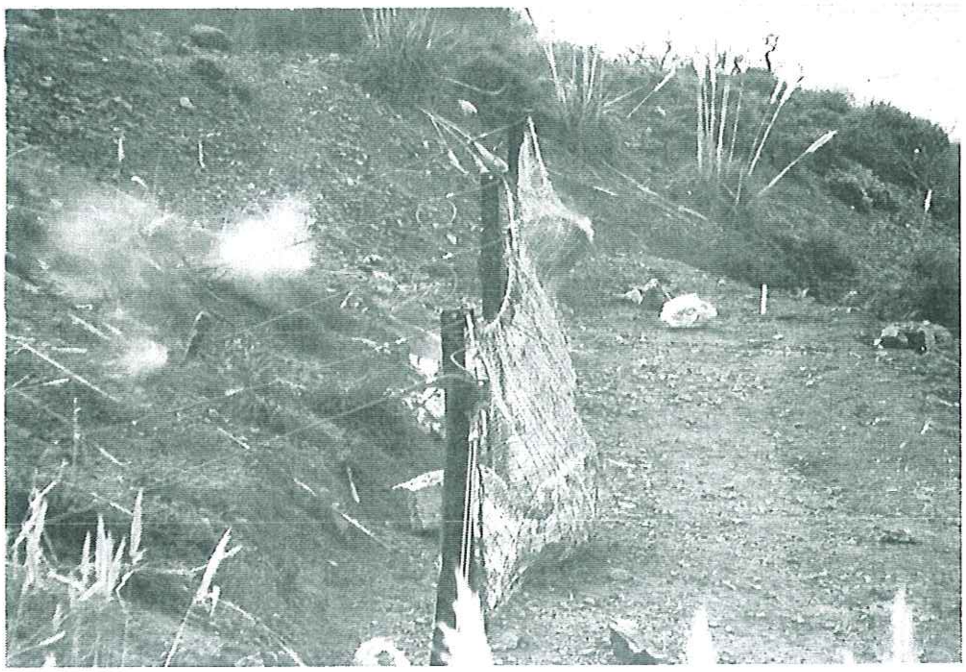


Photo 44. ONE AND ONE-HALF-TON ROCK #35 IMPACTING NET PANEL 1. (Photo Courtesy of John Walkinshaw)

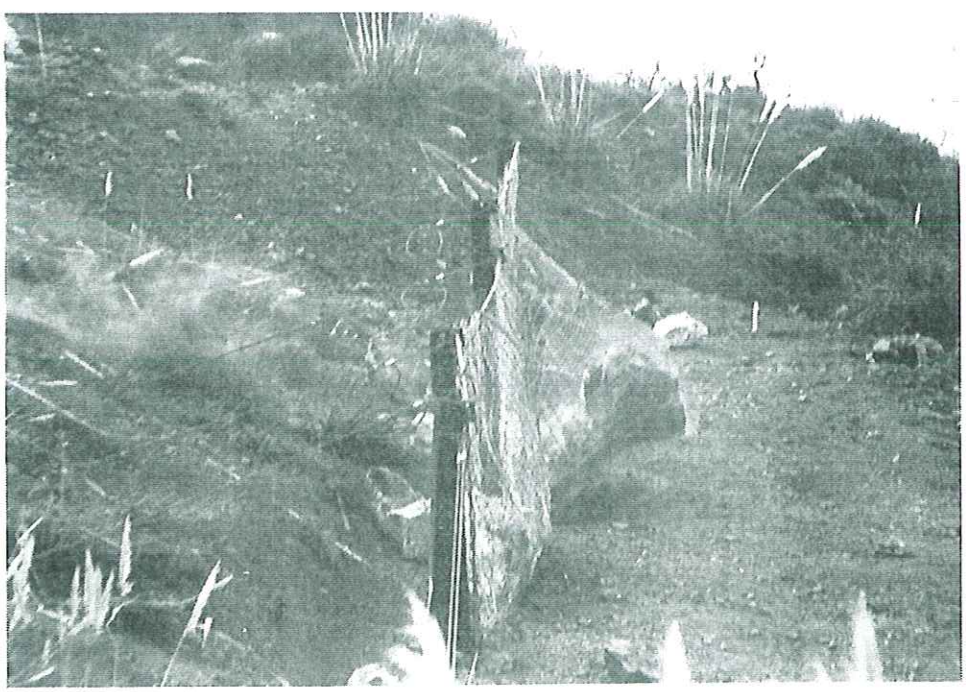


Photo 45. THREE-TON ROCK #36 IMPACTING NET PANEL 2 (Photo Courtesy of John Walkinshaw)

Table 9: Energy, Impact Locations, and Performance for Brugg Test No. 2

The torque in the top and bottom perimeter brakes of Panel 1 and the top perimeter brake of Panel 2 was reduced to 90 ft-lb.

Rock No.	Energy (ft-tons)	Impact Zone	Performance
37	295.3	Panel 3	Rock Roll #37 was 3.9 times the design load. The rock was not stopped in the net, however, the rock's energy was attenuated causing the rock to stop 41 feet downslope from the net. All of the wire rope net strands failed along the top of the net. No other wire ropes failed and no fasteners were damaged. The top perimeter cable brake activated and moved 1/8 inch. At this point, all other net components were intact but the net system appeared stressed.

No other repairs were made and rock rolling continued.

Table 10: Energy, Impact Locations, and Performance for Brugg Test No. 2

Rock No.	Energy (ft-tons) Min. - Max.	Impact Zone	Performance
			Rock Roll #38 was 2.6-3.1 times the design load.
38	190.5 - 232.9	Panel 1	The rock was stopped in the rock net eight feet downslope. The upper right side of the panel tore loose. Failure occurred in the wire rope net strands along the edge of the panel. All other cables, wire ropes, and fasteners were intact.

Maintenance consisted of completely replacing Panels 1 and 3 and the lacing cable in those panels. Other maintenance consisted of replacing missing fasteners with wire rope clips.

Table 11: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

The Industrial Enterprise (EI) net was tested on December 5 and 6, 1989.

Rock No.	Energy (ft-tons)	Impact Zone	Performance
1	27.6	Panel 2	All the rocks were stopped in the rock net. The net sagged approximately three feet. The top row of perimeter rope wire rope clips shifted inward toward the middle of the net. Three fastening bands on the upper left side failed and two on the upper right side failed. Upslope Anchor Brake A on Post 2 activated and slid 6 inches. The upper right net brake activated and slid 12 inches and the upper left net brake activated and slid 4 inches. As a result of this brake movement, the net sagged 3-4 feet. The rest of the net system remained intact (Photo 46).
2	17.1	Panel 2	

The sagging net was raised, the net fastening bands replaced, the perimeter wire rope clips repositioned, and rock rolling continued.

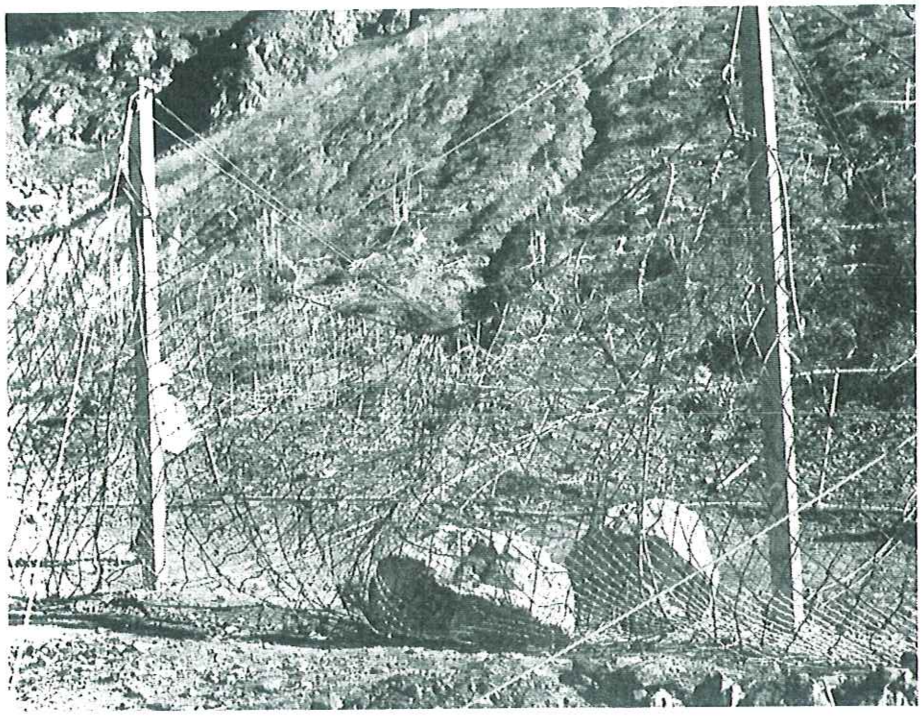


Photo 46. INDUSTRIAL ENTERPRISE ROCK NET PANEL 2 AS VIEWED FROM ROAD LEVEL AFTER ROCK ROLL 1 (1590 POUNDS) AND ROCK ROLL 2 (1860 POUNDS). NOTE CONSIDERABLE SAG IN THE ROCK NET

Table 12: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons) Min.		Energy (ft-tons) Max.	Impact Zone	Performance
					All the rocks were stopped in the rock nets.
3	13.5	-	16.4	Panel 2	Panel 2: Post 2 collapsed upon impact and the post base cable failed. The post was hit three feet above grade and bent 90 degrees. As a result, the net was only two to three feet high. Upslope Anchor Brakes A and B on Post 2 were activated and slid 12 inches and 14 inches, respectively. After Rocks #3 and #4 hit, the net sagged four feet.
4	6.7	-	8.2	Panel 2	
6	13.9	-	17.0	Panel 3	
7a	4.6	-	5.7	Panel 3	
7b	9.4	-	11.5	Panel 2	Panel 3: Eighteen perimeter wire rope clips slid inward toward the center of the net. In the lower left corner of the net, 3 perimeter wire rope clips slid together. The upper right net brake activated and slid 13 inches. After Rock #6 hit, the net sagged one-two feet. After Rock #7a hit, the net sagged three feet (Photos 47, 48, and 49).
8		34.9		Panel 1/Post 2	

Post 2 was replaced, all three nets were raised, and rock rolling continued.

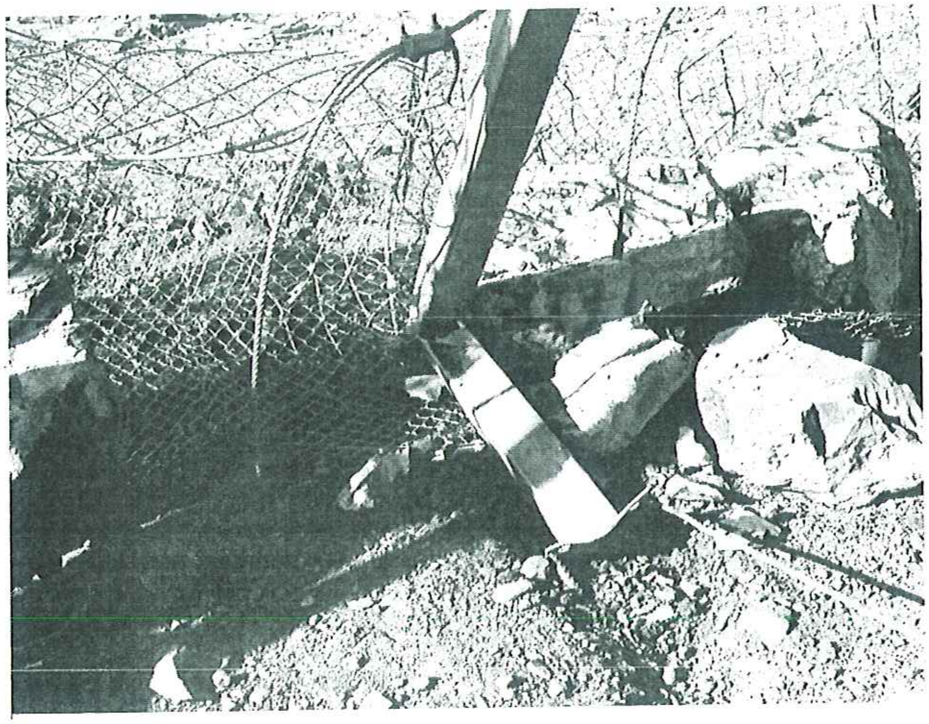


Photo 47. COLLAPSED INDUSTRIAL ENTERPRISE STEEL BOX POST #2 AFTER IMPACT BY A 11/4-TON ROCK. NOTE LOW ROCK NET HEIGHT AT TOP OF PHOTO

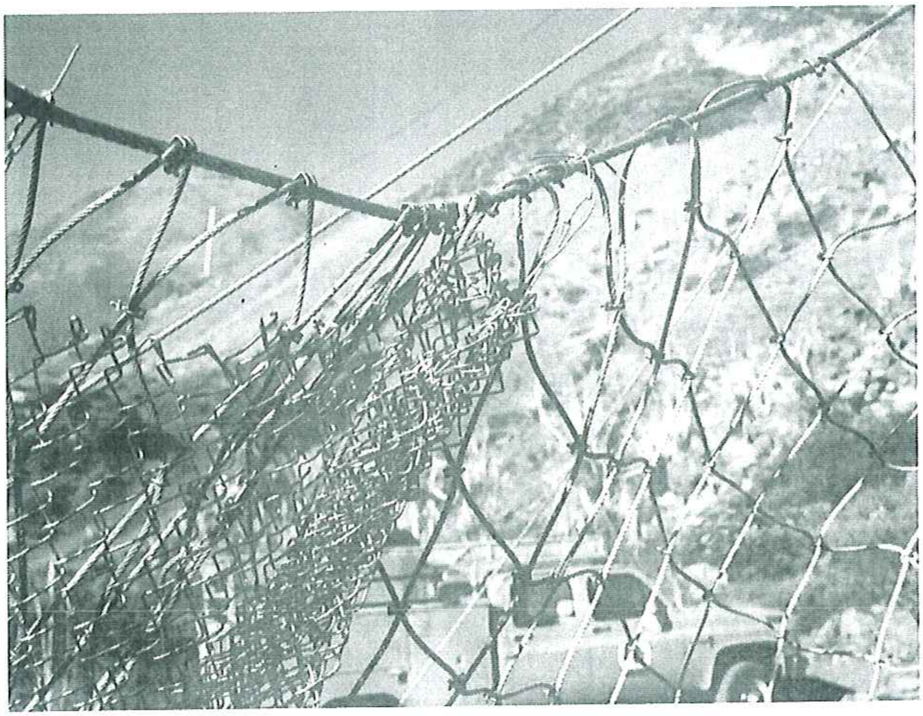


Photo 48. INDUSTRIAL ENTERPRISE ROCK NET PANEL 3 AFTER IMPACTS BY ROCKS #6 AND #7a. NOTE SHIFTING PERIMETER WIRE ROPE CABLE CLIPS AND SEPARATION OF THE CHAIN LINK MESH FROM THE ROCK NET

Photo 49. CLOSE-UP OF BROKEN INDUSTRIAL ENTERPRISE NET PANEL FASTENING BANDS. NOTE CHAIN LINK MESH SEPARATED FROM THE NET

Table 13: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons)	Impact Zone	Performance
9	67.1	Post 1	The rock hit Post 1, collapsing it, and then rolled to the right where there was no net. The base cable broke but no other damage occurred.

The sagging nets were raised and Post 1 was straightened and reinstalled.

Table 14: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons) Min. - Max.	Impact Zone	Performance
10	95.1 - 116.2	Panel 3/Post 3	Rock #10 was stopped by the net. The perimeter wire rope clips slid all around the net panel and the net fastening bands on the right side of the panel all failed. The upper right net brake activated and slid 11 feet. The lower right net brake was activated and slid two inches. Upslope Anchor Brakes A and B on Post 3 were activated and slid 14 inches and three inches, respectively. Post 3 collapsed. The rock stopped in the net nine feet downslope from the net. All other net components were intact (Photo 50).

Post 3 was straightened and reinstalled. The sagging nets were raised and rock rolling continued.

Photo 50. COLLAPSED INDUSTRIAL ENTERPRISE 51/2-x 51/2-INCH STEEL BOX POST #3 AFTER IMPACT BY 5-TON ROCK #10. NOTE ROCK #10 IN NET PANEL #3

Table 15: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons)	Impact Zone	Performance
11	56.3	Post 4	Rock 11 hit the post, collapsing it, and rolled to the left where there was no net panel. The post cable broke but no other damage occurred. Upslope Anchor Brake A and B on Post 4 Anchor Brakes A and B were activated and slid 5 inches and 18 inches, respectively.

Post 4 was straightened and reinstalled. The sagging nets were not raised and rock rolling continued.

Table 16: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons) Min. - Max.	Impact Zone	Performance
12	150.8 - 184.3	Panel 1	Rock Roll #12 impacted with twice the design load. The rocks were not stopped in the rock nets. During impact of Rock #12, the net laid down allowing the rock to pass through. During impact of Rock #15, the friction brake tails slipped enough to lay the net down, allowing Rock #15 to roll over the net. During impact of Rock #18, the net was only two feet above grade and the rock rolled over the net. The net fastening bands between net Panels 1 and 2 all failed. Post 1 upslope Anchor Brakes A and B activated and slid nine feet and one foot, respectively while Post 2 upslope Anchor Brake A activated and slid 11 feet allowing the net to sag nearly to ground level. Post 3 upslope Anchor Brakes A and B activated and slid 11 feet. Post 3 was hit, but was usable. Panels 2 and 3: The upper right net brakes activated and slid 12 inches and 4 inches, respectively. All the other net components were intact.
15	70.8 - 86.6	Panel 2	
18	19.5 - 23.8	Panel 2	

The sagging net was raised six feet above grade and rock rolling continued.

Table 17: Energy, Impact Locations, and Performance for Industrial Enterprise Test No. 3

Rock No.	Energy (ft-tons) Min.		Energy (ft-tons) Max.	Impact Zone	Performance
19a	10.4	-	12.7	Panel 2	All the rocks were stopped in the rock net panel and there was no damage. The net panel sagged six to eight feet.
19b	5.9	-	7.2	Panel 2	
19c	1.3	-	1.6	Panel 2	
19d	0.6	-	0.7	Panel 2	

Maintenance required at this time consisted of resetting all the friction brakes, rehanging the net to its original 10-foot height, and repairing or replacing four posts.

MAINTENANCE OF ROCK NET SYSTEMS

Cleaning the Brugg Rock Net System

Considerable interest has been expressed by maintenance personnel throughout the state concerning the level of repair and methods of cleaning required for rock nets. Although it is generally accepted in Caltrans that this mitigation measure effectively stops rockfall, maintenance requirements are considered important in the practical use of the nets. Therefore, considerable effort was given to evaluating 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 one to four hours.

This section describes the cleaning and repair of the rock net systems. It was found during the study that rockfall accumulations behind a single panel could be removed easily and quickly while still providing maximum protection to the workers and the traveling public.

Access for cleaning boulders and rockfall debris (Photos 51 and 52) from the Brugg rock net was provided by raising individual panels from the bottom or by lowering them from the top (Photos 53 and 54). This required removing the lacing wire rope at the top or bottom along with a portion or all of the lateral or side lacing wire ropes. Both methods worked well.

In cases where large boulders had come to rest on the lower perimeter rope and base of the panel preventing access to the lower lacing rope, it was most expedient to lower the panel so that a front end loader could drive over the panel and remove the boulders. Many of the rocks could be rolled off the net by two people without difficulty.

Repair of the Brugg Rock Net

The lacing wire ropes should be replaced each time they are disassembled because of distortion of the wire ropes near their ends where they are wrapped three times around the perimeter wire rope and the post fittings (Photo 55). After impact, the wrapped lacing wire ropes are permanently distorted with a curl or kink in the rope. Relacing with this distorted rope is difficult and time consuming (Photo 6).

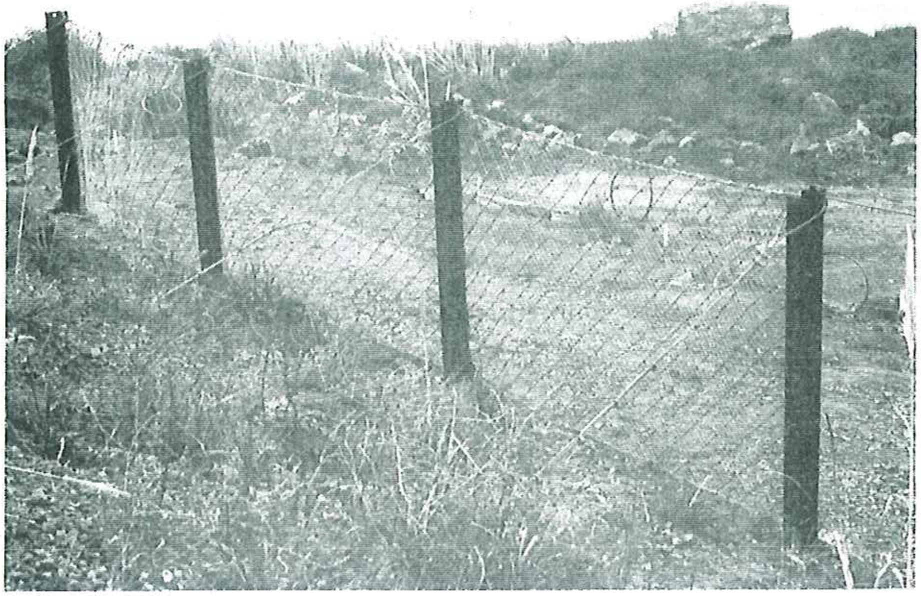


Photo 51. BRUGG ROCK NET LOOKING DOWNSLOPE PRIOR TO ROCK ROLLING

Photo 52. BRUGG ROCK NET LOOKING DOWN SLOPE AFTER 20 ROCK ROLLS

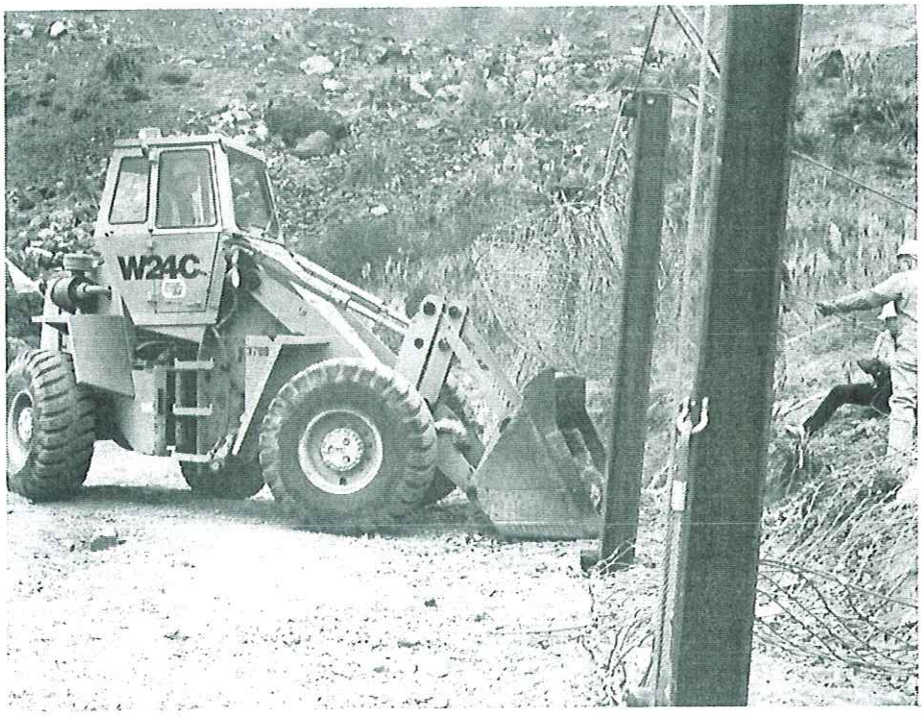


Photo 53. CLEANING BRUGG ROCK NET BY RAISING THE NET PANEL FROM THE BOTTOM

Photo 54. CLEANING BRUGG ROCK NET BY LOWERING THE NET. NOTE THE LOADER WORKING ON TOP OF THE NET

Photo 55. BREAK AND DISTORTION OF WIRE ROPE LACING WHERE IT WAS WRAPPED 3 TIMES AROUND THE PERIMETER WIRE ROPE. NOTE FIBER CORE OF LACING WIRE ROPE EXPOSED IN CENTER OF PHOTO

The heavy wide flange steel posts that support the restraining system were hit by several rocks causing some local distortion to the flanges. In one case, a post was slightly bowed (Photo 56). Damage in all cases was minimal and it was not necessary to remove or replace any posts.

Movement of the steel posts and their concrete foundations was common on impact. Although the bond between the concrete and surrounding soil was broken, the integrity of the restraining system was not compromised.

One post was hit directly by a 2,630 lb boulder which fully activated the friction brake damaging the 5/8-inch wire rope. Because the friction brake was activated, the wire rope was lengthened by almost 4.5 feet causing the post to lean downslope (Photos 57 and 58). A new anchor rope with friction brake was installed in 15 minutes by two men using a come-along to realign the post and tension the new upslope wire anchor rope. This time frame is reasonable for replacement of each of the upslope anchor ropes.

Two panels were replaced by a crew of four men in about an hour. This consisted of removing the chain link mesh on each net panel and the seven lacing wire ropes. Installation of new panels was accomplished by reversing these steps but using new lacing wire rope.

All upslope and lateral anchors performed well up to and beyond the design load. In one case, a boulder delivered at least three times the design load causing about two inches of displacement in the easterly lateral anchor. This anchor was later tested and resisted a 20,000 lb pull (Photo 59). No maintenance of the upslope or lateral anchors was required.

Panel fasteners may occasionally require replacement, particularly if the panel has been repeatedly hit in the same area (Photos 60 and 61). Fasteners are easily and quickly replaced with wire rope clips.

Friction brakes are easily reset after activation by two people. A come-along is used to tension the wire rope and a torque wrench is used to reset the friction brake. The whole process takes less than 20 minutes.

The chain link mesh frequently became detached after repeated impacts. Repairs consisted of repositioning the mesh and reattaching it to the panel with wire ties. Severely distorted mesh can be replaced in a few minutes (Photo 62).

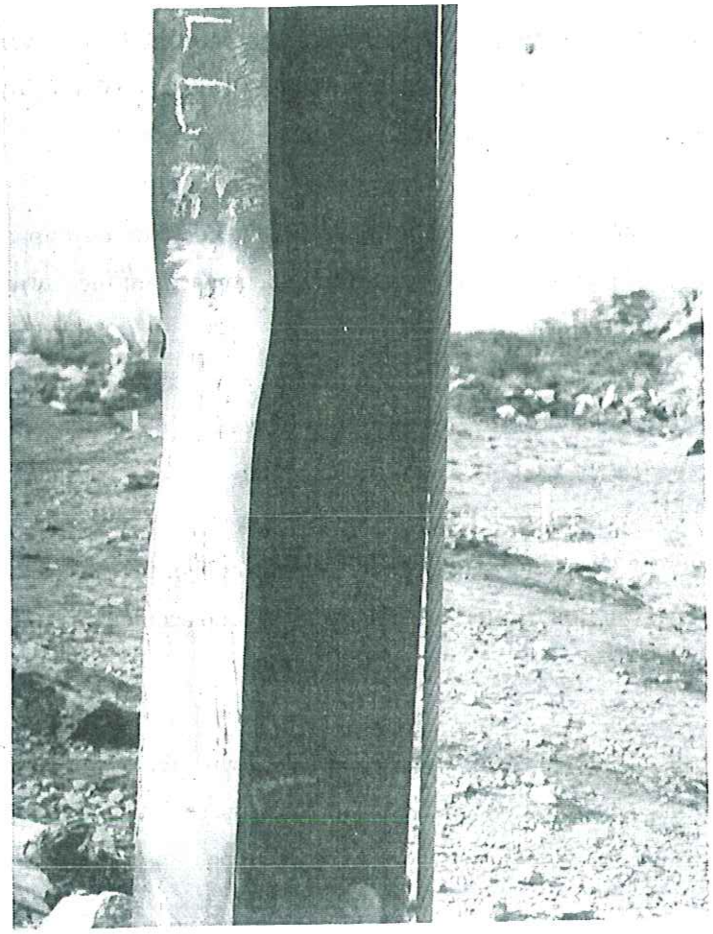


Photo 56. SLIGHTLY BOWED BRUGG 8-x8-INCH-WIDE FLANGE 48 POUND / FOOT STEEL POST AFTER A DIRECT HIT BY A 11/2-TON ROCK

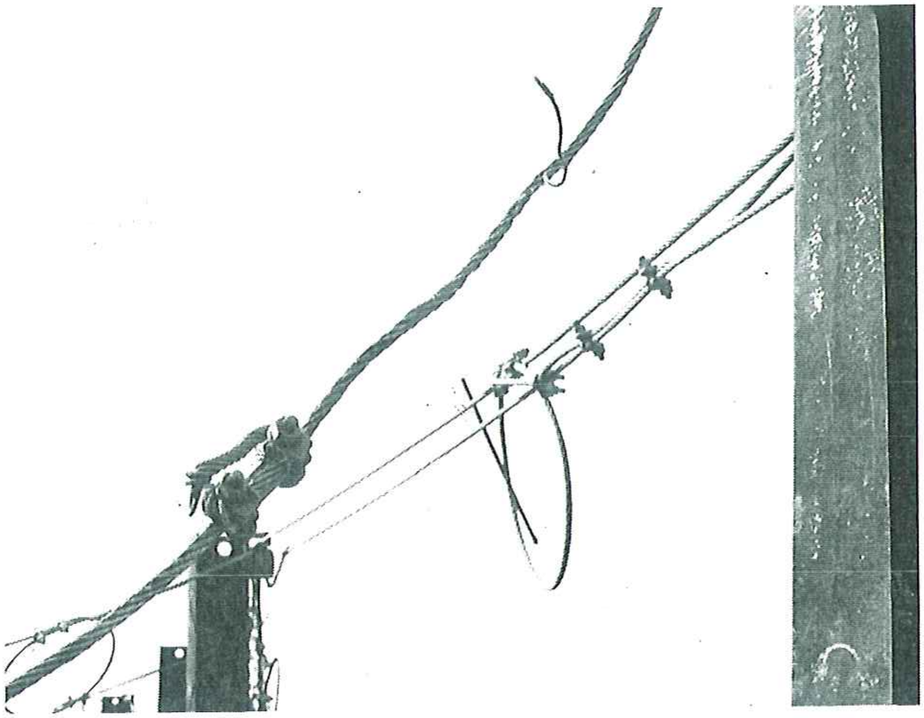


Photo 57. ACTIVATED BRUGG FRICTION BRAKE AND DAMAGED ANCHOR WIRE ROPE CAUSED BY IMPACTING ROCK #32. SEE PHOTO BELOW

Photo 58. ROCK ROLL 32 HITTING POST #5 AND FULLY ACTIVATING THE FRICTION BRAKE AND TILTING THE POST. (Photo Courtesy of John Walkinshaw)

Photo 59. PULLOUT TEST OF ANCHOR USING A LOAD CELL ATTACHED TO FRONT END LOADER. ANCHOR RESISTED 20,000 POUND PULL

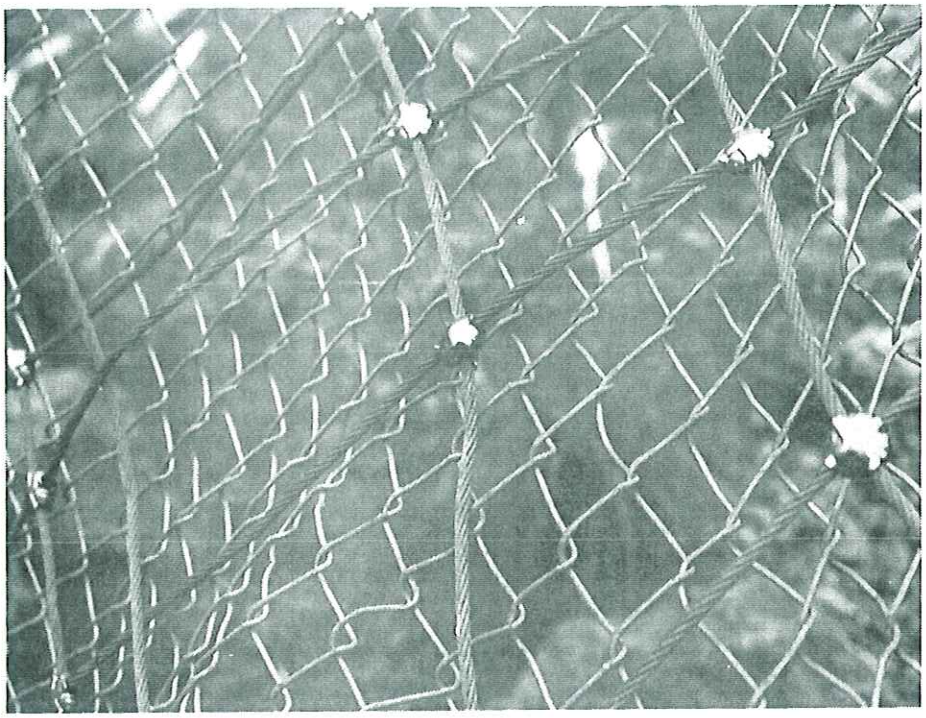


Photo 60. MISSING AND LOOSE BRUGG FASTENERS ON THE NET PANEL

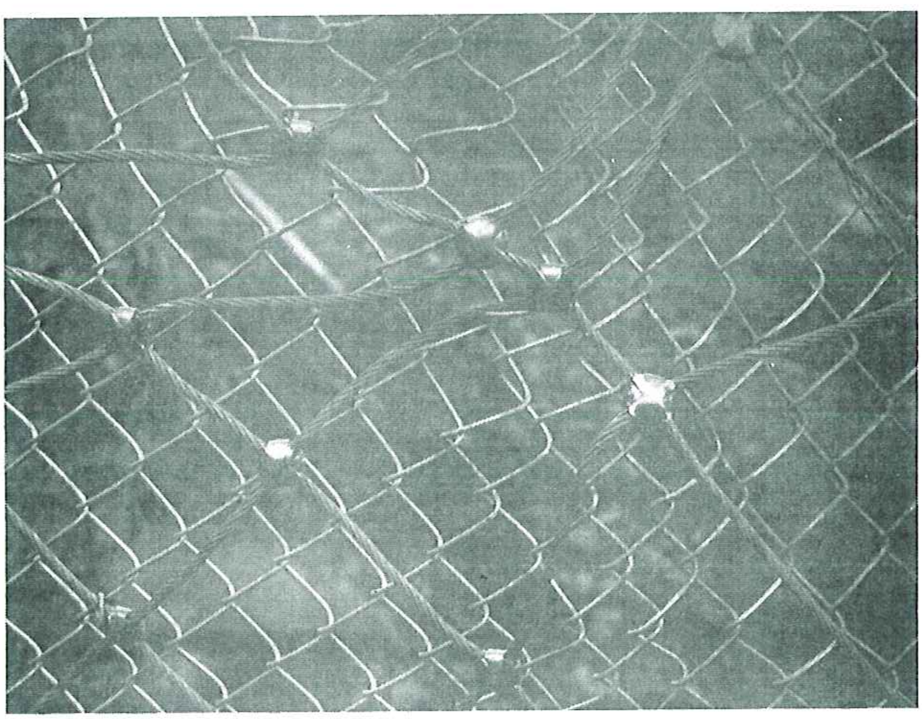


Photo 61. SHIFTING OF LOOSE BRUGG FASTENERS ON THE NET PANEL

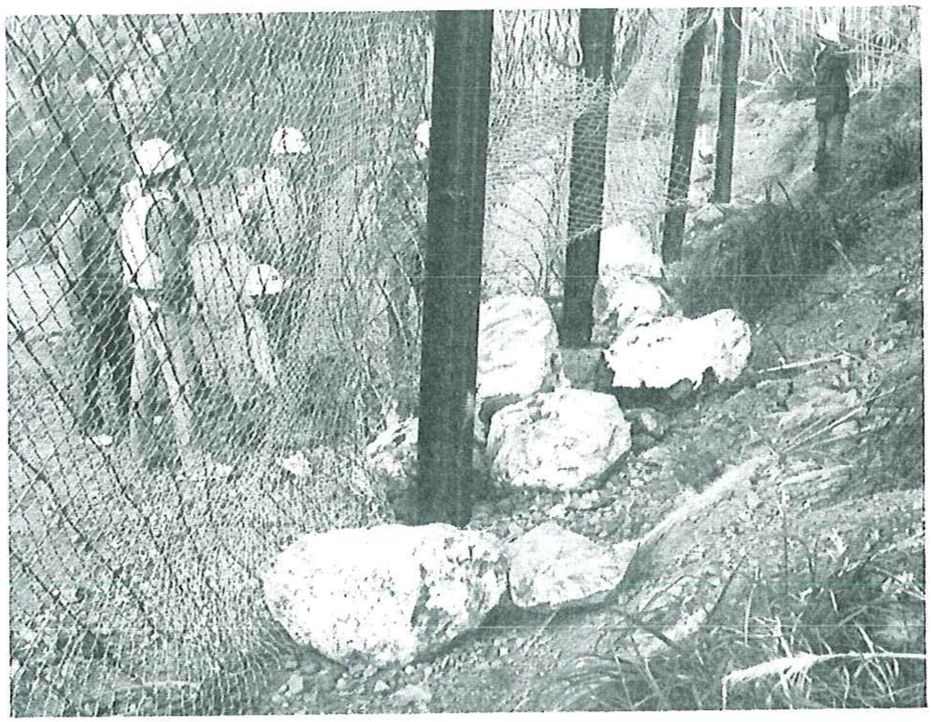


Photo 62. CHAIN LINK MESH SEPARATING FROM NET PANELS AFTER 7 ROCK ROLLS

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

Cleaning the Industrial Enterprise Rock Net

Cleaning and repair of the EI rock restraining system is similar to the Brugg system. The individual panels can be either raised or lowered and boulders and rockfall debris removed by hand or with motorized equipment (Photos 63 and 64). In order to clean behind a single panel, the chain that connects adjacent panels must be disassembled. This is easily accomplished by removing the pin of the connector link with a punch and hammer.

Use of a front end loader to remove the boulders requires the removal of the guy wire ropes from the downslope anchors to allow access by the loader. Without the guy wires, the posts are no longer stable and must be laid down or temporarily secured in an upright position with ropes or braces that are clear of the path of the loader (Photos 65 and 66).

Repair of the Industrial Enterprise Rock Net

Posts that were damaged during the testing were easily replaced (Photo 67). It took four men approximately one hour to remove the three guy wires, disconnect the chain at the top and bottom of the post, and remove the base post cable. Installation of the new or straightened post is done in the reverse order. Guy wires and friction brake wire ropes must be retensioned with come-alongs.

Bent posts that are not too severely damaged can be straightened for reuse. Since the only function of the post is to suspend the panels, a slight bend or distortion is acceptable. Straightening of the posts was done in the field by securing one end to a fixed point and then pulling the other end with a vehicle followed by applying downward pressure to the bend with the bucket of a front end loader (Photos 68 and 69).

Severe sagging of the nets occurs after brake elements are activated. The net height must be maintained in order to provide adequate rockfall catchment area. Therefore, the nets need to be maintained to ensure proper net height. Raising the net is accomplished by resetting the friction brakes (Photo 70). To do this, a come-along is used to relieve tension on the brake to allow loosening

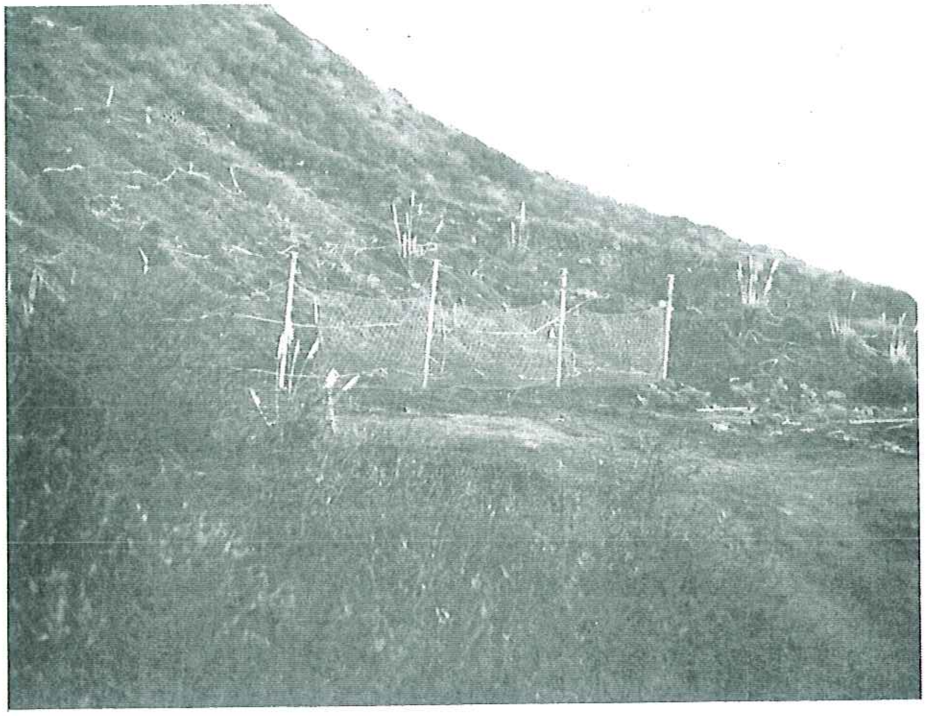


Photo 63. INDUSTRIAL ENTERPRISE NET PRIOR TO ROCK ROLLING AS SEEN FROM ROAD GRADE

Photo 64. INDUSTRIAL ENTERPRISE ROCK NET AFTER TWO ROCK ROLLS OF 1590 AND 1860 POUNDS. NOTE SAGGING ROCK NET IS NOW 6 FEET HIGH

Photo 65. CLEANING INDUSTRIAL ENTERPRISE ROCK NET BY LAYING DOWN THE NET PANEL. NOTE THAT TWO PANELS AND ONE POST ARE LAID DOWN FOR CLEANING. ALSO NOTE THE LOADER WORKING ON TOP OF THE NET

Photo 66. FRONT END LOADER ROLLING ROCK OFF INDUSTRIAL ENTERPRISE NET PANEL

Photo 67. COLLAPSED 51/2-x51/2-INCH STEEL BOX POST AFTER IMPACT BY 5500-POUND ROCK #9

Photo 68. STRAIGHTENING A POST BY SECURING ONE END TO A FIXED POINT AND PULLING THE OTHER END WITH A VEHICLE

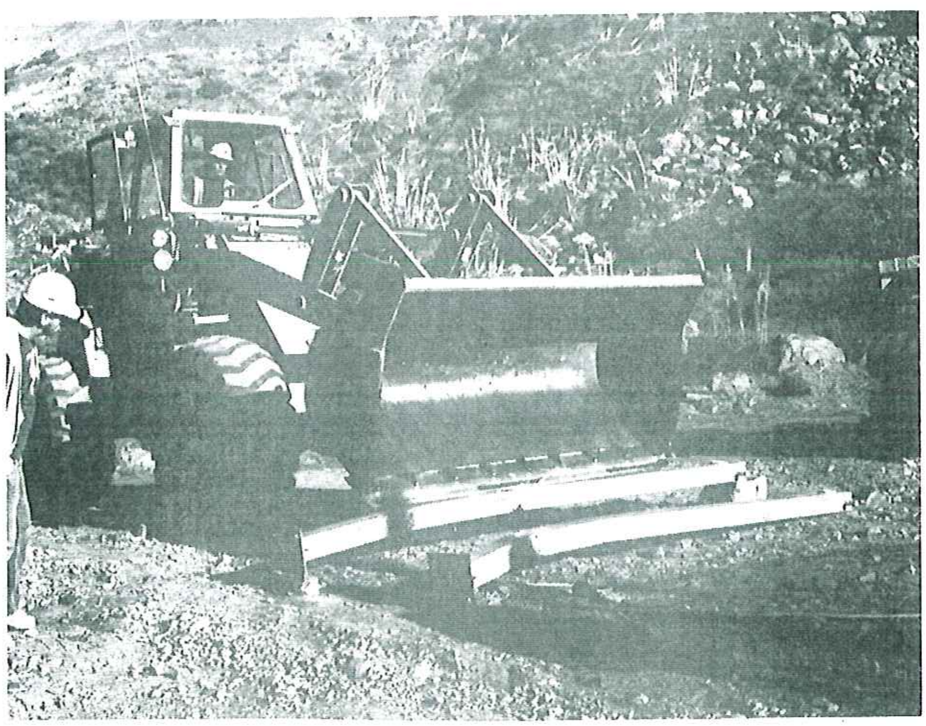


Photo 69. FINAL BOX POST STRAIGHTENING BEING DONE BY BENDING THE POST WITH A FRONT END LOADER

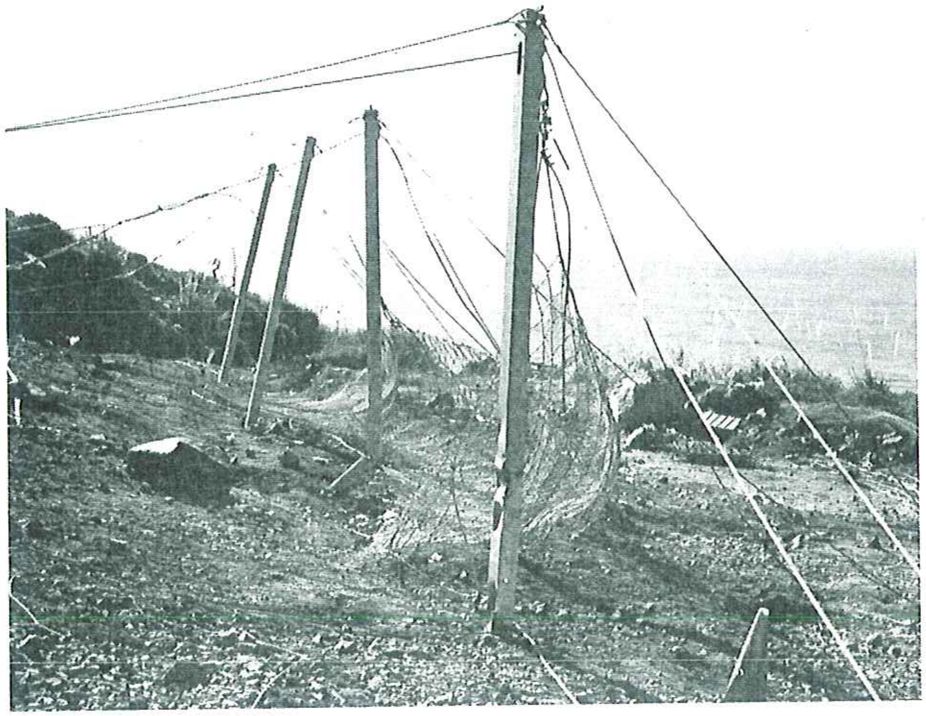


Photo 70. INDUSTRIAL ENTERPRISE ROCK NET AFTER 1300-POUND ROCK #12 IMPACTED THE NET WITH 180 FOOT-TONS OF KINETIC ENERGY. ROCK #12 ROLLED OVER THE NET PANEL

of the brake bolts and repositioning the tails to their original position. Once in place, the bolts are then retorqued to their assigned values (Appendix D).

Since the friction brakes and fuse links are designed to activate prior to failure of other components of the rock nets, it is highly unlikely that damage would occur to either the anchors or panels. Boulders that strike a panel and transmit in excess of 20 tons to the fuse links will cause them to break allowing the panel to lay down, thus permitting the boulder to pass through the installation without doing additional damage.

None of the fuse links were broken during the testing, but they can be replaced easily by bringing the brake loops back into position with a come-along and then threading the chain through the loops and attaching the ends with the connector link.

No wire rope clips on the panels failed during testing. They did, however, shift and require repositioning to reestablish the 8- x 8-inch grid spacing (Photos 48 and 71). This was done by loosening the wire rope clips, sliding them into their proper position, and retightening them.

Replacement of friction brakes, wire rope anchors, or guy wire ropes would probably not be necessary during the life of the rock net, but could be done easily by two people using a come-along to tension the ropes and ratchet wrenches for removing and installing wire rope clips.

Loose or sagging chain link mesh on the rock nets can be corrected by repositioning the mesh and attaching it to the wire rope panels with wire twists.

Photo 71. DOWNSLOPE VIEW OF THE RIGHT SIDE OF INDUSTRIAL ENTERPRISE NET PANEL 3. NOTE THE SHIFTING BORDER WIRE ROPE CLIPS AND SAGGING NET

REFERENCES

1. Beiser, Arthur (1988) Applied Physics 2nd edition, Schaum's outline series, McGraw-Hill Book Company, New York, pp. 37-97.

2. Goldstein, Herbert (1950) Classical Mechanics, Addison-Wesley Publishing Company, Philippines, pp. 9- 203.

3. Heierli, W. (1976) Protection from Rock Slips and Falling Rock by Means of Steel Wire Nets, Shultz gegen Felssturz und Steinschlag mit Drahtseilnetzen (German), Schweiz, Bauztg, pp. 611-614.

4. McCauley, M. L., B. W. Works, S. A. Naramore (1985) Rockfall Mitigation, Office of Transportation Laboratory, California Department of Transportation, Sacramento, California, pp. 1-147.

5. Meriam, J. L (1978) Engineering Mechanics Volume 1 Statics, John Wiley & Sons, New York, pp. 351-391.

6. Paronozzi, P. (1989) Probabilistic Approach for Design Optimization of Rockfall Protective Barriers, Quarterly Journal of Engineering Geology, Vol. 22, pp. 175-183.

7. Tipler, P. A. (1976) Physics, Worth Publishers, Inc., New York, pp. 33-180.

APPENDIX A

ROCKFALL IMPACT DATA SHEET

ROCK RESTRAINING NET TEST DATA SHEET

MANUFACTURER: ____________ VIDEO I.D. : ________ PAGE : /

TEST #: ________

TEST OR ROLL#: ____________

ROLL #: ________

ROCK I.D.: ______________

A. ROCKFALL DATA

1. DIMENSIONS: ____________ METERS(m) ____________ FEET(ft)
2. VOLUME (V): ________ CUBIC METERS ____________ CUBIC FEET
3. UNIT WEIGHT( ): ________ Kg/m^3 ____________ Lb/ft^3
4. WEIGHT(W) ________ Kg ____________ Lb
5. MODE OF TRAVEL BEFORE IMPACT: (ROLL,BOUNCE,SLIDE,FREEFALL) ______________

WEIGHT

ESTIMATED

1. ____________
2. ____________
3. ____________

REAL

____

% ERROR ____________

B. MOMENT OF INERTIA (I):

1. SHAPE: ____________
2. AXIS OF ROTATION: ____
3. I= ______________

C. VELOCITY:

1.TRANSLATIONAL

a. LENGTH OF ROLL IN TIME t ________ m ________ ft

b. TIME t ______________ sec

c. VELOCITY v ________ m/sec ________ ft/sec

d. LENGTH OF ROLL IN TIME t ________ m ________ ft

e. TIME t ______________ sec

f. VELOCITY v ________ m/sec ________ ft/sec

2.ANGULAR

a.ROTATION: ________ degrees

________ radians

b.TIME: ________ secs

c.ANGULAR VELOCITY( ): ________ sec^{-1}

D. ENERGY K.E. = 1/2 m v + 1/2 I

a. ACCELERATION OF GRAVITY(g) = ________ m/sec ________ ft/sec

b. MASS m= W / g ________ $Kg/m/sec^2$ ________ $Lb/ft/sec^2$

c. TRANSLATIONAL K.E.= 1/2 m v

1. maximum ____________ Kilojoules ____________ Foot-tons
2. minimum ____________ Kilojoules ____________ Foot-tons

d. ANGULAR K.E.= 1/2 I

1. maximum ____________ Kilojoules ____________ Foot-tons
2. minimum ____________ Kilojoules ____________ Foot-tons

e. TOTAL KE = TRANSLATIONAL + ANGULAR.

1. maximum ____________ Kilojoules ____________ Foot-tons
2. minimum ____________ Kilojoules ____________ Foot-tons

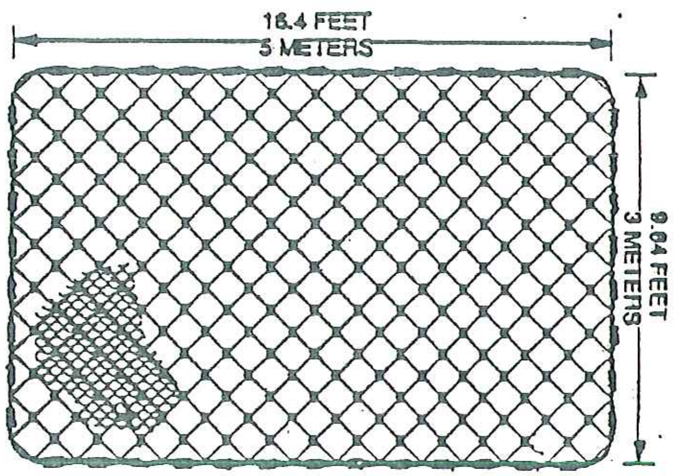
E. REMARKS

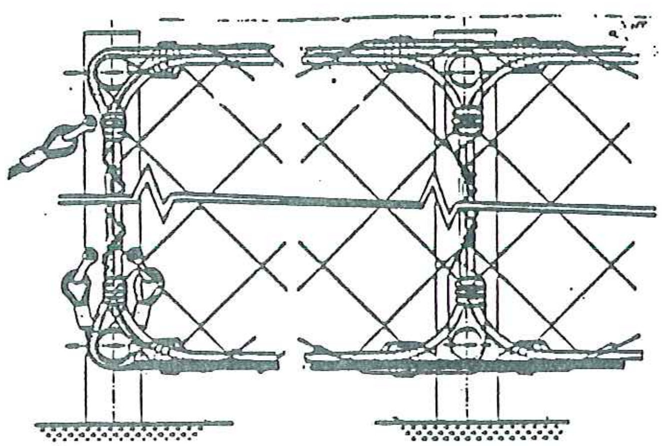
C. ROCK NET DATA:

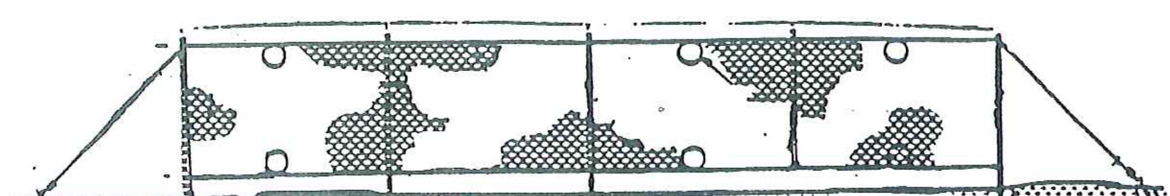
1. ROCK STOPPED BY NET ______ YES ______ NO

2. HEIGHT OF IMPACT IN THE HET PLANE ______ m ______ f t

3. REMARKS:







APPENDIX B

ROCKFALL ENERGY TABLES

Table 18: Weight, Velocity, and Energy Table for Brugg Test No. 1

Rock Roll No.	Weight (lb) max. min.	Velocity (fps)	Translational KE (ft-tons) max. min.	Angular KE (ft-tons) max. min.	Total KE (ft-tons) max. min.
1	MISSED				
2	319 261	40.0	4.0 3.2	.6 .5	4.6 3.7
3	511 419	33.3	4.4 3.6	1.1 .9	5.5 4.5
4	589 482	44.4	9.0 7.4	.8 .7	9.8 8.1
5	880 720	50.0	17.1 14.0	2.2 0.4	19.3 14.4
6	921 754	26.7	5.1 4.2	1.2 1.0	6.3 5.2
7	MISSED				
8	1172 959	66.7	40.5 33.1	5.8 4.7	46.2 37.8
9	MISSED				
10	2021 1653	44.4	31.0 25.4	6.9 5.6	37.9 31.0
11	MISSED				
12	1749 1431	20.0	5.4 4.4	.7 .6	6.1 5.0
13	1504 1232	23.5	6.5 5.3	.8 .7	7.3 6.0
14	MISSED				
15	*1700	50.0	33	2.4	35.4
16	*1860	28.5	11.8	2.0	13.8
17	MISSED				
18	2354 1926	30.8	17.3 14.2	5.7 4.6	23.0 18.8
19	7091 5802	50.0	137.6 112.6	26.8 21.9	164.4 134.5

*Actual weight.

All other weights based on estimated volume times unit weight ± 10 percent for maximum and minimum values.

Table 19: Weight, Velocity, and Energy Table for Brugg Test No. 2

Rock Roll No.	Weight (lb) max. min.	Velocity (fps)	Translational KE (ft-tons) max. min.	Angular KE (ft-tons) max. min.	Total KE (ft-tons) max. min.
1	MISSED				
2	301 246	28.6	1.9 1.6		1.9 1.6
3a	140 114	33.3	1.2 1.0	.2 .2	1.4 1.2
3b	209 171	33.3	1.8 1.5	.4 .3	2.2 1.8
4	535 437	40.0	6.6 5.4	4.9 4.0	11.5 9.4
5	883 722	50.0	17.1 14.0	4.2 3.4	21.3 17.4
6	342 280	36.4	3.5 2.9	.4 .4	4.0 3.2
7	376 307	36.4	3.9 3.2	.7 .6	4.6 3.8
8	MISSED				
9	1254 1026	17.4	2.9 2.4	.5 .4	3.4 2.8
10	MISSED				
11	*950	30.8	7.0	1.2	8.2
**12a	*606	23.5	2.6	.3	2.9
12b	*1820	26.7	10.1	4.8	14.9
13	*1590	42.1	21.9	2.8	24.7
14	*1590	40.0	19.8	1.9	21.7
15	3788 3099	33.3	32.7 26.7	9.8 8.0	42.5 34.8
16	2299 1881	36.4	23.6 19.3	3.0 2.5	26.6 21.8
17	MISSED				
18	*1700	33.3	14.7	3.2	17.8
19	505 413	40.0	6.3 5.1	1.0 .8	7.3 5.9
20	619 506	14.8	1.1 .9	.2 .1	1.3 1.0

Table 19 (Continued): Weight, Velocity, and Energy Table for Brugg Test No. 2

Rock Roll No.	Weight (lb) max. min.	Velocity (fps)	Translational KE (ft-tons) max. min.	Angular KE (ft-tons) max. min.	Total KE (ft-tons) max. min.
21	MISSED				
22	292 239	17.4	.7 .6	.1 .1	.8 .8
23	607 496	28.6	3.8 3.1	.6 .5	4.5 3.7
24	717 586	13.8	1.1 .9	.1 .1	1.2 1.0
25	MISSED				
26	MISSED				
27	MISSED				
28	MISSED				
29	MISSED				
30	917 750	44.4	14.1 11.5	2.7 2.2	16.8 13.7
**31a	773 633	51.9	16.2 13.2	1.2 1.1	17.4 14.3
31b	773 633	41.2	10.2 8.4	.7 .6	10.9 8.9
32	*2630	57.1	67.0	3.0	70.0
33	MISSED				
34	1052 862	30.7	7.7 6.3	.7 .6	8.4 6.9
35	3148 2576	48.2	56.8 46.4	13.5 11.1	70.3 57.5
36	*5500	51.2	112.0	13.4	125.4
37	*12700	51.2	259.3	36.0	295.3
38	10972 8977	46.5	184.3 150.8	48.6 39.7	232.9 190.5

*Actual weight.

**Rock Rolls No. 12 and 31 split and each portion is recorded as a and b.

All other weights based on estimated volume times unit weight ± 10 percent for maximum and minimum values.

Table 20 : Weight, Velocity, and Energy Table for Industrial Enterprise Test No. 3

Rock Roll No.	Weight (lb) max. min.	Velocity (fps)	Translational KE (ft-tons) max. min.	Angular KE (ft-tons) max. min.	Total KE (ft-tons) max. min.
1	*1590	41.7	21.4	6.2	27.6
2	*1860	30.3	13.3	3.8	17.1
3	1746 1430	28.0	10.6 8.7	5.8 4.8	16.4 13.5
4	1793 1467	21.7	6.6 5.4	1.6 1.3	8.2 6.7
5	MISSED				
6	1571 1287	32.2	12.7 10.4	4.3 3.5	17.0 13.9
**7a	916 750	27.7	5.5 4.5	0.2 0.1	5.7 4.6
b	916 750	40.0	11.4 9.3	0.1 0.1	11.5 9.4
8	*2630	33.3	22.6	12.2	34.9
9	*5500	33.3	47.3	19.8	67.1
10	11182 9149	32.3	90.3 73.9	25.9 21.2	116.2 95.1
11	*2630	47.6	46.3	10.0	56.3
12	13845 11328	35.7	137.1 112.2	47.2 38.6	184.3 150.8
13	MISSED				
14	MISSED				
15	7487 6125	33.3	64.6 52.8	22.0 18.0	86.6 70.8
16	MISSED				
17	MISSED				
18	1989 1627	33.3	17.2 14.0	6.7 5.5	23.8 19.5

Table 20 (Continued): Weight, Velocity, and Energy Table for Industrial Enterprise Test No. 3

Rock Roll No.	Weight (lb) max. min.	Velocity (fps)	Translational KE (ft-tons) max. min.	Angular KE (ft-tons) max. min.	Total KE (ft-tons) max. min.
***19a	2257 1847	23.3	9.5 7.8	3.2 2.6	12.7 10.4
19b	1692 1386	19.6	5.0 4.1	2.2 1.8	7.2 5.9
19c	762 624	13.9	1.0 0.8	0.5 0.4	1.6 1.3
19d	167 137	17.9	0.4 0.3	0.3 0.3	0.7 0.6

*Actual weight.

**Rock Roll No. 7 split in half and each half is recorded as 7a and 7b.

***Rock Roll No. 19 was a simulated rockslide where rocks a, b, c, and d were rolled simultaneously.

All other weights based on estimated volume times unit weight ± 10 percent for maximum and minimum values.

APPENDIX C

DYNAMIC LOAD PATH ANALYSIS

by

Mark Seyed-Ranjbari

With Introduction by John Duffy and Duane Smith

APPENDIX C

Dynamic Load Path Analysis

Field tests have shown that both net designs are capable of stopping rockfalls above design loads. This analysis attempts to describe the transfer of rockfall impact energies through the net system -- the load path.

Under ideal conditions, impacting loads in a flexible system are transmitted radially to the perimeter of the system. The load is distributed among the impacted net cable strands which carry the loads to the friction brakes. A flow chart of the load path generated by a 25-inch-diameter rockfall is shown in Figures 14 and 15.

The Brugg net was connected to a 3/8-inch perimeter wire rope at 18 points equally spaced along the top and bottom of the net and at 11 points equally spaced along the sides. The resulting grid squares were diamond-shaped. Flexibility was equal horizontally and vertically. This design transferred equal loads in all directions (Figure 16)

The Industrial Enterprise net was connected to a 5/8-inch perimeter wire rope at 26 points equally spaced along the top and bottom of the net and at 9 points equally spaced along the sides. The resulting grid squares were parallelogram-shaped and more flexible horizontally than vertically. This design transferred more load to the top and bottom of the net than to the sides (Figure 16).

Due to the large deformations inherent in flexible net designs, many approximations are included in this analysis. These approximations are required to estimate the capacity of the system for different size rock impacts. The nets behave elastically under small loads (1000 lb rocks). Larger loads (3000 to 5000 lb rocks) extend the nets beyond the elastic limit. Therefore, the net system has both geometric and material nonlinearities which require considerable effort to model. Because of this complexity, a simpler analysis was developed to model the net system. This simpler analysis involves impulse and momentum where a rock with momentum (m v) impacts a rock net. The resulting action-reaction force (F) between the rock and the net is a function of the contact time (t).

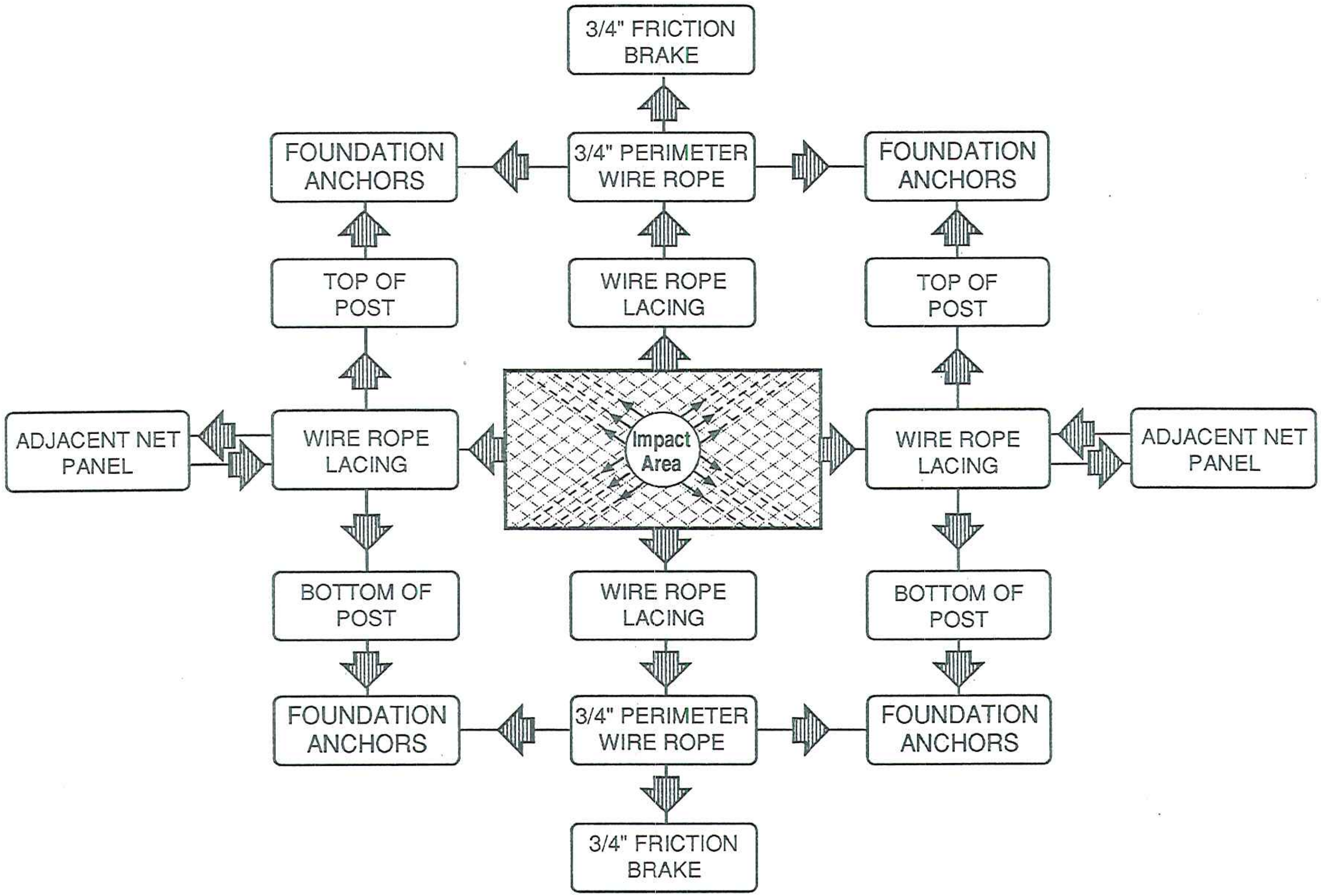


Figure 14. FLOW CHART OF THE BRUGG NET SYSTEM LOAD PATH. SHADED ARROWS INICATE THE DIRECTION OF ROCK IMPACT ENERGY

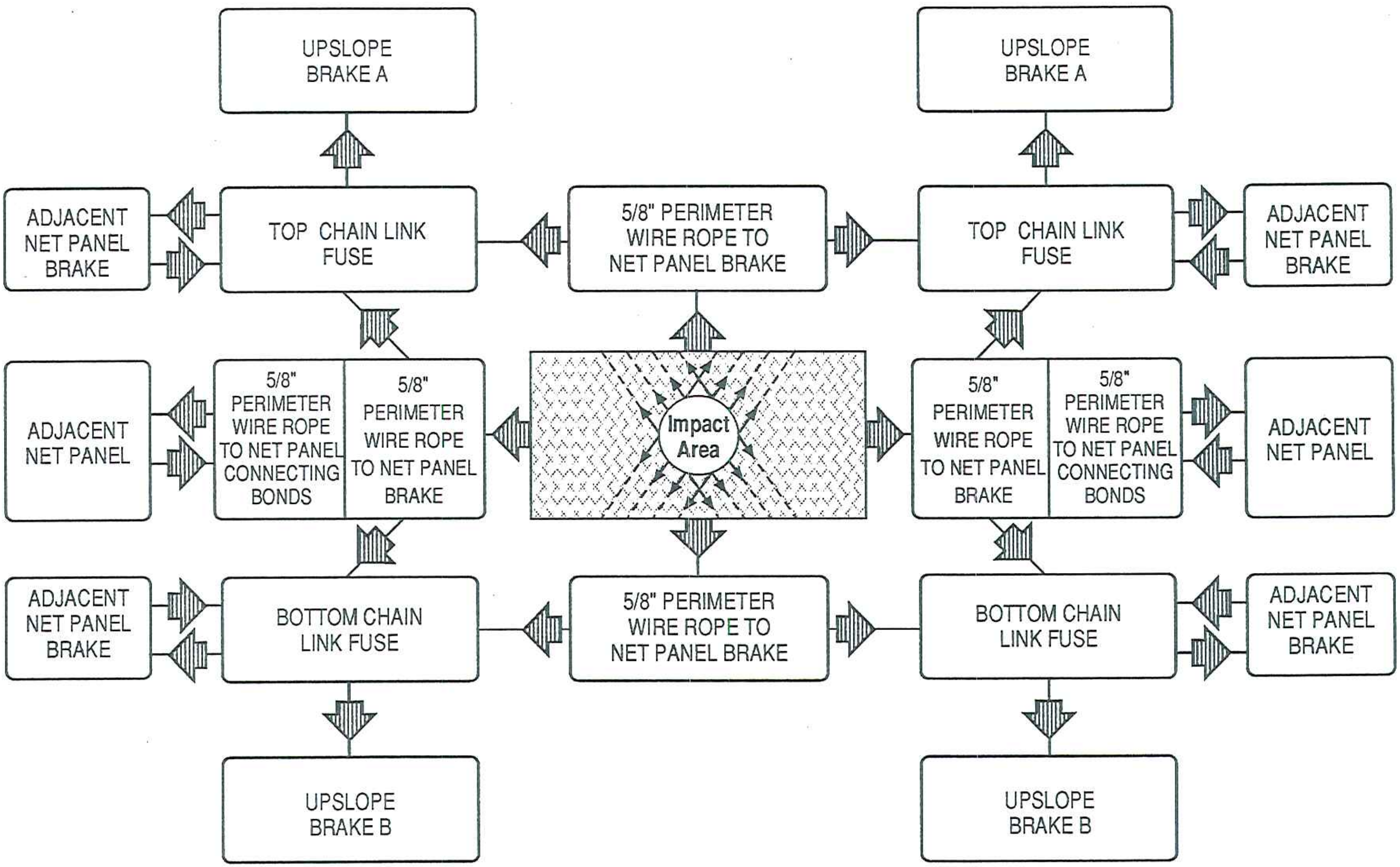
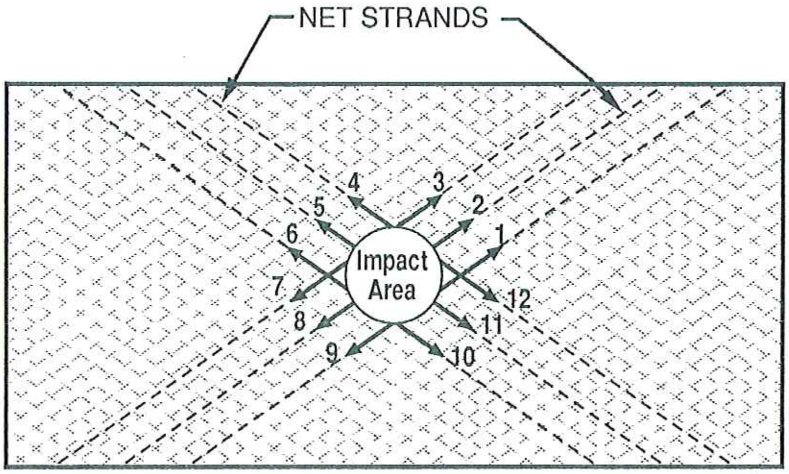
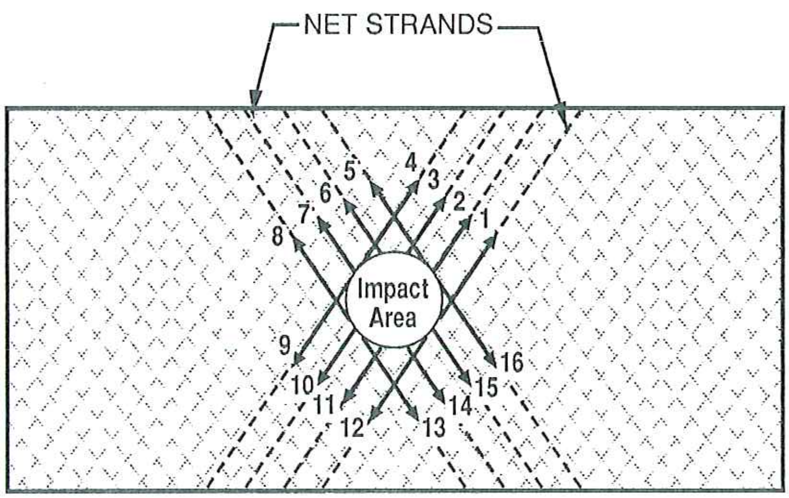


Figure 15. **FLOW CHART OF THE INDUSTRIAL ENTERPRISE NET SYSTEM FLOW PATH. SHADED ARROWS INDICATE THE DIRECTION OF THE ROCK IMPACT ENERGY**



BRUGG



INDUSTRIAL ENTERPRISE

Figure 16. IMPACTED NET STRANDS FROM A 25 INCH DIAMETER BODY

$$F\,t = m\,v \qquad \text{Eq. 1.8}$$

Impulse = momentum change

(where momentum and impulse are vector quantities)

A rock moving down a steep slope has two components of motion. First, the translational velocity produces energy and momentum equal to $1/2\, m\, v^2$ and $m\, v$, respectively. Second, the rotational velocity produces considerable energy and momentum, but it is difficult to include in the analysis and is beyond the scope of this research.

The translational component of momentum, assumed horizontal, is reduced to zero by the force exerted from the net over the time (t) (see Equation 1.8).

Force (F) is assumed constant, mass (m) is measured directly in the field, and t and v are determined from the films. Time is measured from the point of impact where net slack is tightened to the end of the forward motion of the rock. Velocity is the velocity at the point of impact. Force is calculated by:

$$F = m\,v \div t \qquad \text{Eq. 1.9}$$

To calculate the distribution of the load, an idealized net was used with an 8-inch mesh attached to a 3/4-inch perimeter cable. It was assumed that the rock impacted the center of the net panel. Impacts outside the center are more difficult to analyze and are beyond the scope of this research.

EXAMPLE 1

The test case analyzes the impact of a 5500 lb rock traveling at a translational velocity of 51 ft/sec. The net will react with a force (F) of 43556 lb and stop the rock in 0.20 second (t). The geometry of deformation is shown in Figure 17. Points "A", "B", and "C" are the controlling points with the following coordinates:

Point	X	Y	Z
A	0	0	0
B	-4.0	+3.28	-4.1
C	-6.0	+4.92	-8.2

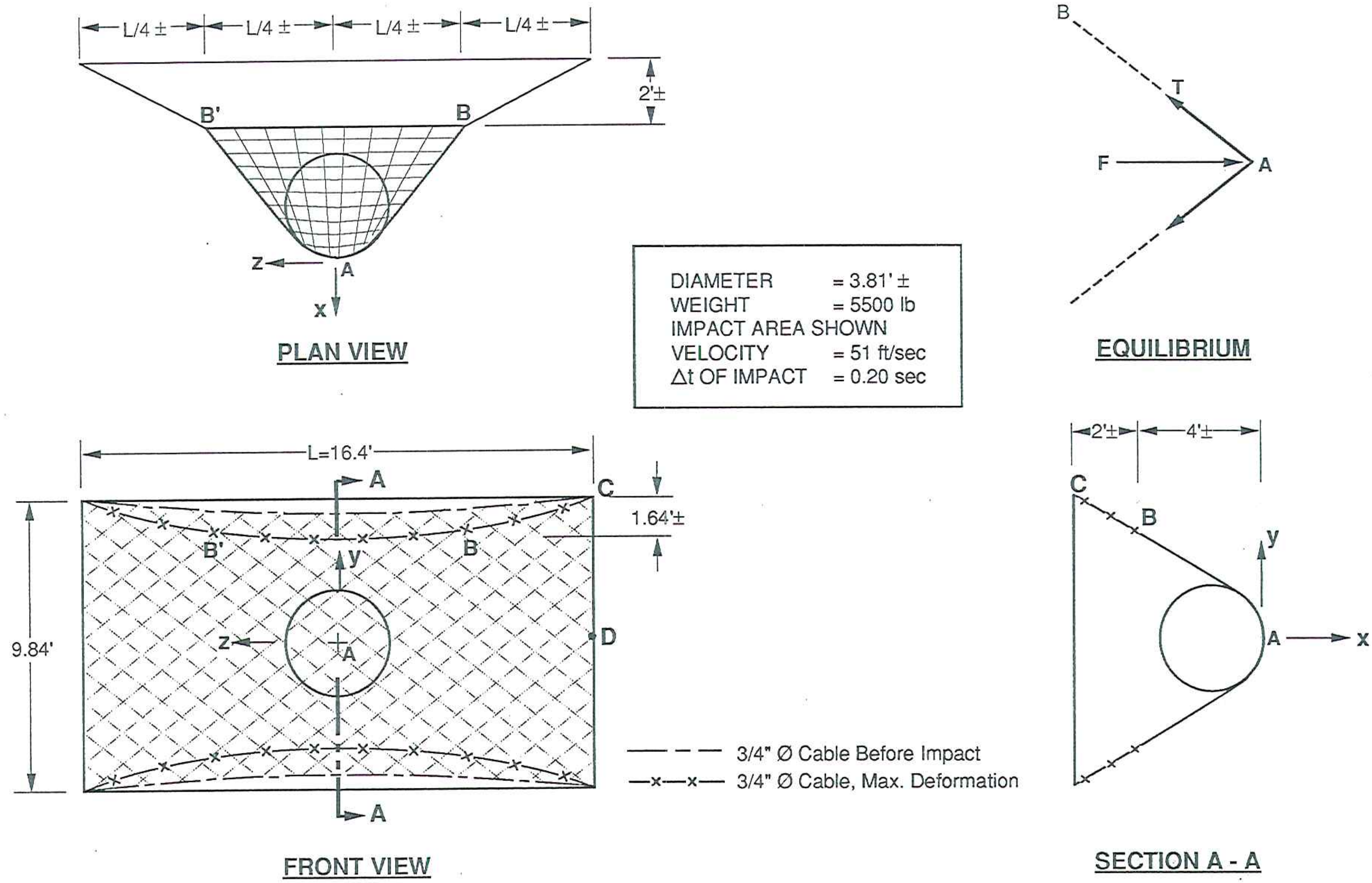


Figure 17. GEOMETRY OF DEFORMATION AND EQUILIBRIUM AT THE POINT OF CONTACT OF THE ROCK BODY

Unit vectors were established for the directions AB, BC, and BB'. To achieve equilibrium at the tip of the rock, the horizontal component of the strand forces should be equal to the impulsive force. This is determined by using vector algebra.

$$\vec{n}_{AB} = -.61\,\underset{\sim}{i} + .50\,\underset{\sim}{j} - .62\,\underset{\sim}{k} = -n_{BA} \qquad \text{Eq. 1.10}$$

$$\vec{n}_{BC} = -.41\,\underset{\sim}{i} + .34\,\underset{\sim}{j} - .85\,\underset{\sim}{k} \qquad \text{Eq. 1.11}$$

$$\vec{n}_{BB'} = + 1\,\underset{\sim}{k} \qquad \text{Eq. 1.12}$$

$$\vec{T}_{AB} = (\text{Tgroup of strands})\,\vec{n}_{AB} \qquad \text{Eq. 1.13}$$

$$\vec{F} = F\underset{\sim}{i} \qquad \text{Eq. 1.14}$$

Examination of the net after the impact indicated that the rock (3.8-foot-diameter) activated a total of five net strands in each direction. The middle three strands are assumed 100% effective while the outer two strands are functioning at 50% load. The concept of "number of effective strands" simplifies the calculations by using four strands for this particular rock.

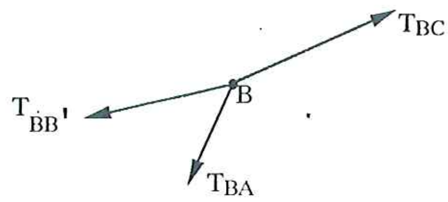
Force "F" = (# of effective strands / per direction) x (2 legs / per strand) x (2 directions) x (COS Θ) x (Tension in each strand) Eq. 1.15

Where Θ is the angle between the force "F" and the direction "AB".

Force "F" = (4 strands) x (2 directions) x (2 legs) x (0.61) x (T) Eq. 1.16

Then "T" is equal to 4463 lb (Force per 100% loaded net strand)

To calculate the force in the 3/4-inch-diameter cable at Point B, equilibrium must be satisfied. With a force of 17852 lb (4*4463 lb) being transferred to Point "B" by T_{BA}, a tensile load of 26421 lb occurs in Segment BC and a load of 11425 lb occurs in Segment BB'.



Equilibrium of Point "B"

The force vectors are:

$$\vec{T}_{BA} = T_g\,(.61\,\underset{\sim}{i} - .50\,\underset{\sim}{j} + .62\,\underset{\sim}{k}) \qquad \text{Eq. 1.17}$$

$$\vec{T}_{BC} = T_{BC}\,(-.41\,\underset{\sim}{i} + .34\,\underset{\sim}{j} - .85\,\underset{\sim}{k}) \qquad \text{Eq. 1.18}$$

$$\vec{T}_{BB'} = T_{BB'}\,(+\,1\,k) \qquad \text{Eq. 1.19}$$

where T_g is the tension in a group of strands.

Vector equilibrium equations:

$$T_{BC} = 1.49\,T_g = 26421 \text{ lb} \qquad \text{Eq. 1.20}$$

$$T_{BB'} = .64\,T_g = 11425 \text{ lb} \qquad \text{Eq. 1.21}$$

(where $T_g = 4 \times 4463$ lb $= 17852$ lb)

Note that Points "A", "B", and "C" should be projecting to a straight line on the x-y plane to satisfy a part of the equilibrium. This can serve as a check for the acquisition of data from the films.

The upslope anchors (5/8-inch cable with friction loop) were at an angle of 23 degrees. The force carried by these anchors is equal to:

$$T = F\,/\,(4 \times \text{COS } 23) = 11829 \text{ lb} \qquad \text{Eq. 1.16}$$

Summary

This analysis shows that under these conditions, the load per 100% loaded net strand is 4463 lb. The load in the top and bottom perimeter wire rope, where the load dissipating friction brakes are located, is 26421 lb in the outer thirds of the wire rope and 11425 lb in the middle third of the wire rope and the load in the upslope anchor cable is 11829 lb.

This approach can be used as a guide to designers in selecting the net grid spacing and minimum tensile strength of the friction brakes.

APPENDIX D

FRICTION BRAKE TESTING AND EVALUATION

APPENDIX D

FRICTION BRAKE TESTING AND EVALUATION

Seven tests on friction brakes were performed to evaluate friction brake capabilities. The testing device was an MTS electro hydraulic machine with a one million pound capacity (Photos 73 and 75). Testing rate was two inches per minute. The purpose of the testing was to confirm manufacturers specifications and evaluate brake performance.

The tests were performed by attaching the wire ropes exiting the brake to the upper and lower platens of the electro hydraulic machine. The connection was made by fixing cable clamped loops in the wire rope to shackles connected to the platens. Tension was applied as the lower platen pulled against the fixed upper platen at a rate of two inches per minute. Load vs lower platen movement was recorded on an x-y recorder. Wire rope movement through the friction brake was recorded manually with a tape measure.

Brugg tensile brake strengths were within ± 8% of the factory specifications. EI tensile brake strengths were 4% to 30% above factory specifications. This variation between specified and laboratory-tested brake tensile strength is acceptable. Variability is expected to occur because of the cable flexibility. Over time, especially when transported, the cable will reseat itself in the brake sleeves, changing bolt torque and, to some degree, brake tensile strength. Bolt torque was less after movement of the cable through the brake in every test.

Brugg brakes were moderately to heavily torqued and had a single friction plate which tended to squeeze the cable in the brake sleeve (Photo 72). Therefore, as the cable entered the brake, it had to change its shape to fit. Once the cable exited the brake, it was out of round, frayed, and not reusable. This action can be seen in the graphs as an oscillating wave (Figures 18 through 21). Each wave crest represents the cable jerking through the brake as it changes shape. Reduction of bolt torque will reduce this effect causing little or no damage to the cable, resulting in a reusable cable. Reducing the torque will reduce brake tensile strength.

EI brakes caused little damage to the cable as it passed through the brake resulting in a reusable cable (Photo 74). This was largely due to the large brake friction surface area and moderate bolt torques which did not squeeze the cable excessively. This action can be seen in the graphs as a smooth curve indicating the cable slides through without a change in its shape (Figures 22 through 24). Tensile brake strength can be increased by increasing the number of brakes. A two-brake system was tested which doubled the tensile braking strength. This indicates the brake strength is cumulative as the number of brakes per system is increased.

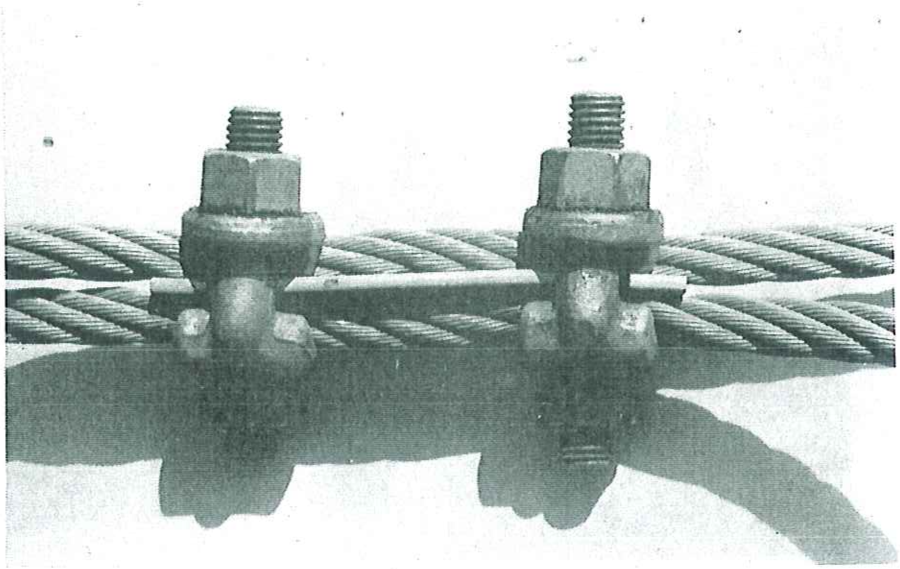


Photo 72. BRUGG FRICTION BRAKE. NOTE DISTORTION OF THE WIRE ROPE IN THE CLAMP

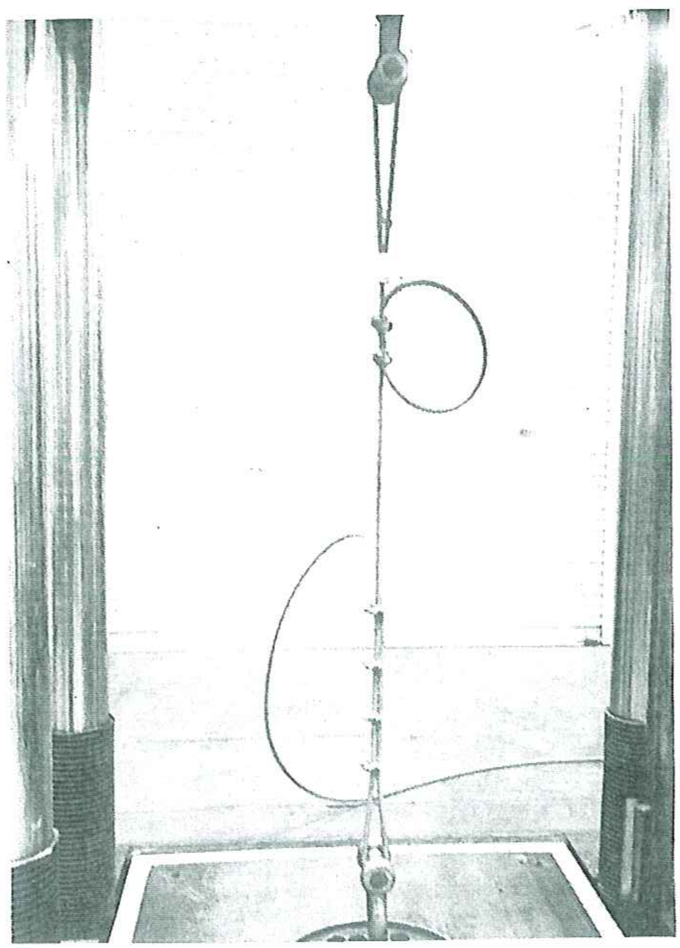


Photo 73. BRUGG FRICTION BRAKE UNDER TENSION IN THE MTS ELECTRO HYDRAULIC MACHINE

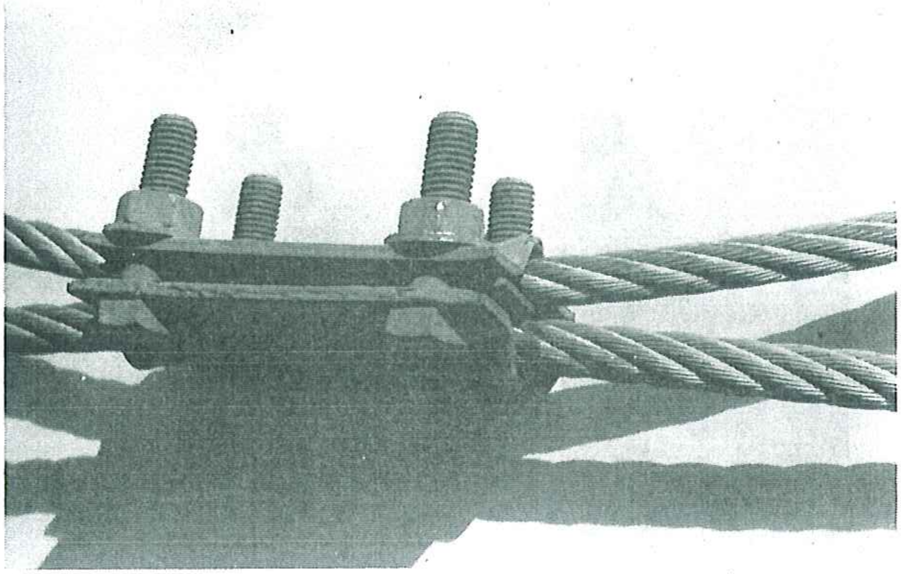


Photo 74. INDUSTRIAL ENTERPRISE FRICTION BRAKE. NOTE FLARED ENDS OF BRAKE PLATES

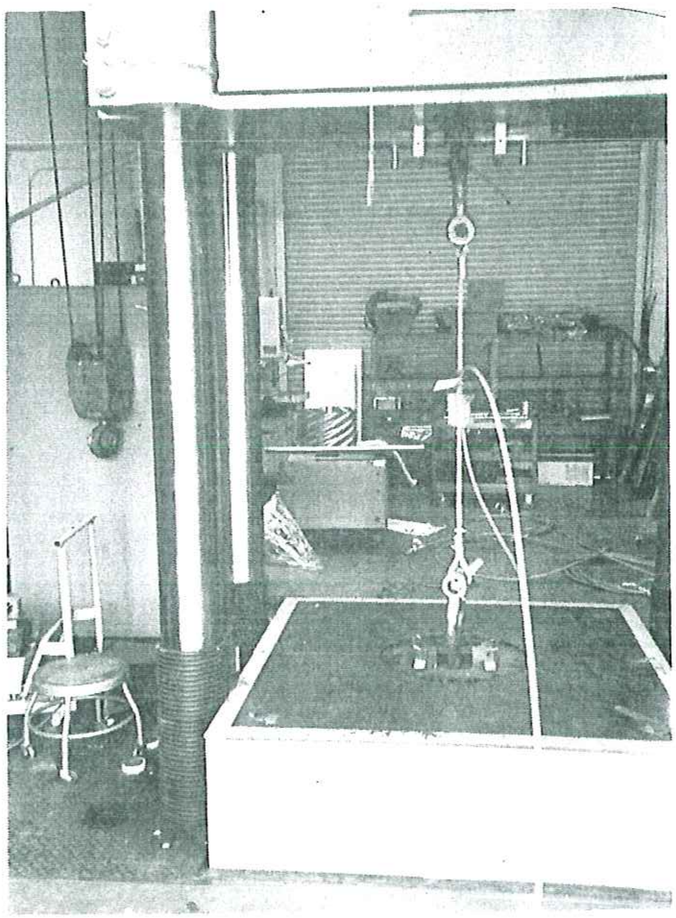
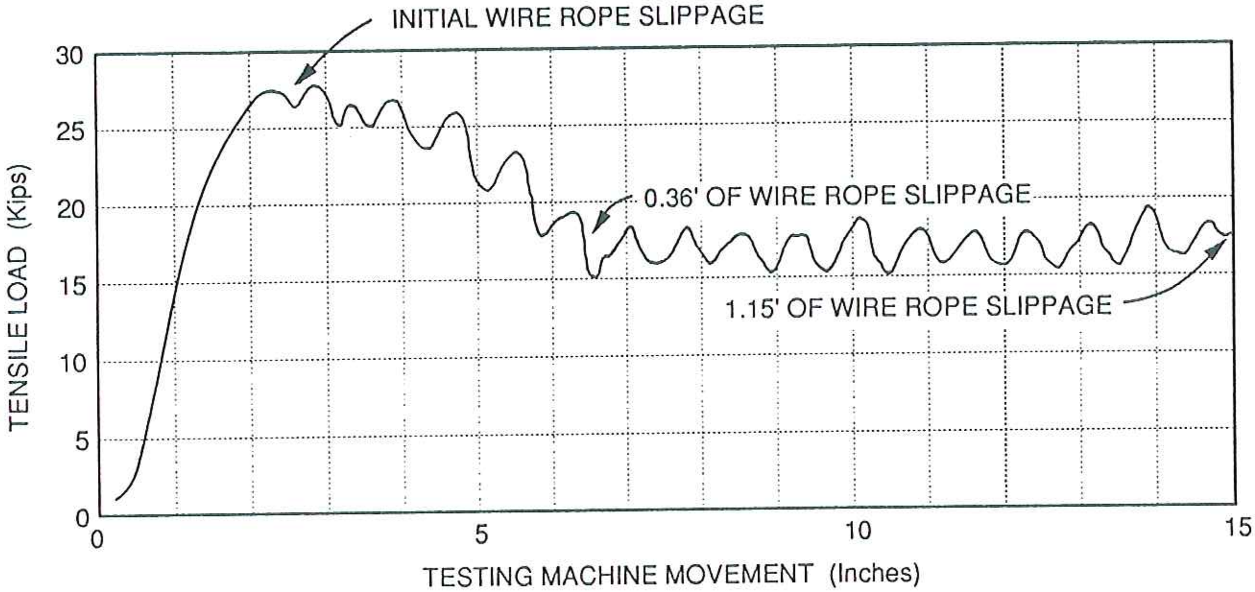


Photo 75. INDUSTRIAL ENTERPRISE FRICTION BRAKE UNDER TENSION IN THE MTS ELECTRO HYDRAULIC MACHINE



LOAD vs MOVEMENT

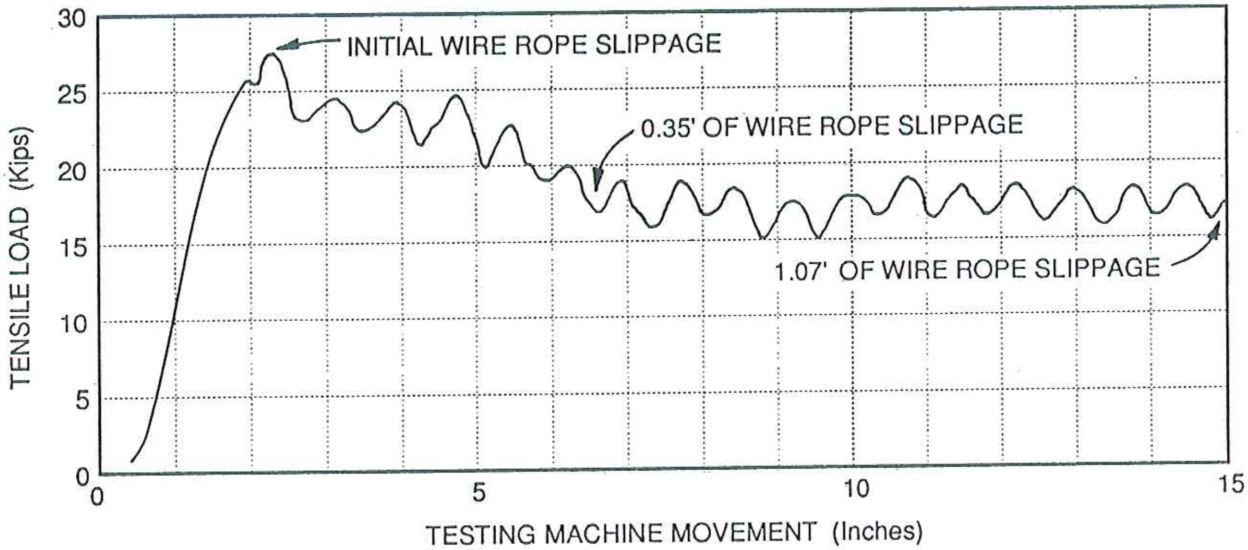
TEST 1	BRUGG 5/8" DIAMETER FRICTION BRAKE

Testing rate ---------------- 2 inches / minute
Tensile strength of wire rope -------- 38304 lbs (Factory specifications)
Tensile strength of brake---------- 26880 lbs (Factory specifications)
Test tensile strength of brake ------- 27800 lbs

Bolt torque in ft-lbs prior to test: 67 / 70 (left), 30 / 30 (right)

REMARKS:
The brake linings were rough and grooved prior to testing.
After the test the metal was scoured, out of round and frayed.

Figure 18. BRUGG FRICTION BRAKE TEST # 1 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING



LOAD vs MOVEMENT

TEST 2	BRUGG 5/8" DIAMETER FRICTION BRAKE

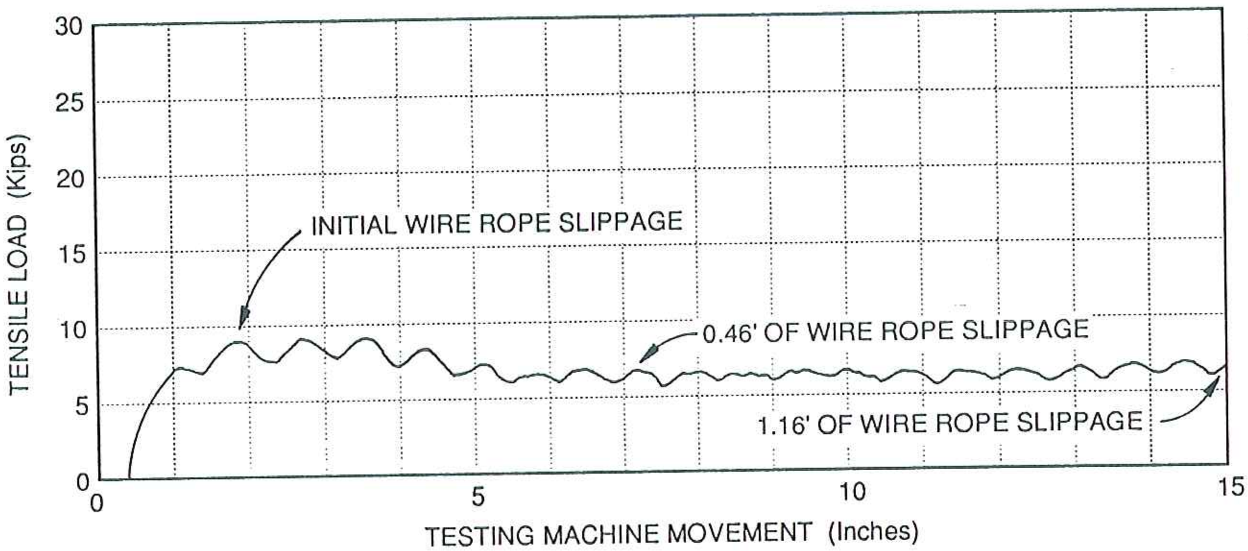
Testing rate ---------------- 2 inches / minute
Tensile strength of wire rope ------- 38304 lbs (Factory specifications)
Tensile strength of brake --------- 26880 lbs (Factory specifications)
Test tensile strength of brake ------- 27800 lbs

Bolt torque in ft-lbs prior to test: 60 55 / 80 60

Bolt torque in ft-lbs after test: 55 50 / 50 50

REMARKS: Initially the bolts may have been torqued to 90 ft-lbs but over time the wire ropes seated themselves and slipped reducing apparent bolt torque. Wire rope was out of round and frayed.

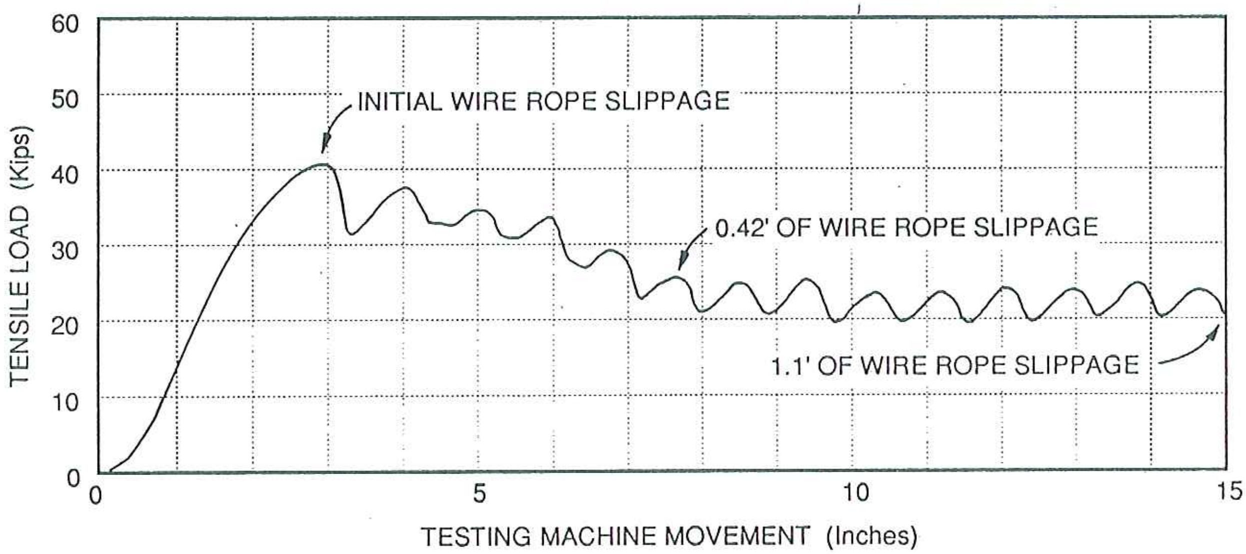
Figure 19. BRUGG FRICTION BRAKE TEST #2 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING



LOAD vs MOVEMENT

TEST 3	BRUGG RE-SET 5/8" DIAMETER FRICTION BRAKE
Testing rate ----------------	2 inches / minute
Tensile strength of wire rope -------	38304 lbs (Factory specifications)
Tensile strength of brake ---------	26880 lbs (Factory specifications)
Test tensile strength of brake -------	8000 lbs
Bolt torque in ft-lbs prior to test:	50 50 / 50 50
Bolt torque in ft-lbs after test:	25 30 / 40 30
REMARKS:	Wire rope damage minimal

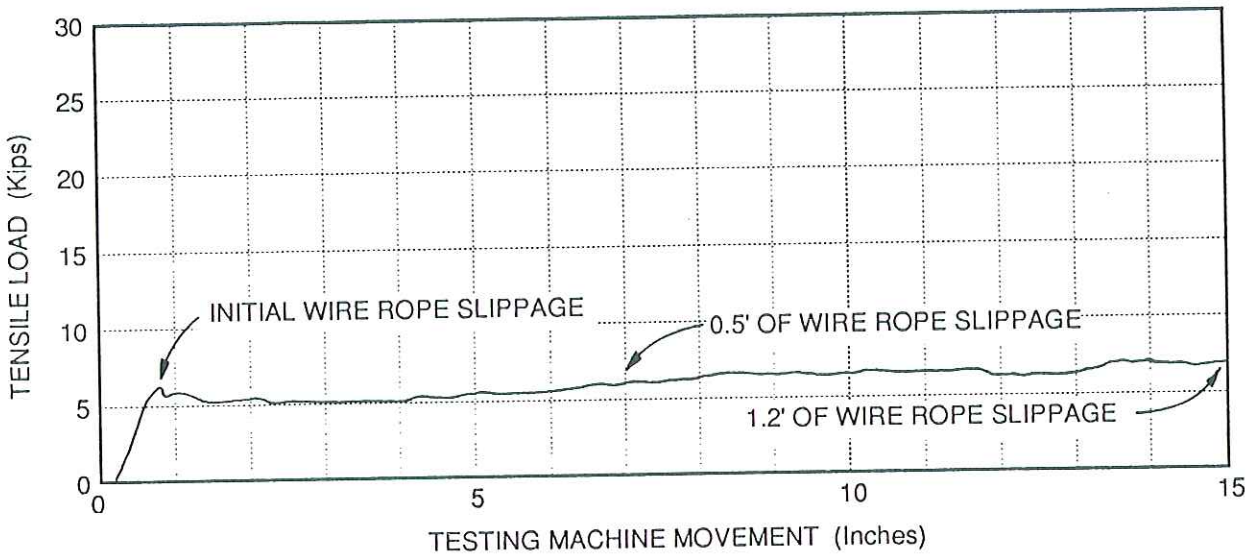
Figure 20. BRUGG FRICTION BRAKE TEST # 3 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING



LOAD vs MOVEMENT

TEST 4	BRUGG 3/4" DIAMETER FRICTION BRAKE
Testing rate	2 inches / minute
Tensile strength of wire rope	48160 llbs (Factory specifications)
Tensile strength of brake	44800 lbs (Factory specifications)
Test tensile strength of brake	41000 lbs
Bolt torque in ft-lbs prior to test:	160, 170, 140, 150
Bolt torque in ft-lbs after test:	140, 120, 110, 120
REMARKS:	Wire rope was out of round and frayed.

Figure 21. BRUGG FRICTION BRAKE TEST # 4 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING

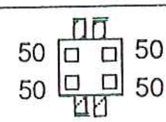


LOAD vs MOVEMENT

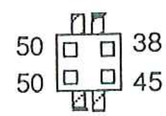
TEST 5	INDUSTRIAL ENTERPRISE 5/8" DIAMETER FRICTION BRAKE

Testing rate ----------------- 2 inches / minute
Tensile strength of wire rope ------- 37477 lbs (Factory specifications)
Tensile strength of brake---------- 5500 lbs (Factory specifications)
Test tensile strength of brake ------- 6500 lbs

Bolt torque in ft-lbs prior to test:

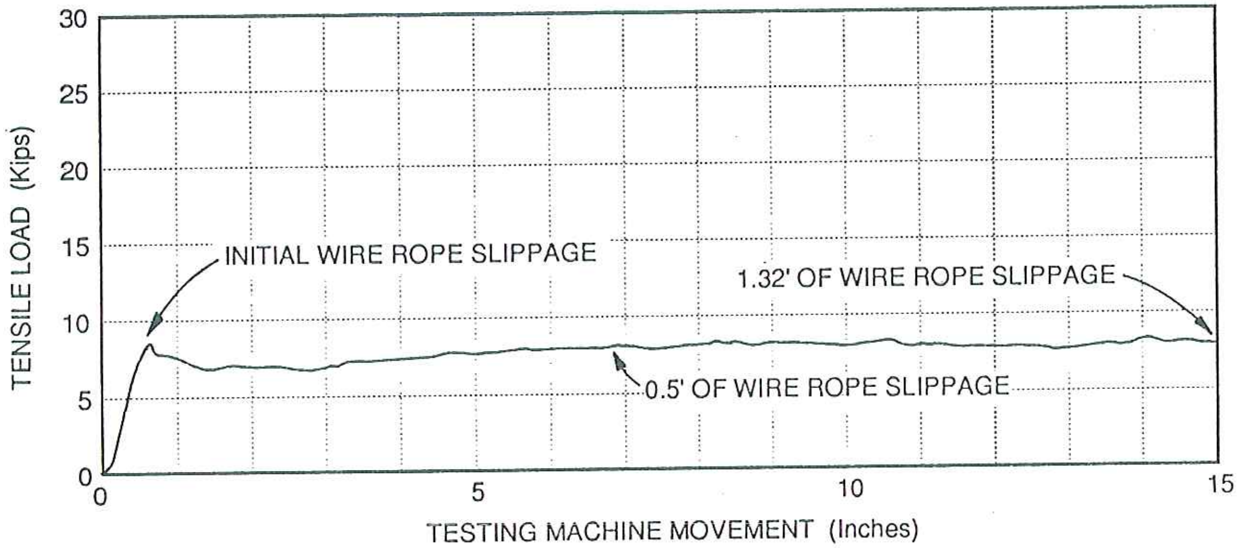


Bolt torque in ft-lbs after test:



REMARKS: Wire rope on the nut side, fastened to the upper grip, moved. Wire rope damage was minimal.

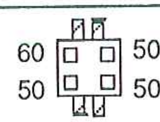
Figure 22. INDUSTRIAL ENTERPRISE FRICTION BRAKE TEST # 5 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING



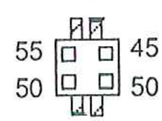
LOAD vs MOVEMENT

TEST 6	INDUSTRIAL ENTERPRISE 5/8" DIAMETER FRICTION BRAKE
Testing rate	2 inches / minute
Tensile strength of wire rope	37477 lbs (Factory specifications)
Tensile strength of brake	5500 lbs (Factory specifications)
Test tensile strength of brake	8000 lbs

Bolt torque in ft-lbs prior to test:

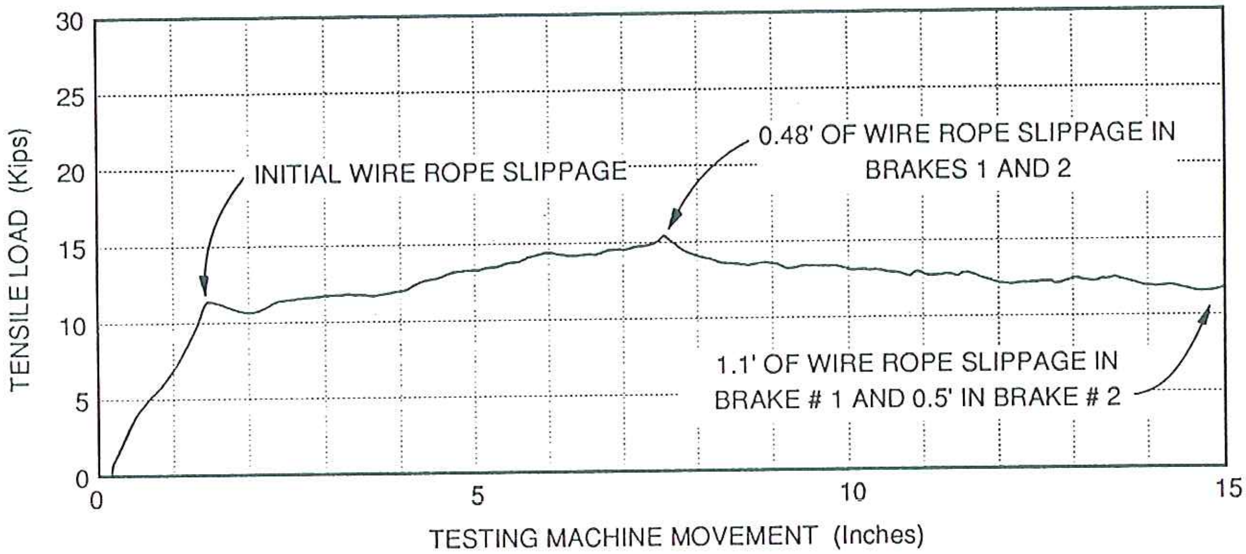


Bolt torque in ft-lbs after test:



REMARKS: Wire rope on the nut side, fastened to the upper grip, moved. Wire rope damage was minimal.

Figure 23. INDUSTRIAL ENTERPRISE FRICTION BRAKE TEST # 6 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING



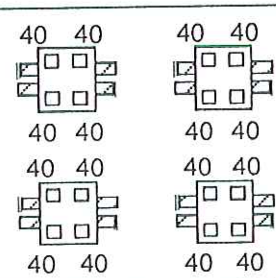
LOAD vs MOVEMENT

TEST 7	TWO INDUSTRIAL ENTERPRISE 5/8" DIAMETER FRICTION BRAKES

Testing rate ---------------- 2 inches / minute
Tensile strength of wire rope -------- 37477 lbs (Factory specifications)
Tensile strength of brake---------- 11000 lbs (Factory specifications)
Test tensile strength of brake ------- 11500 lbs

Bolt torque in ft-lbs prior to test:

Bolt torque in ft-lbs after test:



REMARKS: Wire rope on the nut side, fastened to the upper grip, moved. Wire rope damage was minimal.

Figure 24. INDUSTRIAL ENTERPRISE FRICTION BRAKE TEST # 7 SHOWING FRICTION BRAKE SLIPPAGE UNDER LOADING

APPENDIX E

WIRE ROPE SPECIFICATIONS

TABLE 21

SPECIFICATIONS FOR WIRE ROPE SUPPLIED BY BRUGG

Wire Rope Diameter		Construction	Minimum Breaking Strength
5/32"	(4 mm)	6 x 7	2,175 lb
3/16"	(5 mm)	6 x 7	3,360 lb
1/4"	(6 mm)	6 x 7	4,838 lb
5/16"	(8 mm)	6 x 7	8,691 lb
3/8"	(9.5 mm)	6 x 7	13,485 lb
1/2"	(12 mm)	6 x 19	19,667 lb
5/8"	(16 mm)	6 x 31	37,362 lb
3/4"	(18 mm)	6 x 31	48,160 lb
7/8"	(22 mm)	6 x 41	65,632 lb
1"	(28 mm)	6 x 41	109,088 lb

TABLE 22

SPECIFICATIONS FOR WIRE ROPE SUPPLIED BY THE INDUSTRIAL ENTERPRISE (EI)

Wire Rope Diameter		Minimum Breaking Strength
1/4"	(6 mm)	3,748 lb
5/16"	(8 mm)	7,716 lb
1/2"	(12 mm)	19,841 lb
5/8"	(16 mm)	37,477 lb
3/4"	(18 mm)	48,500 lb
7/8"	(22 mm)	77,160 lb