Final Design Guidelines

DESIGN GUIDELINES FOR

WIRE MESH/CABLE NET SLOPE PROTECTION

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16. ABSTRACT

Since the 1950s, heavy gage wire mesh has been used along North American highways to control rockfall on actively eroding slopes. More robust fabrics, such as cable nets, have more recently been introduced to improve the capacity of these rockfall protection systems. To date, however, the design of these systems has been based primarily on empirical methods, engineering judgment, and experience.

These design guidelines are based on research that characterized existing performance, tested critical system components, back-analyzed system failures, evaluated typical loading conditions, and developed analytical models to refine the engineering design of these systems. The guidelines were developed to support the design of these systems for a variety of loading conditions. Specifically, they provide design guidance on site suitability, characterizing external loads, fabric selection, anchorage requirements, and system detailing.

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1. INTRODUCTION

These design guidelines are the principal outcome of a four-year, pooled-fund research project, the complete findings of which are summarized in a technical report (Muhunthan et al., 2005). The primary objective of this research was to develop a rational and broadly applicable methodology for designing wire mesh and cable net systems to control rockfall on steep slopes. The research sought to pragmatically combine several decades of field performance, recent testing of system elements, and quantitative analyses of system function when exposed to various external loads. A large component of the research focused on the back-analysis of observed system failures and the characterization of factors contributing to them, as well as those that have performed satisfactorily. This proved to be a difficult task because loading conditions were often not directly observable/measurable and, therefore, did not allow for direct quantitative analyses. Fortunately, most systems have performed satisfactorily, and as a result, the guidelines below in many respects confirm the best of existing practice and can more widely disseminate these successes.

Nevertheless, examination of system failures confirmed that in some cases there was a fundamental lack of understanding of loading conditions and load transfer. This is particularly true for snow and impact loads. As a result of the research, some advancement was made in the evaluation of and design for snow loads. On the other hand, determining and analyzing the impact loads and load transfer resulting from rockfall trajectories, both sub-parallel and perpendicular to the mesh/slope, proved less productive, predominantly because full-scale testing was needed to confirm the analyses but was not achievable within the scope of the research. This remains an important research topic, as systems are now

frequently being located on slopes that require the containment of more horizontally directed, high-energy rockfall. Last, the examination of both global and localized failures of these systems and their components revealed that, in part, "the devil is in the [fabrication and construction] details."

In recent years, designers have utilized wire mesh and cable net systems for increasingly demanding conditions, and as expected, failures have resulted. A goal of this research was to identify and quantify the limiting states of the system components and external loads.

The guidelines that follow provide a generalized approach, recommendations, and limitations for

- evaluation of site suitability
- characterization of potential external loads
- fabric selection
- anchorage requirements
- system details and specifications
- consideration of aesthetic concerns
- construction and maintenance.

A flow chart summarizes the overall design approach presented in these guidelines (Figure 1). The approach first entails an assessment of site conditions: characterization of the mode(s), size, volume and frequency of slope instability and evaluation of the potential external loads that the system must withstand. Following this assessment and a favorable determination of site suitability, the fabric is selected that is best suited for the anticipated conditions. A juncture is then reached at which the potential for snow load must be

considered. Anchor loads for either mesh weight or snow load are then determined. A recommended range for the factor of safety is then applied to the mesh weight to account for debris and impact loads and to the snow load to account for variability in the maximum potential loading state. Anchor capacity and spacing are then determined, followed by the specific detailing of the system.

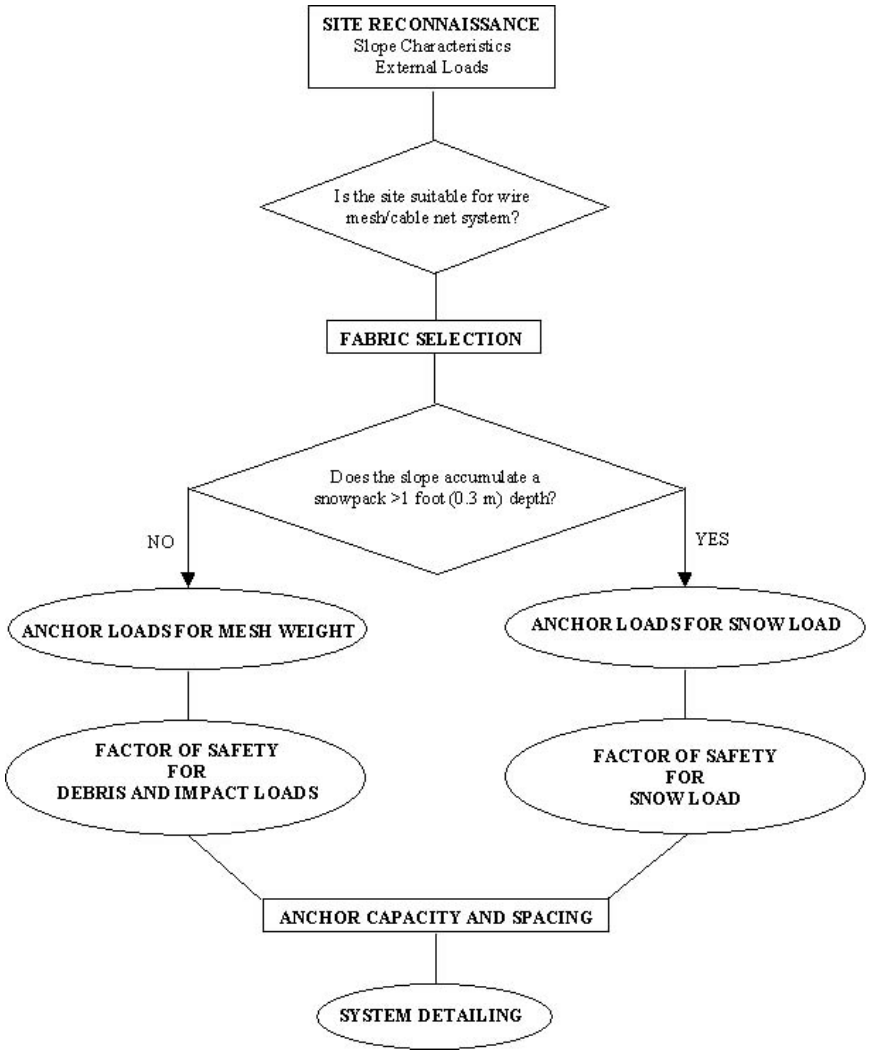

Figure 1. Recommended design approach for wire mesh/cable net systems.

The greatest challenge in preparing guidelines is anticipating the range of site conditions and external loads that could be experienced, yet avoiding an excessively

cumbersome or complex design process. Where feasible, the guidelines provide specific design recommendations for certain system elements. However, for a number of conditions, such specificity is not practical or the mechanical behavior of the system is not sufficiently understood to provide detailed recommendations. In these instances, the guidelines attempt to highlight dominant concerns or limitations, and designers must then exercise their best judgment.

These guidelines and recommendations are based on the collective geologic and engineering experience and judgment of this project's Technical Advisory Committee (TAC), as well as the findings of the study's Principal Investigator, Professor Muhunthan, and his graduate students. The guidelines address generalized site and loading conditions, and, where appropriate, recommend a range of safety factors for these anticipated conditions. Undoubtedly, site conditions exist that exceed and/or are different from those anticipated in the guidelines or that have been presented in this research report. It is the expectation of the authors and the TAC that due care and sound geologic and engineering judgment be exercised by designers when they apply these guidelines, and that caution is warranted in utilizing these systems for conditions that lie outside the bounds provided in this research report.

2. SITE SUITABILITY AND CHARACTERIZATION

Wire mesh/cable net systems have been installed on slopes of all shapes and sizes for mitigating rockfall hazards. However, numerous examples exist where systems that have been installed on slopes that are poorly suited for this mitigation, or that are over- or under-designed for the site/loading conditions. Characterization of the site and loading conditions is the first and most important step in determining site suitability and in designing an appropriate system for the expected conditions.

2.1 BLOCK/EVENT SIZE

As with any structural system, there are limitations on repeated sustainable loads for mesh systems. The size of individual blocks or small-scale instabilities is the most important factor in determining site suitability. While there are many examples of installations that have sustained apparent extreme debris or impact loads, in practice, wire mesh/cable net systems have well demonstrated limitations in terms of block size. That threshold is roughly block sizes of 5 ft (1.5 m). If potentially unstable block sizes exceed this threshold, other mitigation measures should be considered or added, such as removal or reinforcement with anchors/shotcrete. Rockfall consisting of single or several blocks is the mode of slope instability intended to be addressed by draped mesh systems. Again, there are many examples of systems that have sustained little or no damage when subjected to slope instabilities tens to hundreds of cubic yards (meters) in volume. However, forensic assessment of such cases has generally shown that little load was actually transferred to the system, and the debris simply slid beneath the system. Analyses and case histories presented in the research report (Muhunthan et al., 2005) bear out that systems secured only at the top,

as is the general practice in North America, cannot sustain loads much in excess of 10 cubic yards (meters) of debris (assuming full load transfer of the debris). If anticipated modes of slope instability would result in single events larger than roughly 5 to 10 cubic yards (meters) in volume, additional or alternative mitigation measures should be considered.

Evaluation of block sizes or potential debris volumes per event should entail not only direct observation but also anecdotal information from past events.

2.2 SLOPE CONDITIONS

Slope configuration largely controls rockfall trajectory. Rockfall on near-vertical slopes is dominantly governed by a trajectory of freefall, whereas flatter slope orientations result in a bouncing or rolling trajectory path. It is also well known that slope asperities, sometimes referred to as launching features, can impart a significant horizontal component to a free falling trajectory. Mesh systems on near-vertical slopes function somewhat differently than those on flatter slopes. Given the orientation and often limited contact on near-vertical slopes, the mesh imparts little stabilization effect through its weight, and rocks can generally pass unimpeded between the mesh and the slope. On flatter slopes, mesh contact is often greater, and its weight can impart a significant resistance force on individual blocks. As a result, in many cases, rockfall frequency is reduced, and the trajectories of dislodged blocks are generally slowed considerably. Entrapment of loose blocks and debris is commonly observed with mesh systems installed on flatter slopes.

For a variety of reasons, it is important to anticipate, as well as to design and construct, how the mesh will lay on the slope. To this end, slope uniformity needs to be assessed. Mesh contact is typically greatest on uniform slopes and least on concave slopes. Slope uniformity also influences where and how rockfall impacts the system and debris

accumulates or passes beneath the system. As examples, figures 2A and 2B illustrate typical concave and convex slopes, respectively, and the influence that slope configuration has on debris accumulation and impact loading.

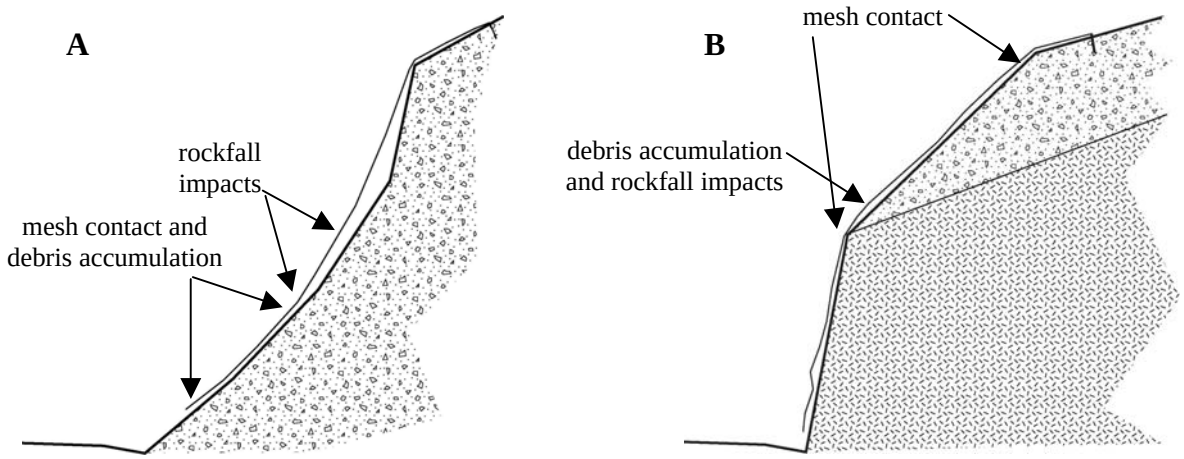

Figure 2. Cross-sections show typical (A) concave and (B) convex slopes and the areas of mesh contact, debris accumulation, and rockfall impacts.

Slope height and length, as well as area of coverage, need to be defined. In North America, mesh systems have been successfully installed on slopes approaching 450 feet in slope length and 300 feet in height. When coverage area and slope length are considered, the bottom elevation of the mesh is largely a function of the available catchment area at the base of the slope and its effectiveness at containing debris as it clears the installation. Aesthetic concerns or snow accumulation at the base of the installation may also influence the lower terminus. Unless the top of the mesh is raised or suspended (modified systems), the mesh should cover all the observed/anticipated source areas of rockfall. It is also important to consider ongoing slope degradation, so the mesh should extend upslope a sufficient distance to cover the expected long-term configuration of the slope. Although mesh may often slow

erosion, there are numerous examples of installations where the top of mesh and the anchors have been undermined because of retrogression of an actively eroding slope crest (Figure 3). With respect to slope width, salients and reentrants increase surface area and, generally, result in an increase in the required mesh quantity. While mesh systems are often a highly economical and effective measure for mitigating rockfall, other containment or avoidance alternatives may be more cost-effective if the coverage area becomes excessive.

Figure 3. Ongoing erosion threatens a wire mesh system installed in the late 1980s in the North Cascades of Washington.

An evaluation of slope characteristics should also include an assessment of anchoring conditions. Difficult access generally necessitates small portable drills for anchor installation. This is not usually a problem for installations in bedrock, but loose, cobble/ boulder deposits can pose challenging installations for small, hand-operated equipment.

2.3 INTERFACE FRICTION

Where the mesh is in contact with the slope, interface friction provides a resistance component to the stability of the system. The interface friction is controlled by macro and micro roughness of the surface. Macro roughness is defined by large-scale irregularities of the slope, and micro roughness is defined as the texture of the surface. Where the slope is planar and the surface is smooth, minimal interface friction may occur, and the mobilized force on the system is carried largely by the anchors. Where slopes are highly irregular and the surfaces are rough or have abrupt protrusions, very high interface friction may occur. In these cases, very little to no mobilized force may be imparted to the anchors.

Unfortunately, interface friction is a difficult parameter to quantify in practice. Furthermore, to include this contribution with the necessary resistance force for a system, a designer must estimate the amount of mesh contact. This task is also difficult, since mesh contact is influenced by slope configuration, fabric flexibility, and installation methods. Because of weathering, interface friction can also be a transient condition. For these reasons, the guidelines do not include the resistance contribution of interface friction to determine anchor requirements for mesh weight, debris load, and impact load. Instead, the guidelines apply a factor of safety to a range of system configurations for a vertical slope (no interface friction) to determine the anchor requirements for these loading conditions.

The one exception is that where snow load is anticipated, interface friction should be assessed. In the absence of either back-calculated or field measurements, the interface friction angle can be estimated for the observed slope irregularity and surface roughness by using the guidelines below.

i. *Rough*: The slope surface is very irregular and undulating and/or has many prominent protrusions on the surface (Figure 4). For such cases, the interface friction angle is assumed to be above 60°.

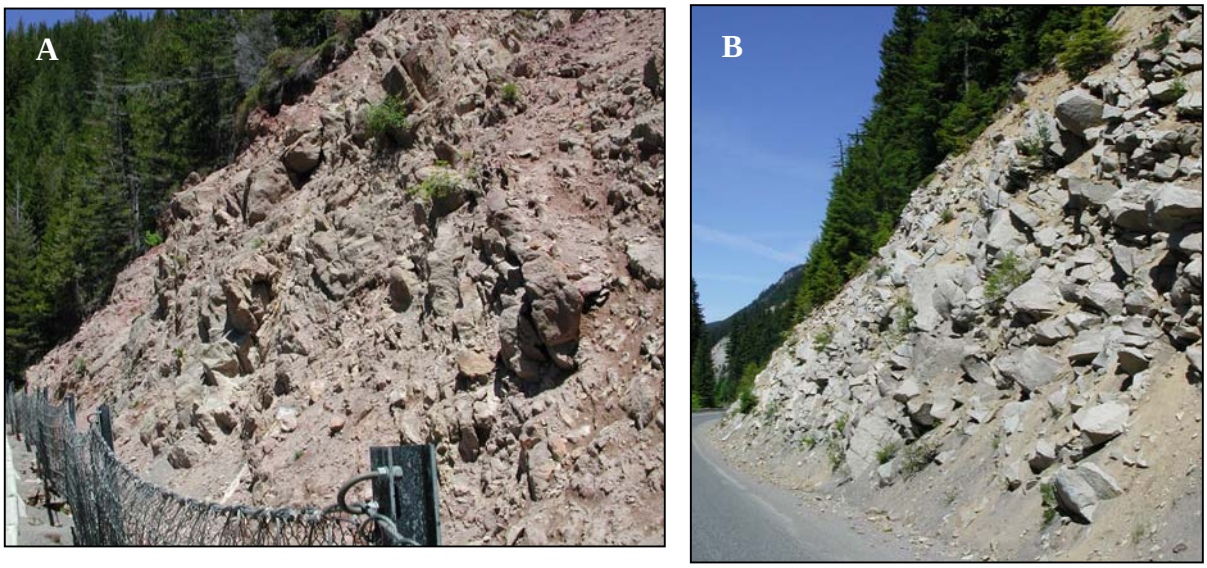

Figure 4. Rough slopes exhibit a high degree of surface roughness with planar, uniform profiles.

ii. *Undulating:* The slope is undulating, and the surface contains some minor protrusions (Figure 5). The interface friction angle is assumed to be between 36°-59°.

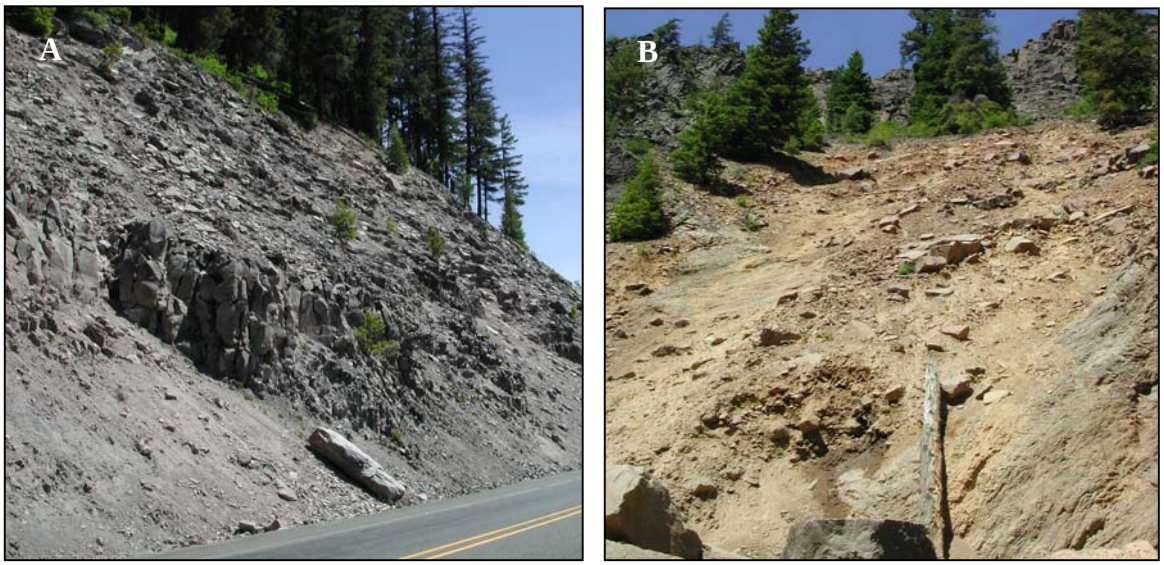

Figure 5. Undulating slopes exhibit profiles with (A) somewhat uniform particle distribution with limited overall roughness, and (B) numerous localized protrusions.

iii. *Planar:* The slope is planar, and the surface is relatively smooth and has few small undulations (Figure 6). The interface friction angle is assumed to be between 25°-35°.

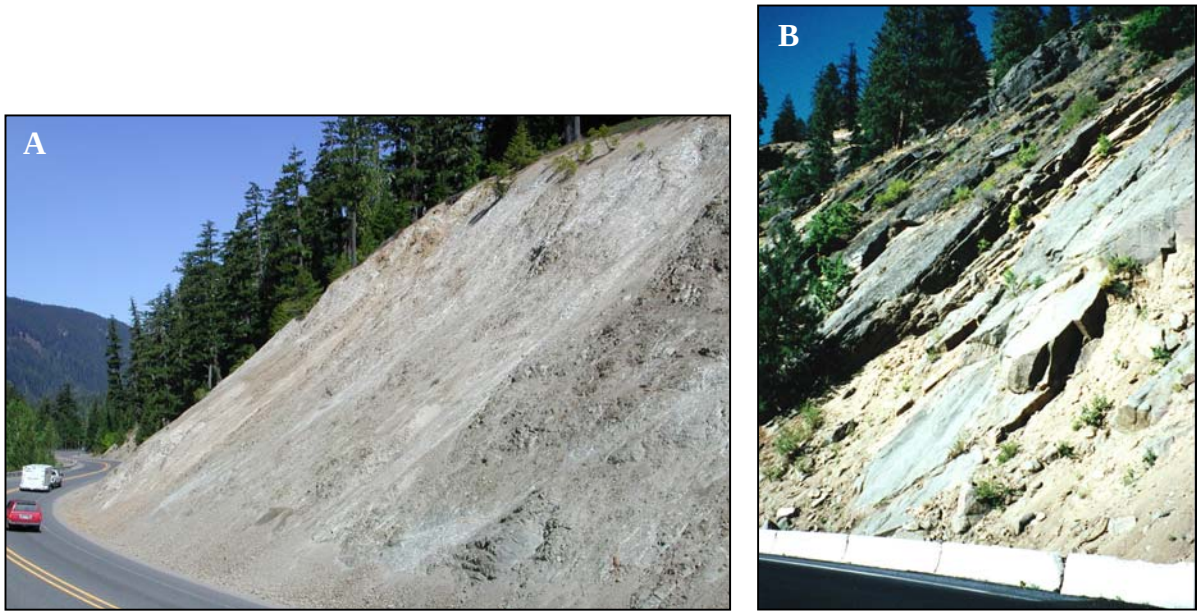

Figure 6. These planar slopes exhibit little surface roughness or slope irregularity. In the case of (A), the slope profile is controlled by the very highly fractured condition of the rock mass. The slope profile in (B) is the result of a highly persistent set of discontinuities that dips coincident with the slope.

2.4 DEBRIS LOADS

Debris loading is a common source of both local and global system failures. As discussed previously, wire mesh/cable net systems begin to yield with debris accumulations as low as 5 to 10 cubic yards (meters). Therefore, it is critical that an assessment be made of the expected type, size, volume, and frequency of slope instabilities. This assessment should be coupled with an evaluation of how and where debris might accumulate once the mesh has been installed. Common accumulation locations include slope convexities and salients, along the base of the mesh, and above any restraints/anchors along the perimeter or interior field of the mesh. One often unanticipated restraint is snow and debris covering the base of the mesh that either accumulates as snow slides off the mesh or from snow plowing. It is

important to note that debris simply caught beneath the mesh that is otherwise stable may impart little load on the system. Where the mesh impedes movement of unstable debris, significant load can be transferred to the system.

2.5 IMPACT LOADS

Rockfall impacts apply transient, short-term loads on the system. The actual load imparted is a function of the mass and velocity of the block and the manner in and orientation at which the block impacts the system. On near-vertical slopes where the mesh is sub-parallel to the slope and in limited contact, the rockfall trajectory is generally also sub-parallel to the slope. Unless the falling rock snags the mesh or deflects horizontally upon striking some asperity, there is little opportunity to transfer a large portion of the kinetic energy to the system. On moderately steep slopes, the velocities of rolling/bouncing blocks are significantly reduced by the greater mesh contact. Thus, kinetic energy should be (significantly) less for a rolling/bouncing rock beneath the mesh than what would be expected on an undraped slope.

Significant impact loads can be imparted to the system when blocks impact sub-normal to the mesh. Such is the case where systems are suspended across chutes or raised on posts to contain rockfall that originates upslope of the installation. Increasingly in recent years, systems have been installed for these applications. Another common configuration exposed to sub-normal impact loading occurs on slopes with abrupt convexities, such as a moderately steep slope in surficial deposits overlying a near vertical cutslope in rock (Figure 2B), midslope benches, and transitions between excavated lifts. Rockfall initiating near the top of the installation impacts the mesh just above the slope inflection; this is a frequent location of puncture failures.

The kinetic energy of scenario rockfalls can be estimated by using widely available rockfall modeling software, such as the public domain Colorado Rockfall Simulation Program (Jones et al., 2000). What remains poorly understood, however, is how kinetic energy is transferred as a load to the system. Regrettably, this research was unable to fully quantify the mechanism of impact load transfer to the system through full-scale testing. As a result, only limited design guidance is provided to account for impact loads, the basis of which is summarized in the technical report (Muhunthan et al., 2005). This includes mesh systems that are raised above ground level and subjected to sub-perpendicular impacts. For double-twisted hexagonal wire mesh, impacts near the top of the installation should not exceed 4 ft-tons (10 kJ), and impacts should not exceed 11 ft-tons (30 kJ) within 25 feet (7 m) of the mesh perimeter. For 5/16-inch wire rope, 8-inch square grid cable nets, the very limited available data suggest that an upper bound of puncture resistance for a restrained panel would be in the range of 20 to 25 ft-tons (54 to 68 kJ). Guidance for the puncture resistance of a 5/16-inch wire rope, 12-inch square grid panel, which was the basis for the testing and analysis of the research, is not presently available.

2.6 SNOW LOADS

For installations in regions that develop winter snowpack, the respective loads potentially transferred to the system must be evaluated. However, only slopes that accumulate snow need to be considered; this would only include slopes of moderate inclination, that is less than 55° to 60°. Slopes flatter than 30° to 35° generally do not produce rockfall. A minimum threshold of 1-foot (300-mm) depth is specified in the design flow chart (Figure 1) for design consideration. The design methodology presented later is only intended to consider the static load of the snowpack on the installation. If the slopes

above the installation are prone to unstable snowpack and these outside forces could be transferred to the installation, the site is probably not suitable for a draped mesh system.

Both climatological and anecdotal data sources should be consulted in determining a design snowpack. In the western U.S., the Western Regional Climate Center collects climatological data from a large number of sites and maintains a database of historical observations that includes temperature, precipitation, snowfall, and snow depth. Data can be accessed at its website (http://www.wrcc.dri.edu/summary/). The database does not include data on snow density or moisture, so direct measurement or estimation must be made to determine snow load. The U.S. Department of Agriculture Natural Resource Conservation Service collects snow data (SNOTEL) that include daily historical records of snow water equivalent, which can be used directly to estimate snow load. SNOTEL data can be accessed via the USDA website (http://www.wcc.nrcs.usda.gov/snotel/). Anecdotal data sources, such as area maintenance personnel, often provide valuable site-specific information. This might include localized weather and/or slope conditions that influence snow depth and density, and the retention (stability) of snow on and above the planned installation.

When evaluating site suitability for anticipated snow loads, caution is warranted on

- all smooth planar slopes (low interface friction)
- slopes oriented between 45° and 60°
- concave slopes where ground contact would be limited.

3. DESIGN METHODOLOGY

Once the site has been determined to be suitable for a wire mesh/cable net system, the recommended design process is to first select the appropriate fabric and then determine the needed anchor capacity and spacing for design load conditions.

3.1 FABRIC SELECTION

Selection of the appropriate fabric should be primarily based on the expected block/event size that the system will retain. Other fabric properties besides strength, such as puncture resistance and flexibility/rigidity, may also be relevant, depending on site conditions. The guidelines for fabric selection are based mostly on observed performance and are augmented with limited strength testing of relatively small-sized samples. The scale-dependence of the test data must be emphasized when overall system performance is considered. While fabric strength is important for static loading, flexibility, especially within the entire system, is an attribute that has been well-demonstrated to be necessary for sustaining dynamic loads.

Fabric types currently available in North America for rockfall protection systems include chain link (diagonal) wire mesh, double-twisted hexagonal wire mesh, high tensile steel wire mesh (TECCO®), cable nets, ring nets, and a hydrid fabric that combines both wire mesh and cable nets. For each of these fabrics, variations are available in wire/cable size and grid/opening size; square and diagonal weaves are also available for the cable net fabric. In North America, current performance experience is with three basic fabrics: chain link (diagonal) mesh, double-twisted hexagonal mesh, and cable nets. Within the last decade, hexagonal mesh has replaced chain link mesh in current practice among departments of

transportation. This change has been implemented because of its greater strength, better performance after the fabric has been damaged, and comparable unit cost (Agostini et al., 1988). The hexagonal mesh most typically used is an 8x10 type mesh with either 0.12-inch-(3-mm) diameter galvanized wire or 0.11-inch (2.7-mm) pvc-coated wire. Presumably, the best performance should be realized with the galvanized hexagonal wire mesh because of the slightly larger wire diameter, although no documented field performance has been acquired to verify this assumption. Cable nets are typically specified to use 5/16-inch (8-mm) wire rope and a square weave with 6-, 8-, or 12-inch (150-, 200-, or 300-mm) opening size. As shown by fabric testing (Carradine, 2004), a diagonal weave has superior strength to a square weave. The performance of a 6-inch (150-mm) grid should be superior to that of larger grid openings; however, no documented field performance has been acquired to verify this assumption. Unless otherwise stated, a 12-inch (300-mm) square grid with a 5/16-inch (8-mm) wire rope was used in preparing these guidelines.

On the basis of the limited fabric testing performed for this study by Carradine (2004), high tensile steel wire mesh (TECCO®) has a strength comparable to that of cable nets. A fundamental difference between the fabrics, however, is the weight; TECCO®'s weight is about half that of a 12-inch (300-mm) grid cable net and very near that of hexagonal wire mesh. Because of the recent introduction of this fabric in North America, performance experience is limited.

In summary, two primary fabric types have been used in North America for roughly the last decade: hexagonal wire mesh and cable nets. The current North American practice for their use is presented in Table 1. It should be emphasized that, at the present time, there

is no widely accepted test method for evaluating cable net, ring net, or hybrid fabrics and, hence, no quantifiable means for comparing fabrics from different manufacturers.

Table 1. Recommended fabric usage as a function of block size.

Fabric	Block Size
double-twisted hexagonal mesh	≤ 2 ft (0.6 m)
cable net	≤ 4 – 5 ft (1.2 – 1.5 m)

The intended application of wire mesh/cable net systems is to retain rockfall that would involve a single block up to several blocks. That said, both fabrics have repeatedly withstood localized slope failures with volumes of 5 to 10 cubic yards (meters) with minimal damage, if individual block sizes have not exceeded the respective size limit for each fabric. Typically, fabric damage increases with decreasing slope angle, since debris is more likely to accumulate on slopes of flatter orientation. Thus, a designer might consider using hexagonal mesh for a near vertical slope where block sizes approached 3 ft (0.9 m) and rockfall frequency was low. Conversely, localized damage to hexagonal mesh has been observed on moderately inclined slopes (~ 40° to 50°) that actively produce 2-foot (0.6-m) boulders; cable net fabric might be better suited for such conditions.

Fabric flexibility and optimal slope contact may also be important factors for certain sites. These may be important if snow loads or aesthetics are a concern. On near vertical slopes, however, it is more difficult, and perhaps less important from a structural perspective, to achieve a high degree of slope contact. Of the fabrics in current use, double-twisted hexagonal wire mesh is the most inflexible. Comparatively, chain link and cable nets are more flexible. TECCO® mesh is flexible in the longitudinal direction but quite stiff in the transverse direction. To maximize flexibility of cable nets, chain link fabric is recommended

over hexagonal wire mesh for backing. Hexagonal mesh, however, has greater strength than chain link, and thus probably provides somewhat better puncture resistance for small-sized rocks.

3.2 ANCHOR CAPACITY AND SPACING

While interface friction alone can provide, in some cases, sufficient resistance to hold a mesh system on a moderately inclined slope, anchors should provide the primary support for mesh systems. Unlike interface friction, the resistance contribution from anchors is easily quantifiable and unchanging over the life of the system. For these reasons, it is recommended that the design of system support for debris and impact loads relies solely on the anchors. Snow loads, however, require the consideration of interface friction to develop a cost-effective anchor design. These two approaches to anchor design are treated separately in the sections that follow.

Current practice in North America generally utilizes anchor elements that exceed a 20,000-lbf (90-kN) minimum yield strength in both tension and shear. Common tendons include a 1-inch (25-mm), continuously threaded deformed steel bar and ¾-inch (19-mm) wire rope. Consequently, a minimum capacity of 20,000 lbf (90 kN) has been assumed in the design chart presented below. The charts presented in figures A-19, A-20, and A-21 in Appendix A can be used for anchors of different capacity for common fabric types with an appropriate safety factor. Additional charts for common fabric types are provided in Appendix A (figures A-1 through A-18) that account for interface friction for slopes oriented at 45° and 60° with planar, undulating, and rough slope surfaces. An appropriate factor of safety should also be applied to these anchor loads and spacings.

3.2.1 Debris and Impact Loads

The recommended design methodology attempts to account for potential variability in debris and impact loads for a given site, as well as the current lack of understanding of how impact loads are transferred to the system. This is done by applying a large factor of safety (5 to 10) to the anchor requirements for the system weight alone, with no resistance contribution from interface friction (figures A-19, A-20 and A-21). The maximum recommended anchor spacings presented in Table 2 also coincide with repeated successful application of the wider range of anchor spacings discussed in the technical report (Muhunthan et al. 2005). For simplification, the recommended maximum spacings are suitable for hexagonal mesh, TECCO® G65 mesh, and 12-inch (300-mm) square grid cable nets backed with either hexagonal or chain link mesh. Narrower spacings should be considered if different fabrics are used that are significantly heavier than the specified cable net. Other factors, such as topography, may also warrant closer spacings.

Table 2. Recommended maximum anchor spacing as a function of slope height

Slope Height *ft (m)*	**Anchor Spacing[1,2]** *ft (m)*
≤ 100 ft (30 m)	50 ft (15 m)
100 – 200 ft (30 – 60 m)	35 ft (10 m)
200 – 300 ft (60 – 90 m)	20 ft (5 m)

[1]Maximum spacings suitable for hexagonal mesh, TECCO® G65 mesh, and 12-inch (300-mm) square grid cable nets backed with either hexagonal or chain link mesh.
[2] Anchor spacing is based on a minimum anchor capacity of 20,000 lbf (90kN).

Anchor load charts for 45° and 60° slopes with planar, undulating, and rough configurations are included in Appendix A. As an alternative to the use of Table 2, these charts can be used to determine the anchor loads from mesh weight alone for these flatter

slope orientations. A similar factor of safety should then be applied to determine anchor capacity and spacing.

3.2.2 Snow Loads

As documented in the technical report (Muhunthan et al., 2005), snow loads have been responsible for numerous system failures. All known system failures have occurred as a result of anchor yielding, either through exceeding the strength or passive resistance of the ground or the yield strength of the tendon. No ancillary damage to the mesh, support ropes, or connections has been observed at any of these snow-related failures. The anchor capacities and spacings used at these sites were in general accordance with those presented in Table 2, supporting the conclusion that these spacings may be too wide for systems exposed to snow loads. However, if the anchors were assumed to carry the entire snowpack weight and interface friction was neglected, unrealistically large anchor loads would be calculated. The instrumented Tumwater Canyon and the U.S. 20 Rainy Pass sites summarized in the technical report clearly demonstrate the important resistance contribution provided by interface friction. The anchor force due to snowpack per unit width of mesh, F_a, can be calculated with the following equation:

$$F_a = \rho g H L \sin\theta - \rho g H L \cos\theta \tan\phi$$

where ρ is the overall density of the snowpack, g is the gravity constant (for metric units), H is the thickness of the snowpack oriented normally to the slope, L is the slope length of the installation, θ is the slope angle, and ϕ is the interface friction angle. The design challenge lies in characterizing the interface friction of the entire installation. The case histories presented in the technical report and the photos in section 1.3 can aid in this characterization.

A safety factor of 2 to 3 should be applied to account for larger than anticipated snowpack and overestimation of interface friction.

It is evident from the equation that for slopes that have an interface friction equal to or greater than the slope angle, a snowpack should cause no load increase on the anchors. Conversely, when interface friction is less than the slope angle, a portion of the snow load is transferred to the anchors, and load increases rapidly as the angles diverge. Two examples are provided to illustrate the effect of interface friction (ρ = 25 lbf/ft^3; H = 2 ft; L = 150 ft; θ = 45°; ϕ = 30°, 40°) for an assumed anchor capacity of 20,000 lbf (90kN):

$F_{a30°}$ = 2240 lbf/ft; a FS=2 results in a roughly 5 ft anchor spacing

$F_{a40°}$ = 850 lbf/ft; a FS=2 results in a roughly 12 ft anchor spacing

4. DESIGN DETAILS AND SPECIFICATIONS

The research results are compiled into specific design details in the following section and in a set of generic plan sheets included in Appendix B.

4.1 SLOPE COVERAGE

The area of coverage is determined from geologic/geotechnical assessment of the potential source areas of rockfall. The necessity of extending the mesh beyond the current slope brow should be considered and defined in the final design. A distance of 10 to 15 ft (3 to 4 m) beyond a potential source area is often considered a minimum. Additional upslope extent may be warranted if the crest of the slope is actively eroding, like the slope in Figure 3, to ensure slope coverage for the life of the system. Generally, the bottom of the mesh should extend to within 3 to 5 ft (1 to 1.5 m) of the base of the slope. If it is located much higher, the catchment area becomes more critical in retaining debris that passes the mesh system. If the base of the slope serves as an area for snow storage, then consideration should be given to raising the bottom of the mesh to reduce the potential of accumulating debris during winter months excessively loading the system. If little catchment area is available, it may be advisable to lower the mesh to near the ditch line; however, these installations will require more frequent inspection and maintenance if debris accumulates and loads the system.

The coverage area is well depicted on photographs of the slope area taken in elevation view (Figure 7). Slope lengths at station intervals can be included to facilitate the estimation of material quantities. Salients and reentrants increase surface area. Quantity estimates

should be increased if the slope is not uniform; a range of 10% to 15% is common. A more accurate method is to determine quantities by surveying the slope.

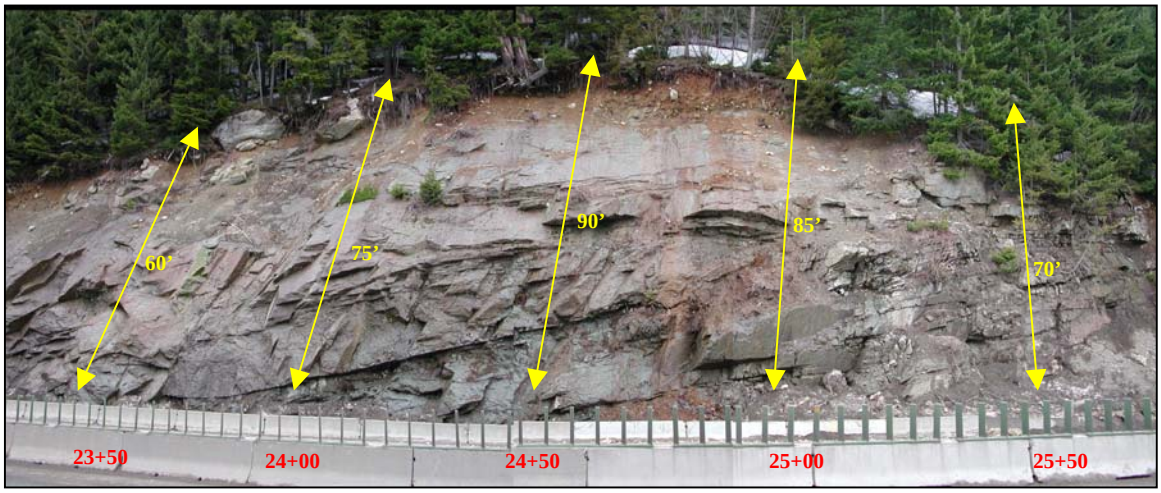

Figure 7. Coverage area depicted by stationing and slope length.

4.2 ANCHORS

Anchors can be located either along or upslope of the top horizontal cable. Often there are benefits to allowing latitude in siting anchors, such as ease of installation or avoiding obstructions. Siting anchors upslope of the top horizontal cable optimizes anchoring opportunities and often results in a superior anchor. Siting the anchors upslope also reduces the risk of the anchors being undermined by ongoing erosion. On the downside, there is additional cost for the wire rope and connectors required to link the anchors and top the horizontal support rope.

Unlike most ground anchors, anchors for mesh systems are generally loaded perpendicular to the anchor. This is noteworthy for two reasons. First, rigid tendons, such as deformed steel bars that might be used to anchor in rock, are loaded more in shear than in tension. It is well known that the strength of steel in shear is about 75 percent of the ultimate tensile strength. In recent years, current practice has moved more toward the use of wire

rope for anchor tendons for both soil and rock conditions. Because of its flexibility, wire rope accommodates load in tension by bending toward the direction of loading, thus optimizing the strength of the tendon. The second reason that the direction of loading is important involves the mobilization of passive resistance of the ground. Anchors oriented normally to the ground surface optimize passive resistance. Passive resistance, and thus capacity, is reduced when anchors are oriented toward vertical. While passive resistance is not a concern when anchors are set in rock, it can be a significant concern for systems anchored in soil that are exposed to severe loading conditions.

The anchor testing performed as part of this research resulted in some valuable observations about the capacity and performance testing of anchors founded in soil. All but one of the anchors loaded vertically held 20,000 lbf (90 kN) and did so within 1 inch (25 mm) of displacement. Continued loading resulted in visible ground deformation over a diameter of at least the length of the anchor. Anchors loaded horizontally typically required 6 to 10 inches (150 to 250 mm) of displacement to mobilize a similar load, and they were able to sustain increasing load with displacement often well beyond 20,000 lbf (90kN). These results have significant bearing on the field verification of anchors. For nearly every installation, a minimum number of every anchor type should be tested. Depending on the criticality of the installation, 25 percent is a recommended minimum. If possible, the verification testing should be oriented in the direction of actual loading (sub-horizontal). This can be accomplished by extending a cable from the anchor to the base of the slope and tensioning the cable in the manner shown in Figure 8. If vertical load testing is performed, it is important that the load frame be sufficiently wide to not influence stresses within the soil.

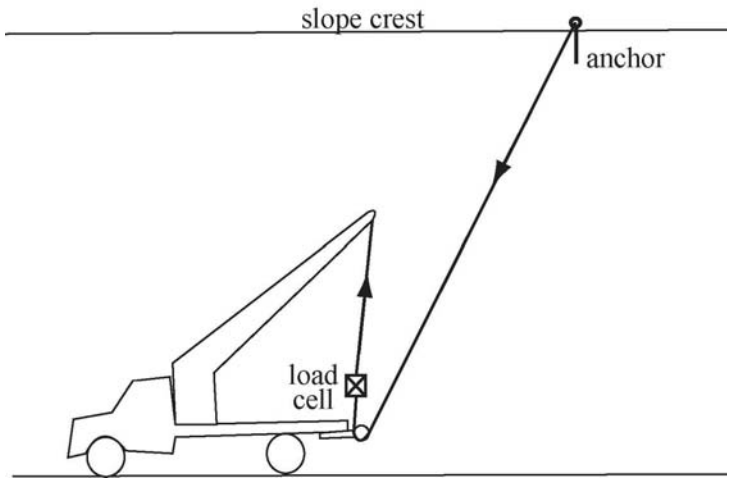

Figure 8. Testing setup of anchors in a sub-horizontal direction.

4.3 SUPPORT ROPES

The finite element modeling completed for this research proved useful in refining the design of support for mesh systems. The modeling confirmed observations that horizontal and vertical support ropes below the top horizontal support cable provide effectively no structural function. In addition, interior horizontal support ropes located between the mesh and the slope have repeatedly been the cause of debris accumulation leading to local and global system failures. Therefore, interior support ropes (both vertical and horizontal) are unnecessary and should be avoided. A possible exception would be the use of a horizontal rope along the bottom of the mesh to facilitate cleanout behind the mesh. If a bottom rope is included, it should be placed on the outside of the mesh and either it should be fastened to the mesh with lacing wire or the mesh should be folded outwardly over the cable and fastened with high tensile steel rings.

Another refinement of current practice addresses the maximum uninterrupted length of the top horizontal support. For the purposes of analysis and design uniformity, cable diameters of ½ inch (13 mm) and ¾ inch (19 mm) with breaking strengths of around 25,000

lbf (110 kN) and 50,000 lbf (220 kN), respectively, have been considered for top horizontal support ropes. Based on a factor of safety of approximately 2 for the top horizontal support rope, the recommended maximum lengths for double-twisted hexagonal and TECCO® G65 mesh are provided in Table 3A and for cable nets backed with hexagonal mesh in Table 3B.

Table 3A. Recommended maximum length for top horizontal support rope *v.* slope height for double-twisted hexagonal and TECCO® mesh.

Slope Height *ft (m)*	**Max. length for ½" (13 mm) cable fabric weight only** *ft (m)*	**Max. length for ¾" (19 mm) cable fabric weight only** *ft (m)*
50 ft (15 m)	230 ft (70m)	400 ft (120 m)
100 ft (30 m)	120 ft (35 m)	200 ft (60 m)
200 ft (60 m)	60 ft (18 m)	100 ft (30 m)
300 ft (90 m)	40 ft (12 m)	75 ft (22 m)

Table 3B. Recommended maximum length for top horizontal support rope *v.* slope height for cable net backed with double-twisted hexagonal mesh.

Slope Height *ft (m)*	**Max. length for ½" (13 mm) cable fabric weight only** *ft (m)*	**Max. length for ¾" (19 mm) cable fabric weight only** *ft (m)*
50 ft (15 m)	80 ft (25m)	150 ft (45 m)
100 ft (30 m)	40 ft (12 m)	75 ft (22 m)
200 ft (60 m)	20 ft (5 m)	40 ft (12 m)
300 ft (90 m)	15 ft (4 m)	25 ft (7 m)

These tables may be conservative for flatter slopes because they do not account for the resistive contribution of interface friction. Conversely, the maximum length of the top horizontal support rope should be reduced if extreme sustained loads (i.e., snow) are anticipated. As an example of an extreme loading condition, the instrumented Tumwater

Canyon cable net installation employs two anchors spaced at about 20 ft (6 m) and breaks the horizontal support rope at each anchor group.

The use of thimbles and wire rope clips should follow the manufacturer's recommendations for size, number, spacing and torque. Steel rings that join sections of the top horizontal rope should also be sized to have an ultimate breaking load that is compatible with the ultimate yield strength of the wire rope. Note that the ultimate load for weldless steel rings is substantially higher than the published minimum working load. As an example, a 7/8-inch x 4-inch-diameter, galvanized, weldless steel ring with a minimum working load of 10,000 lbf would be suitable for use with a ¾-inch-diameter, 6x19 IWRC wire rope with a minimum breaking strength of 45,000 lbf.

4.4 FABRIC SEAMING AND FASTENING

The fabric must be both fastened to the support ropes and seamed together. For hexagonal mesh, testing performed for this research of different seaming configurations with high tensile steel fasteners (i.e., King Hughes, Spenax) revealed that all the seams were about half as strong as the mesh. Lacing wire would be needed to achieve a seam that would approach the strength of the hexagonal mesh. A supporting argument could be made for incorporating weaker elements in a system so that when an unanticipated yielding condition occurs, only a portion of the system fails rather than the entire system. In other words, repairing a ruptured seam is considerably cheaper than reinstalling an entire system. If a "weak link" is desired, then vertical seams of hexagonal mesh should be fabricated with either a butted seam or a one-cell overlap of approximately 3 inches (8 cm) and fastened with a high tensile steel fastener at every cell, resulting in a 4-inch (10-cm) fastener spacing. There appears to be no benefit to using the often-specified overlap of 8 to 12 inches (200 to

300 mm). If used, lacing wire should be of similar gauge as the mesh or larger and should pass through each cell. Moderate tensile strength fasteners (i.e., standard hog rings) should not be used for seaming hexagonal mesh in draped rockfall protection systems. Horizontal seams should be discouraged; if needed, they should be closed with lacing wire, with the lower panel placed on the outside to prevent debris accumulation.

Current practice for attaching hexagonal mesh to the top horizontal rope typically utilizes a 12-inch (300-mm) fold over the rope and fastening the overlap with either lacing wire or high tensile steel rings at a spacing of 6 to 12 inches (150 to 300 mm). Although no failures attributed to steel ring fasteners were reported, lacing wire instead of rings is recommended for this application in conjunction with the fold.

The manufacturer, Geobrugg, provides recommendations for both the seaming and hanging of TECCO® mesh.

Cable nets should be similarly seamed and hung with lacing cable of similar gauge or larger, ensuring that the cable passes through each cell of the interior weave of the net panel. The cable nets backing can be of either chain link or hexagonal mesh. Chain link mesh is recommended if flexibility and conformance to the slope is of primary importance. Hexagonal mesh should be used if puncture resistance is of greater importance. The fabric should be fastened with high tensile steel rings to each side of the wire rope grid to inhibit differential movement of the fabrics. The backing mesh should be fastened to the nets on the ground; it is nearly impossible, as well as highly inefficient, to do it separately on the slope. The backing fabric should be placed on the inside of the cable net against the slope.

5. AESTHETIC CONCERNS AND MITIGATION

Increasingly, the selection of the preferred mitigation for rockfall is judged not only on the method's engineering and economic merits but on aesthetic concerns as well. This is particularly the case in areas of considerable scenic or recreational value, where a design objective to visually subordinate engineered facilities may be required or legislated. In some cases, managers and design professionals responsible for aesthetic stewardship have found the use of wire mesh/cable nets objectionable. The principal concerns have stemmed from the typically large coverage area, the visual contrast between the wire mesh and the slope, and the potential for poor mesh contact with the slope. Design efforts to mitigate these aesthetic concerns may focus on

- reducing/limiting the coverage area
- achieving greater mesh contact with the slope
- colorizing system components or promoting vegetation to visually merge the system with the slope
- considering other slope stabilization alternatives.

5.1 LIMITING COVERAGE AREA

For some slopes, it may be possible to reduce or limit the coverage area of a mesh system and still provide adequate rockfall containment. Rather than draping the entire rockfall source area on a slope, the top of an installation can be lifted off the ground to effectively contain rockfall originating upslope. Such an approach is commonly used for chutes/swales and along abrupt convexities. If such a design approach is pursued, the prospective impact energy on the raised portion of the system must be considered.

Conversely, opportunities may exist to limit the bottom elevation of the system to keep it above the immediate view of passing motorists. However, when the bottom of the mesh is raised more than a few feet above the ditch line, debris passing from beneath the mesh may not be contained in the available catchment area. In these cases, catchment should be evaluated. Provisions to increase or improve the catchment area may be required.

5.2 INCREASING MESH CONTACT

For many moderately inclined slopes (40° to 60°) and some steeply inclined slopes (>60°), efforts to maximize mesh contact with the slope yield both functional and aesthetic benefit (Figure 9A). Functional benefits can include greater interface friction and overall system capacity, as well as decreased slope erosion and rockfall. A reduction of slope erosion commonly promotes revegetation of the underlying slope. Mesh contact also reduces/eliminates the gap between the mesh and the slope, which is often quite discernable when the installation is viewed from the side, as by a passing motorist (Figure 9B). On steep slopes, it is often more difficult to achieve mesh contact, and because of the reduced component of normal force, it is difficult to maintain contact as the system is loaded.

Mesh contact, particularly on moderately inclined slopes, commonly reduces slope erosion, which in turn can promote reestablishment of vegetation. Growth of vegetation into the mesh can significantly reduce visual contrast and aid in the visual blending of the mesh with the slope, as well as increase the stability of the surface materials. More proactive revegetation efforts have been undertaken, such as placing erosion-control fabrics beneath the wire mesh, hydro-seeding, and installing plantings. Although installing mesh around existing vegetation can increase installation costs, in some cases protecting existing vegetation may be either beneficial or even required.

Figure 9. (A) The mesh was carefully installed to closely conform to this moderately inclined slope. (B) On a steep to overhanging slope where mesh conformance is generally more difficult to achieve, the mesh can become more visually apparent.

While vegetation most often provides benefit, installation damage/failures have occurred because of trees growing through the mesh. The damage has occurred when trees have subsequently fallen (a common occurrence on steep slopes) or when the substrate in which they have grown has crept or experienced other shallow instability. If the slope is prone to such shallow instability, the growth of larger woody vegetation through the mesh should be discouraged, or another mitigation measure besides wire mesh/cable nets should be considered.

5.3 COLORIZING SYSTEM COMPONENTS

Wire mesh and cable net fabrics are generally supplied with a galvanized or other corrosion-protection coating. When installed, these coatings and some cross-clips of cable net fabrics have a metallic, often shiny or light colored appearance that may strongly contrast with the slope. Over time, the shininess of galvanizing typically fades to a dull gray color. Coloring of fabrics has become more common in recent years to reduce the visual contrast between the mesh and the slope.

Three methods of coloring are currently used: painting, polyvinylchloride (pvc) coating, and powder coating. While painting may be preferred for system components, painting a large area of fabric is typically not practical because of environmental and logistical constraints, as well as the laboriousness of the task. Coating the wire or cable with colored pvc has been used extensively for double-twisted hexagonal mesh, chainlink, and, more recently, cable net fabric. The coating is applied before the fabric is woven, which results in a very cost-effective colorizing method. Extreme exposure of pvc to ultraviolet radiation has been known to cause considerable lightening of the coating. Powder coating is a fused colorized coating that provides a durable coloring alternative to painting and pvc coating. Powder coating is typically applied after fabrication and is used predominantly for cable net fabric. Note that this treatment can be two to three times as expensive as standard galvanizing.

6. CONSTRUCTION CONSIDERATIONS

Consideration for how a system will be installed and inspection of its construction best ensure that the design objectives of function, aesthetics, and cost-effectiveness are met. Generally, other specified stabilization work (e.g., scaling and installing rock anchors) should be performed before placement of a mesh installation; however, in some cases it may be safer to install rock anchors after mesh placement. Also note that slope scaling before mesh installation often provides only limited long-term benefit. Furthermore, slopes best suited for mesh/cable nets are often more hazardous to scalers than slopes that require other stabilization measures (e.g., rock anchors). Scaling before the mesh installation should focus on the slope preparation necessary for mesh installation and the removal of occasional, potentially damaging oversized blocks or other discrete zones.

Prior to construction, the contractor, construction inspector, and designer should field verify and measure the coverage area. The actual locations of the top, bottom, and lateral extent of the installation should be determined at this time, as well as the optimal location of each anchor. Depending on the criticality of the installation, a minimum number of anchor tests should be specified and successfully completed. Wire rope clips should be carefully inspected for proper clamping orientation, spacing, and torque. In some cases, wire rope clips have loosened over time. Re-tightening them several days or more after the initial installation may be necessary.

Unless individual panels will be rolled out from the top of the slope, a staging area near the base of the slope will be required for layout and seaming. For cable nets with a wire mesh backing, a staging area is essential to properly prepare the panels. The contract should

require that the backing fabric be fastened to the net panels on the ground. The selection of the staging area will be influenced by the method of placement (boom truck, crane, or helicopter) and the size of the installation. For large installations, helicopter placement is usually the fastest and most cost-effective method. However, helicopter work requires an emergency landing area as part of the staging operations; traffic control and proximity to aerial utilities also need to be considered.

Load is often concentrated on the anchors and the top support rope during the hanging of the mesh/net panels. In one known instance, this concentration led to anchor failures. Design guidelines provided for the maximum length of the top horizontal rope should be adhered to, and care should be exercised during hanging to minimize load concentrations on the anchors. If mesh conformance/contact with the slope is a design objective, the maximum width of fabric placement in any crane/helicopter pick should be limited to one panel width. After the top of the panel has been secured to the top support rope, workers should walk down each panel, pushing the fabric into slope irregularities. The next panel can then be placed and secured to the top support rope, seamed longitudinally to the adjacent panel, and then similarly walked-down.

7. MAINTENANCE

For most slope conditions, the recommended design methodology presented above should result in an installation requiring minimal maintenance over the design life of the system. The dominant maintenance concern is averting damaging debris loads. Some debris accumulation should be expected. Often, this debris does not directly load the system. Deformation or bulging of the fabric is an indication that the system is being loaded, and maintenance to remove or pass the debris should be initiated. A horizontal bottom cable or cable at other constriction points laced to the outside of the mesh can be used to lift the mesh.

While the growth of vegetation on an actively eroding soil slope is generally desirable to reduce erosion, the growth of shrubs and trees through the mesh can create problems. Toppling of trees that have grown through the mesh has caused localized and global failures. Additionally, creeping of underlying slope materials (common in some surficial deposits) can induce unanticipated load on the anchors if excessive intertwining of shrubby vegetation with the mesh has occurred. In these cases, some management of vegetation growth through the mesh may be required to ensure long-term performance of the system.

Where snow load is anticipated, it is prudent to periodically inspect the anchor and support ropes, particularly after a heavy snow year.

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- Don Turner, Oregon Department of Transportation
- Steve Lowell, Tom Badger, and Keith Anderson, Washington State Department of Transportion
- Jim Coffin, Wyoming Department of Transportation
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- Howard Ingram, HI-TECH Rockfall Construction
- Larry Pierson, Landslide Technology

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APPENDIX A

ANCHOR SPACING/LOAD CHARTS

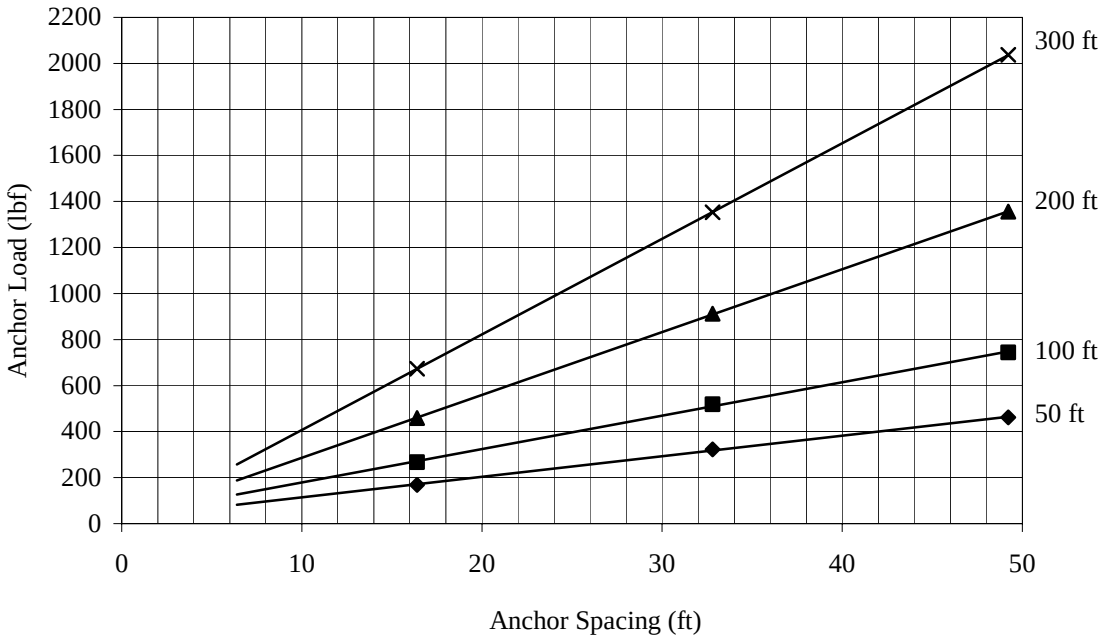


Figure A-1. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for a planar, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

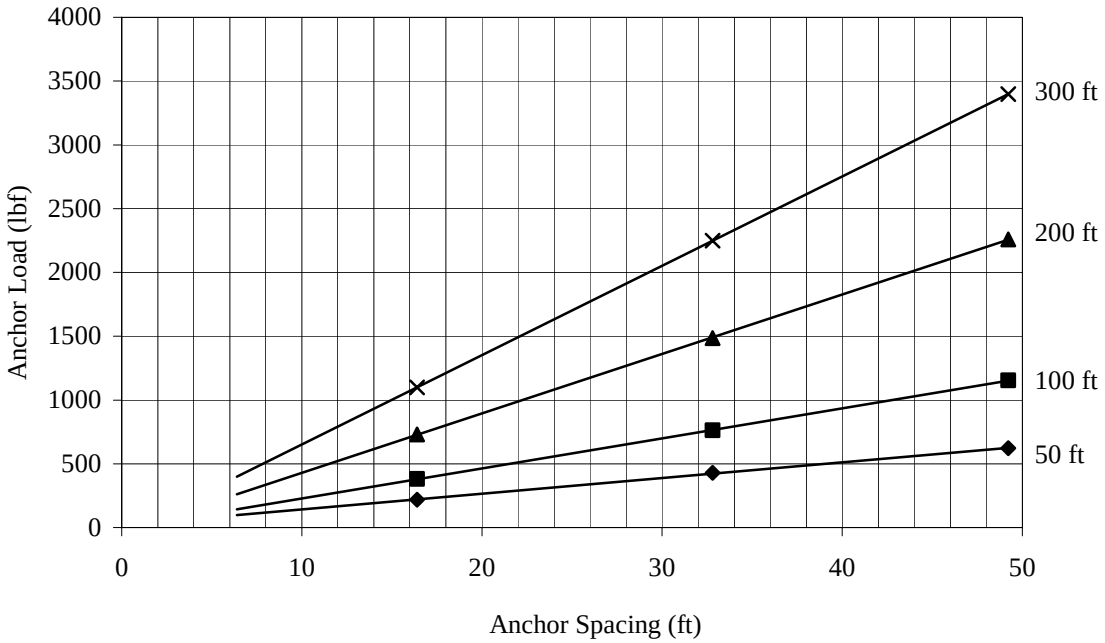


Figure A-2. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for a planar, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

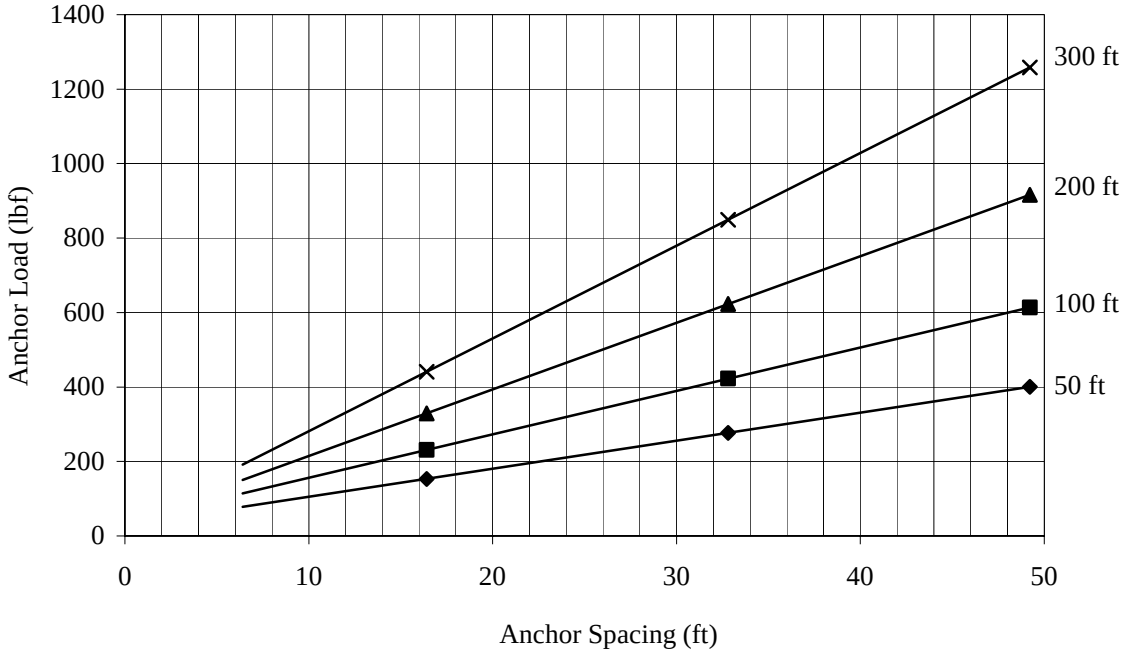


Figure A-3. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for an undulating, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

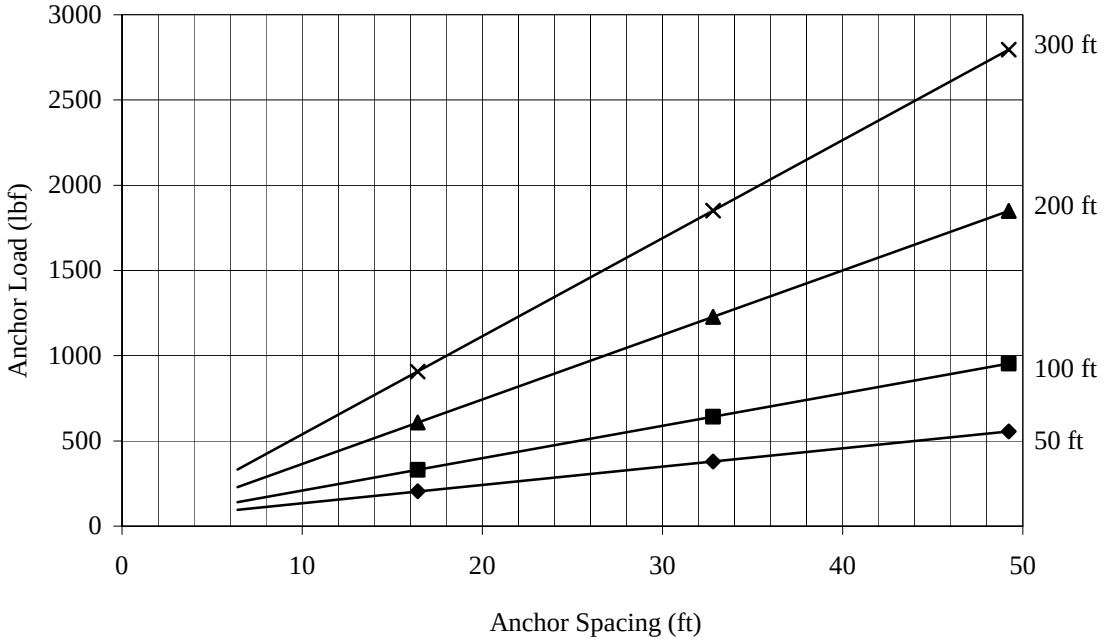


Figure A-3. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for an undulating, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

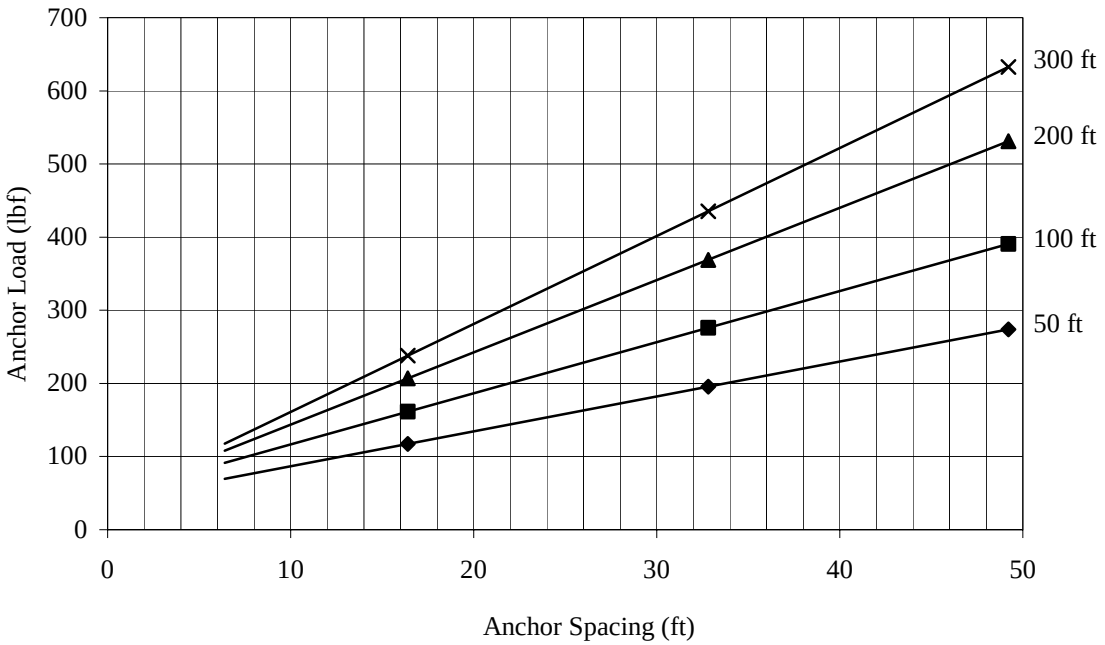


Figure A-5. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for a rough, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

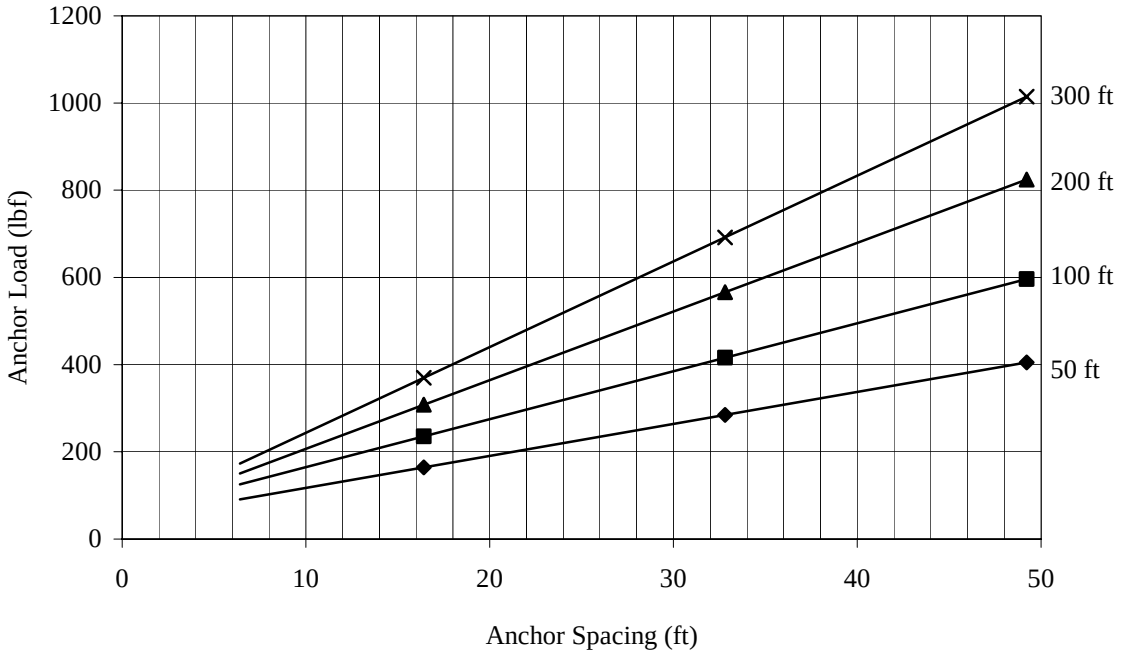


Figure A-6. Graph plots anchor load *v*. spacing for double-twisted hexagonal wire mesh for a rough, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

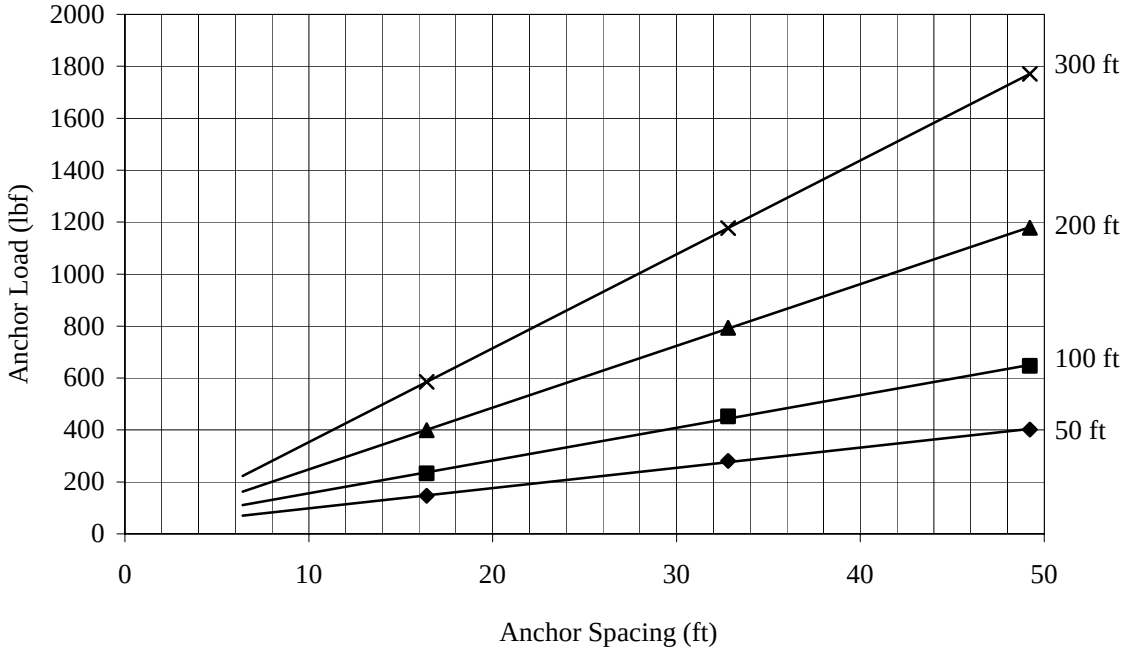


Figure A-7. Graph plots anchor load *v*. spacing for TECCO® mesh for a planar, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

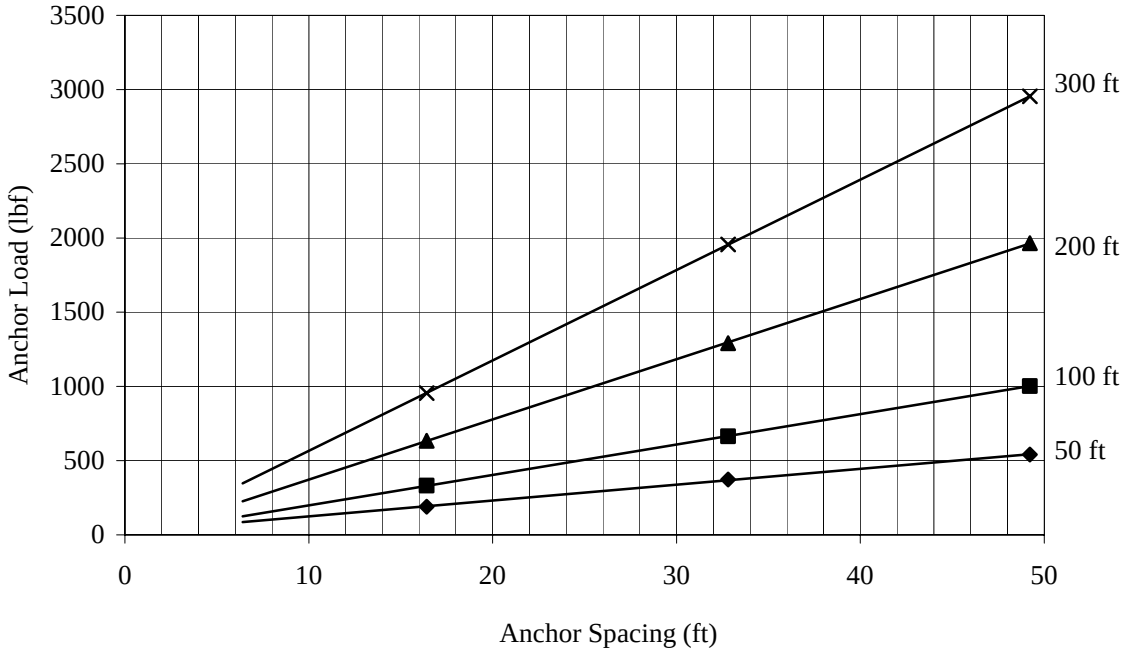


Figure A-8. Graph plots anchor load *v*. spacing for TECCO® mesh for a planar, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

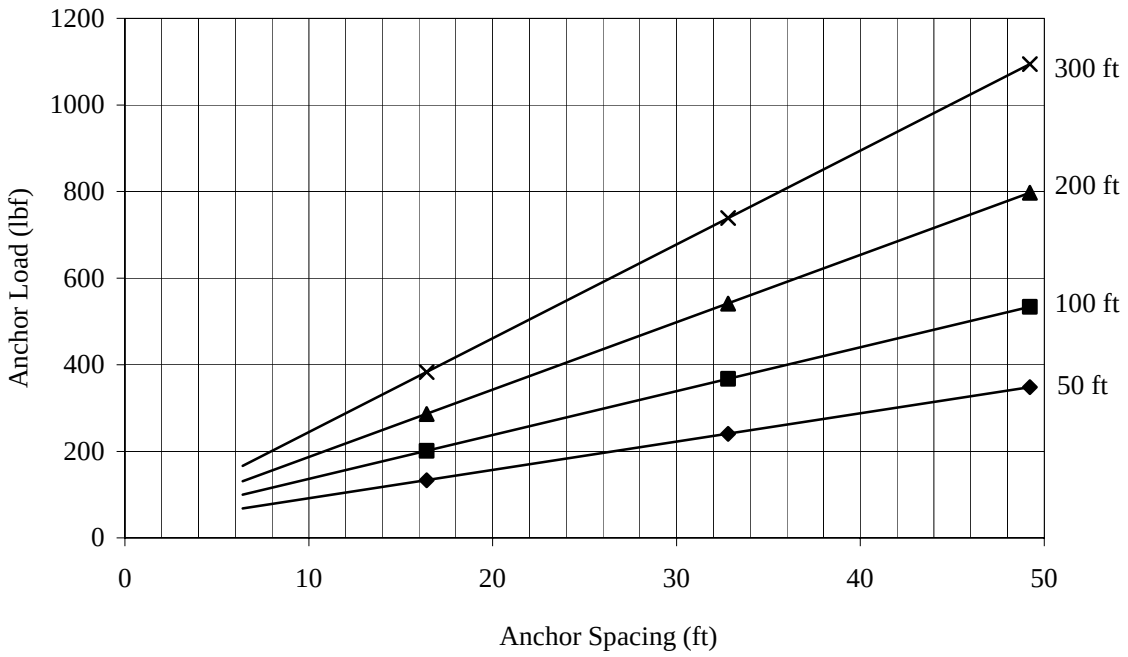


Figure A-9. Graph plots anchor load *v*. spacing for TECCO® mesh for an undulating, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

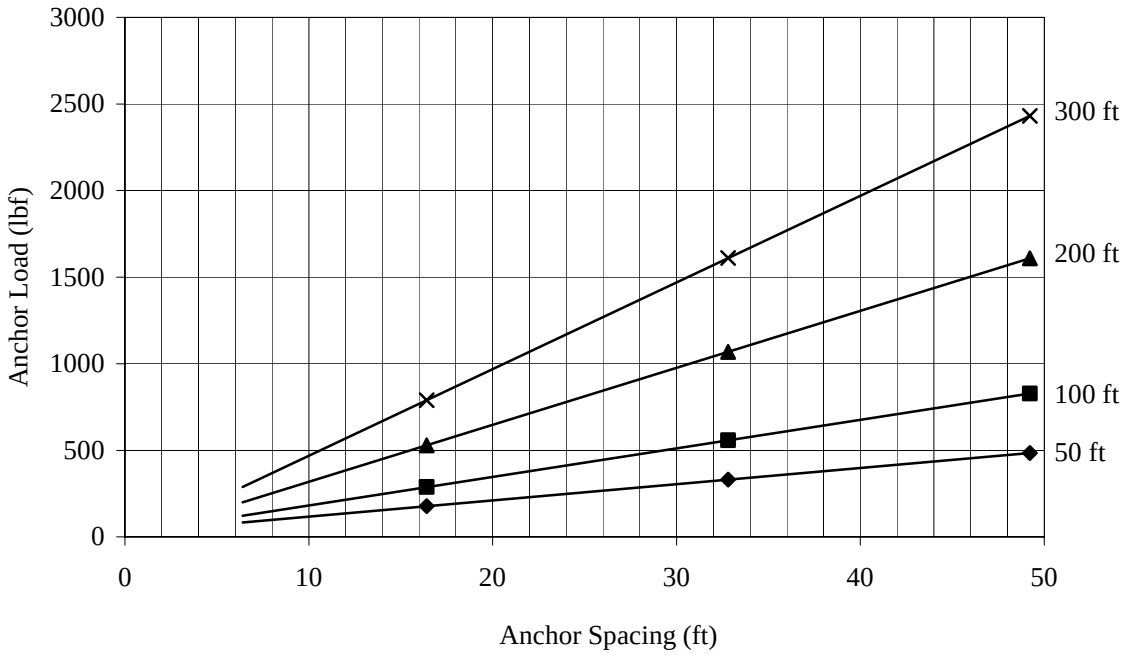


Figure A-10. Graph plots anchor load *v*. spacing for TECCO® mesh for an undulating, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

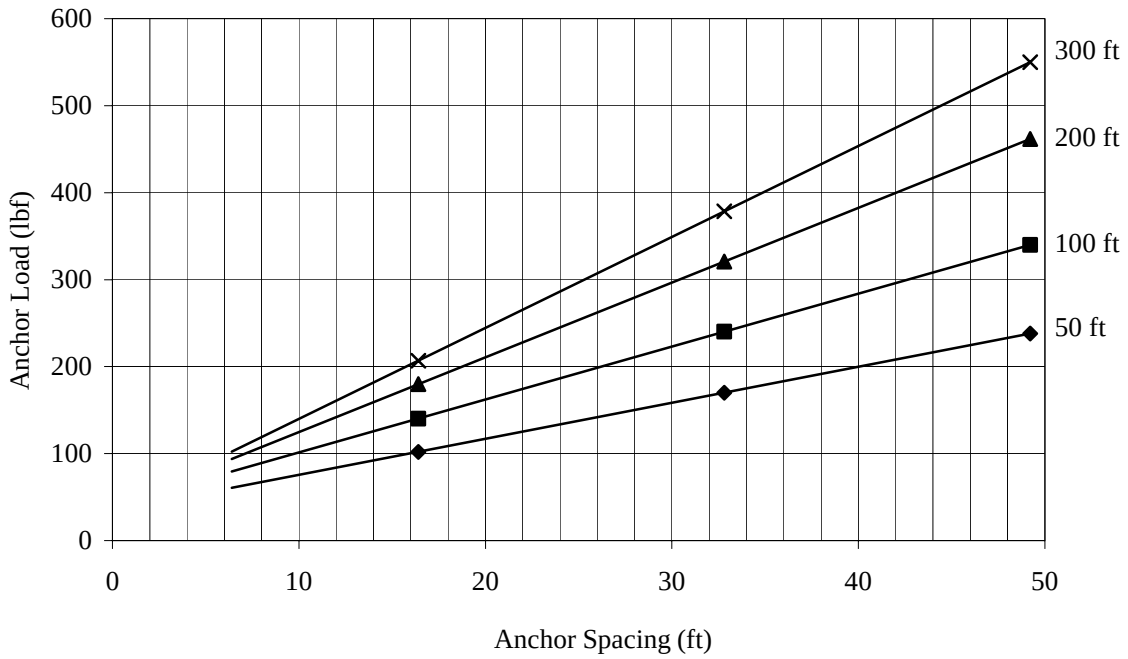


Figure A-11. Graph plots anchor load *v*. spacing for TECCO® mesh for a rough, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

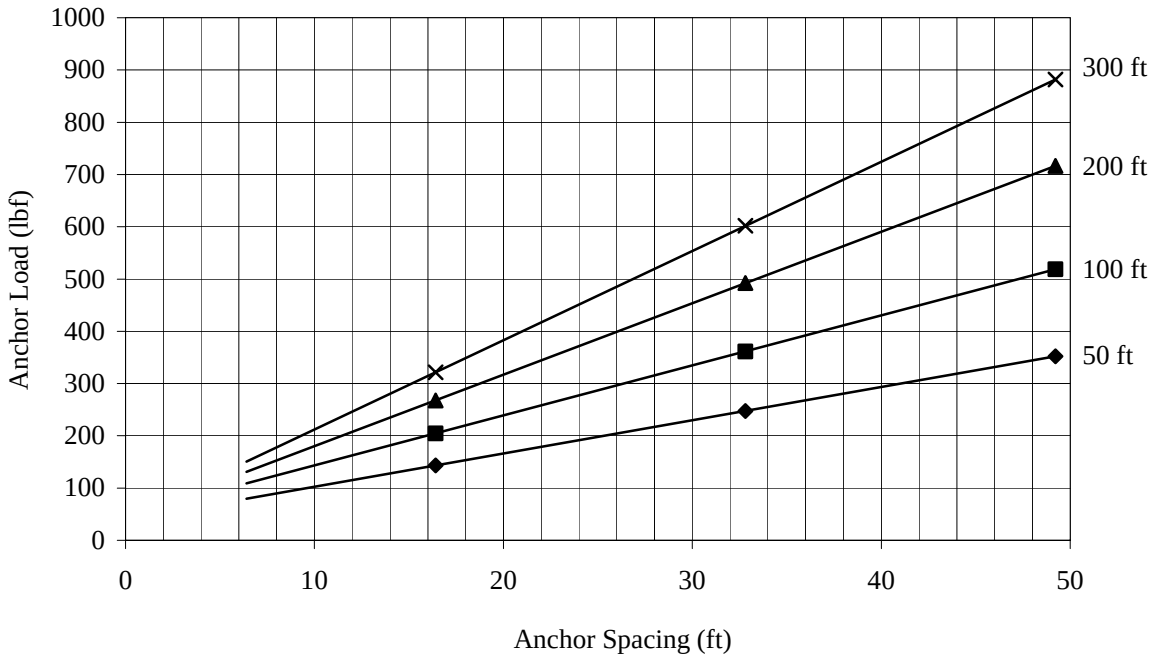


Figure A-12. Graph plots anchor load *v*. spacing for TECCO® mesh for a rough, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

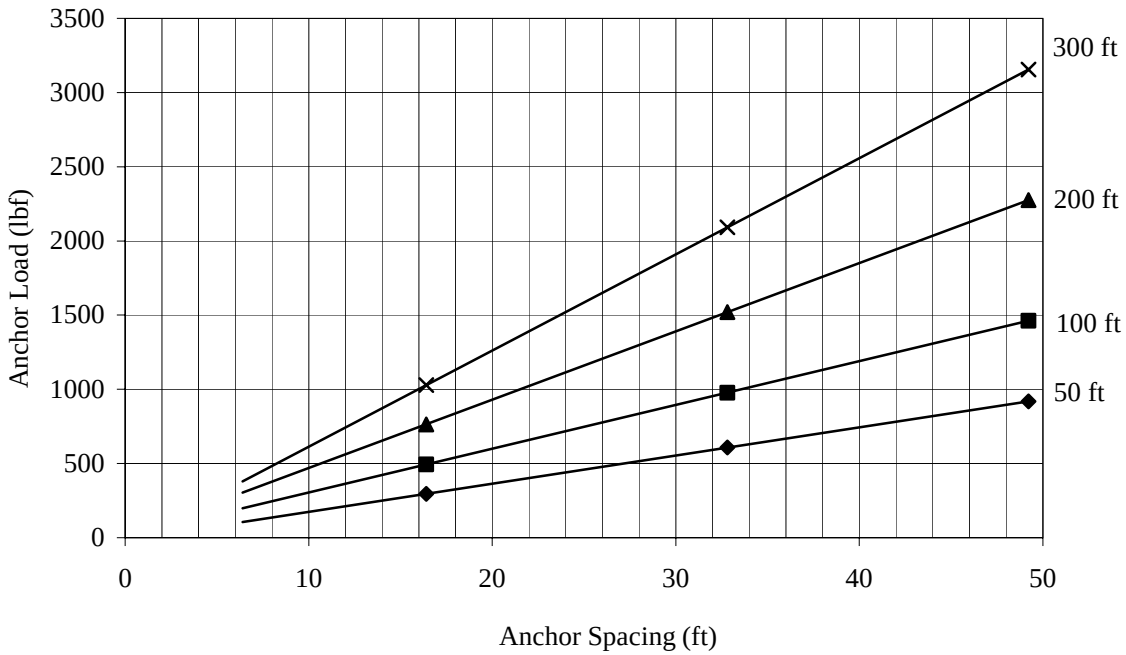


Figure A-13. Graph plots anchor load *v*. spacing for cable nets for a planar, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

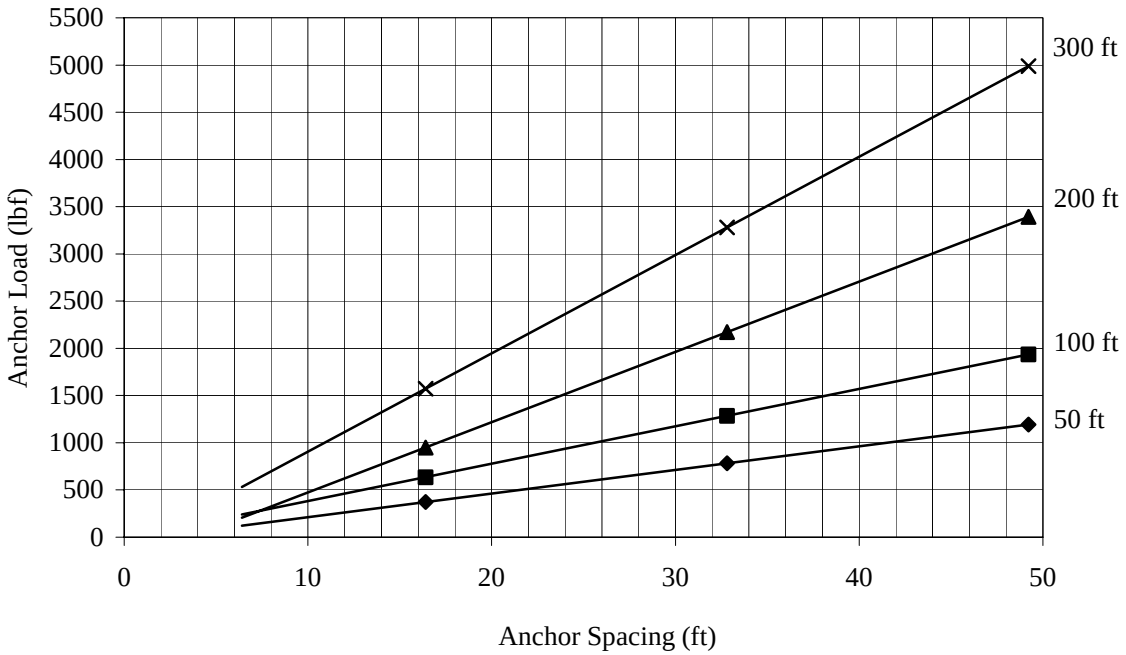


Figure A-14. Graph plots anchor load *v*. spacing for cable nets for a planar, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

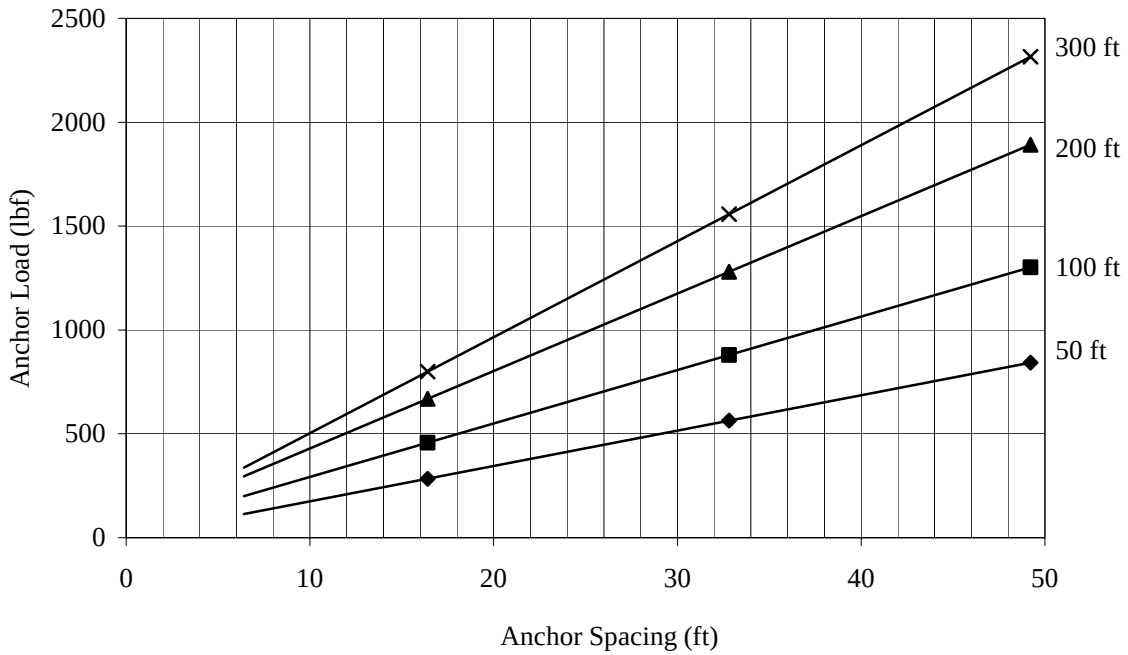


Figure A-15. Graph plots anchor load *v*. spacing for cable nets for an undulating, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

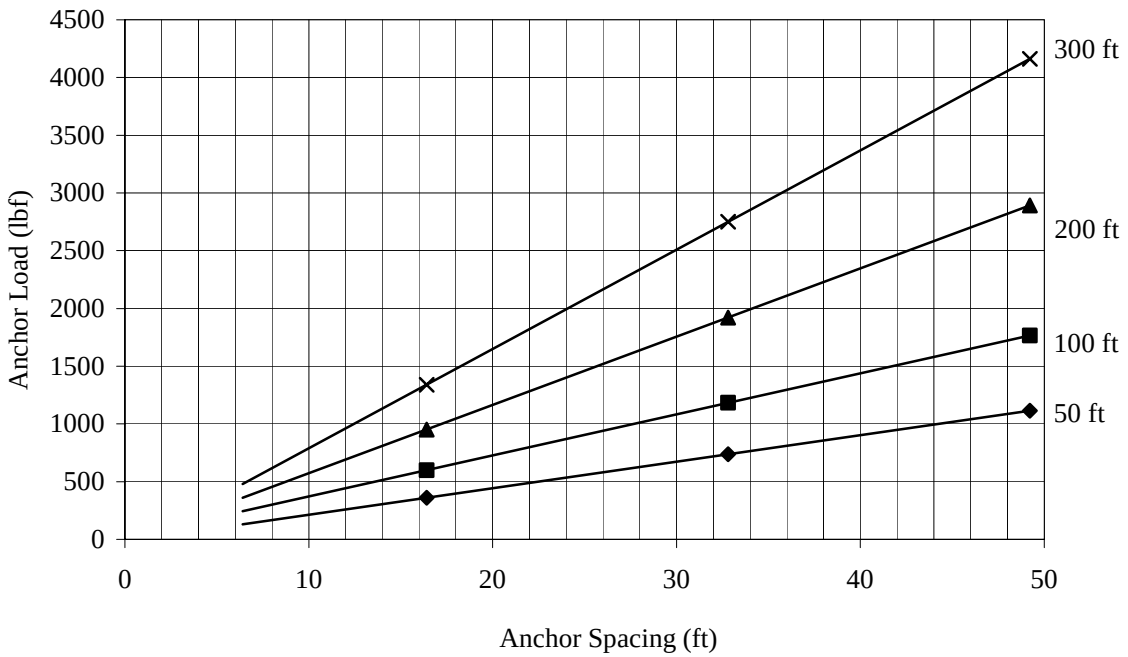


Figure A-16. Graph plots anchor load *v*. spacing for cable nets for an undulating, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

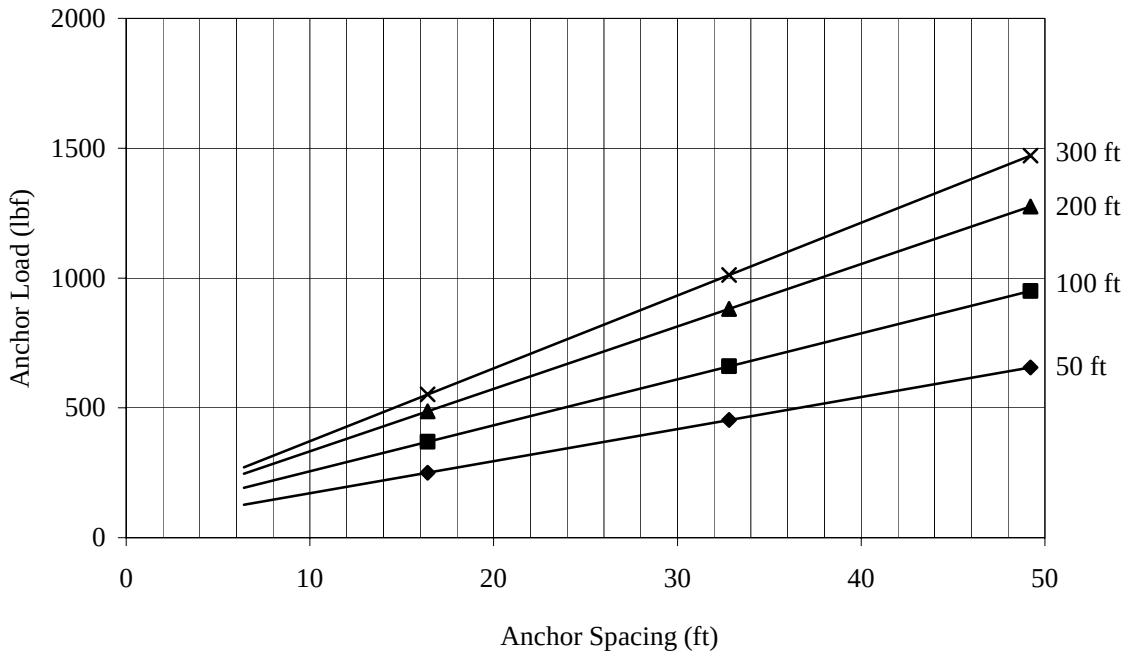


Figure A-17. Graph plots anchor load *v*. spacing for cable nets for a rough, 45° slope ranging in height from 50 to 300 ft (15 to 90 m).

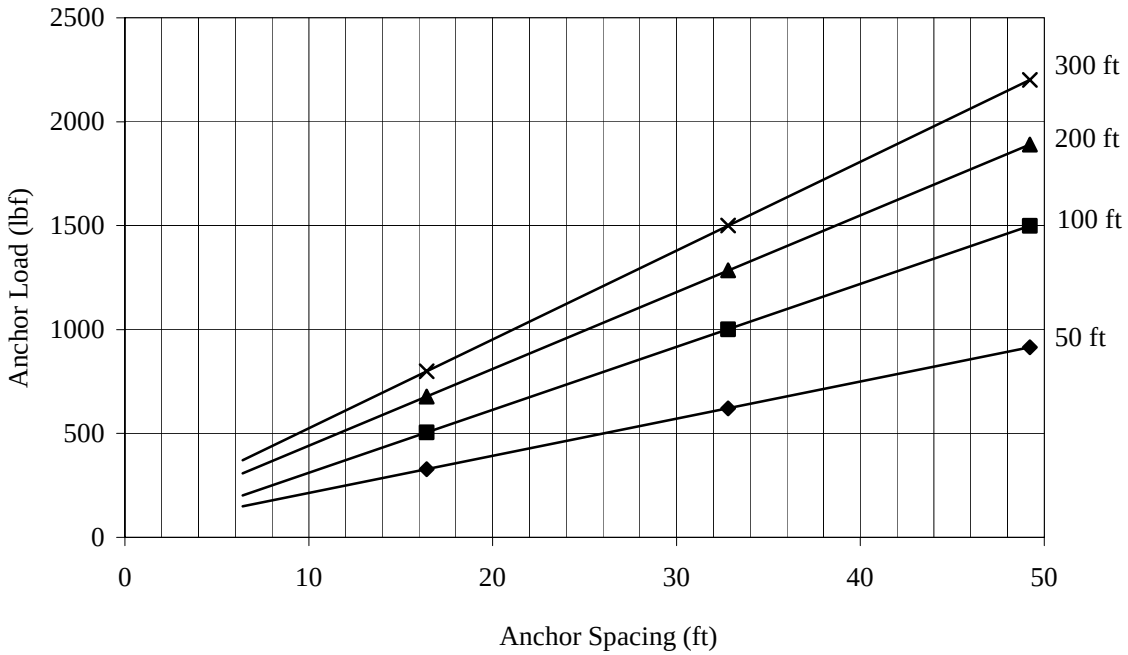


Figure A-18. Graph plots anchor load *v*. spacing for cable nets for a rough, 60° slope ranging in height from 50 to 300 ft (15 to 90 m).

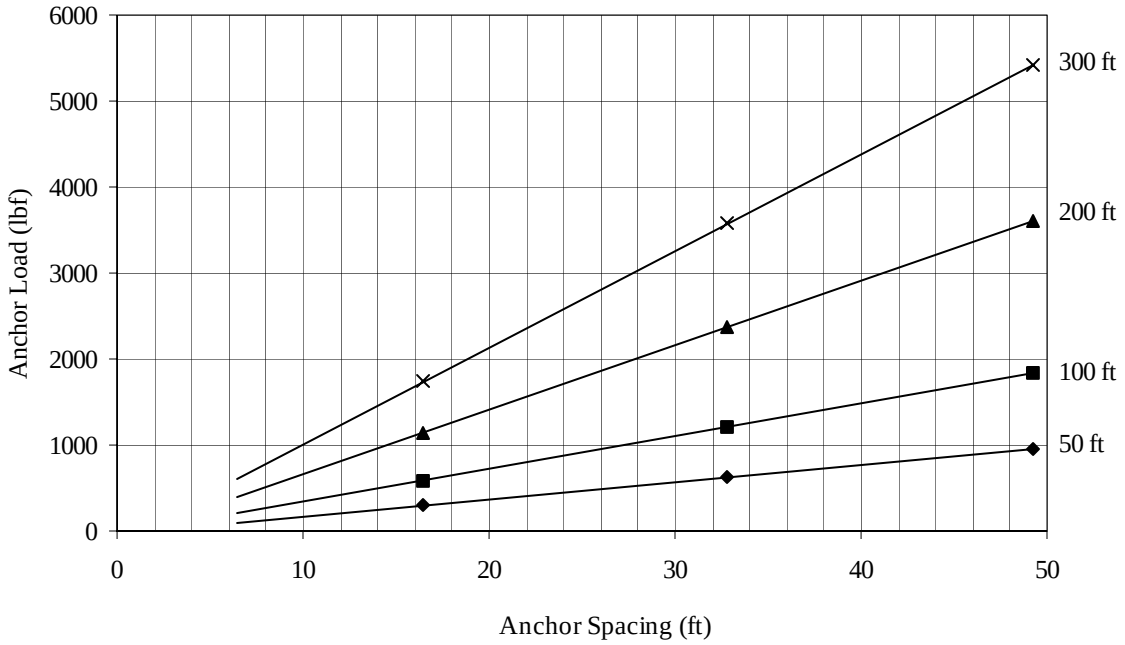


Figure A-19. Anchor load *v*. spacing for double-twisted hexagonal wire mesh for a vertical slope (no interface friction) ranging in height from 50 to 300 ft (15 to 90 m).

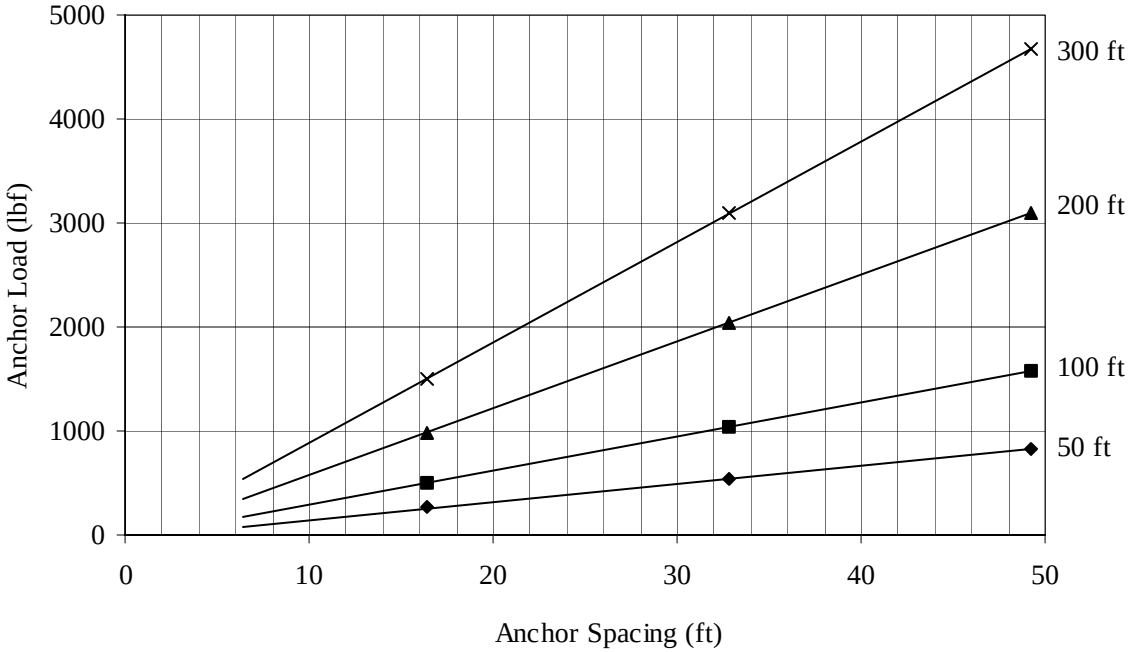


Figure A-20. Anchor load *v*. spacing for TECCO® G65 mesh for a vertical slope (no interface friction) ranging in height from 50 to 300 ft (15 to 90 m).

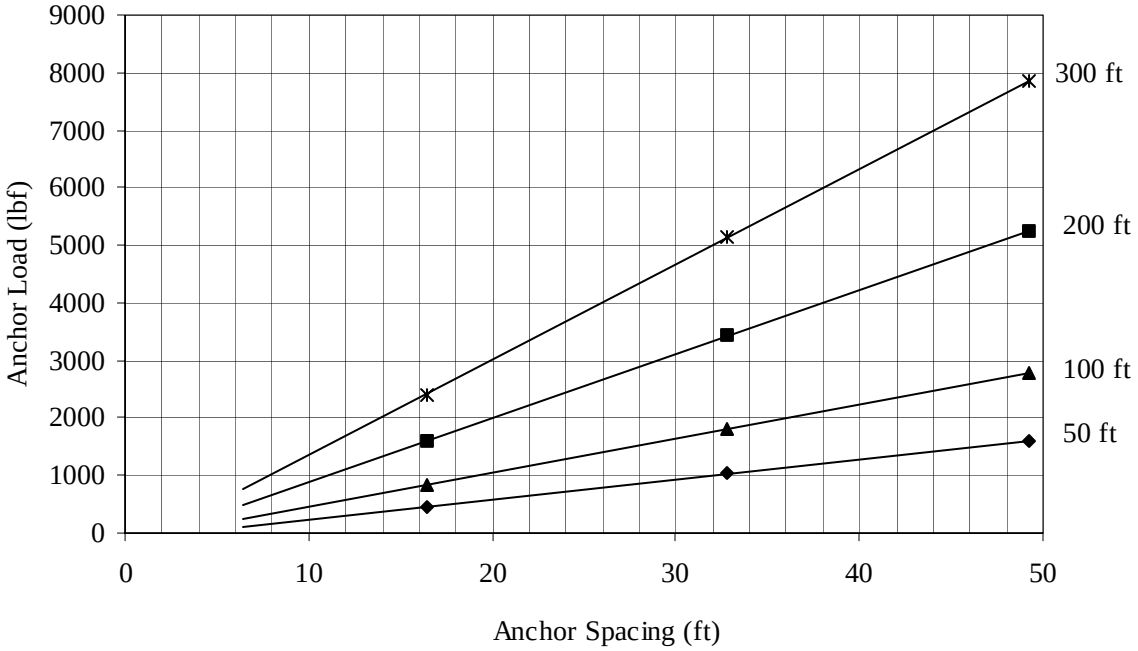
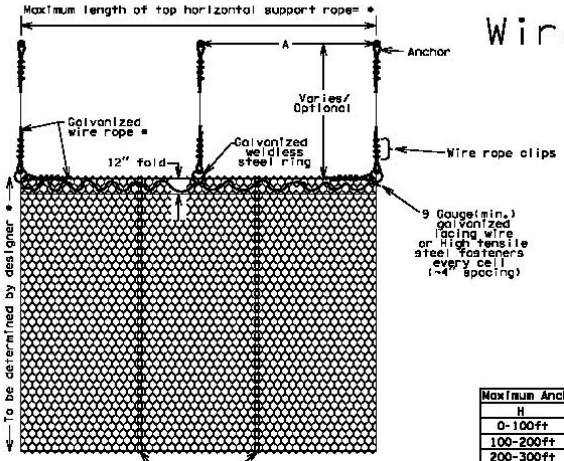


Figure A-21. Anchor load *v*. spacing for cable nets for a vertical slope (no interface friction) ranging in height from 50 to 300 ft (15 to 90 m).

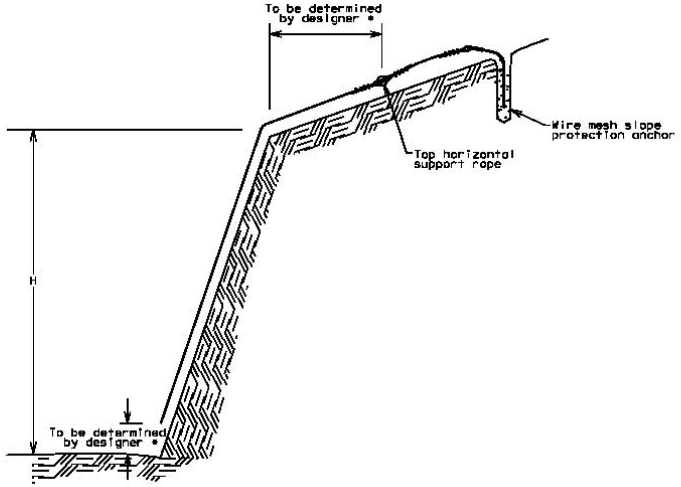
APPENDIX B

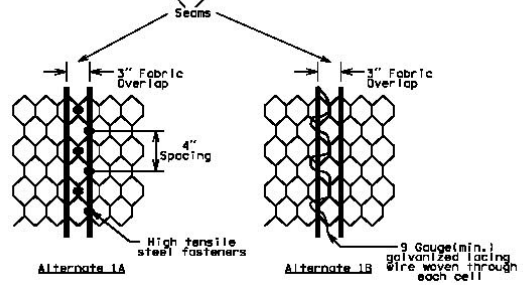
PLAN SHEETS

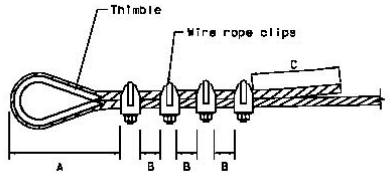
Wire Mesh Slope Protection



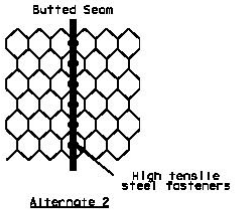
Maximum Anchor Spacing	
H	A
0-100ft	50ft
100-200ft	35ft
200-300ft	20ft







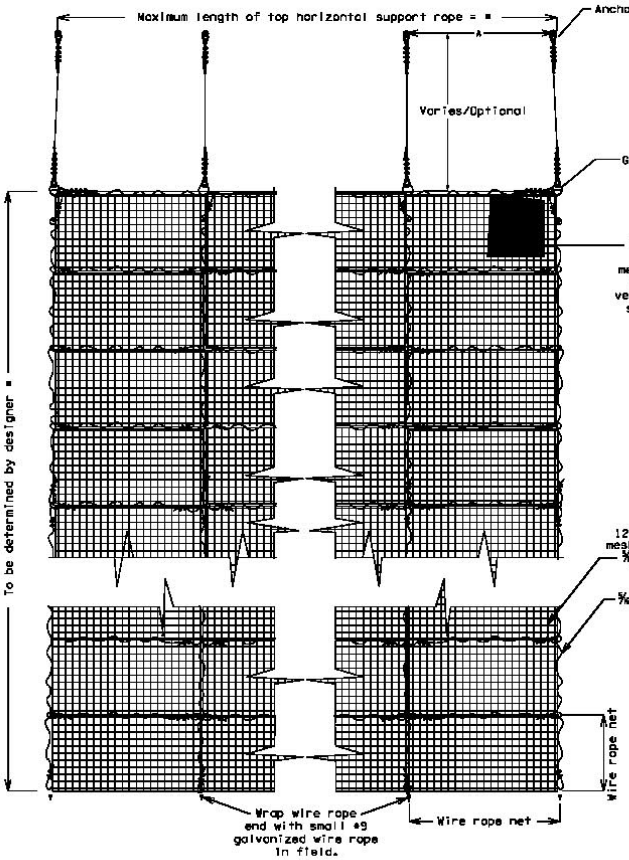
Distances A,B,C and torque to comply with manufacturer's specifications



NOTES

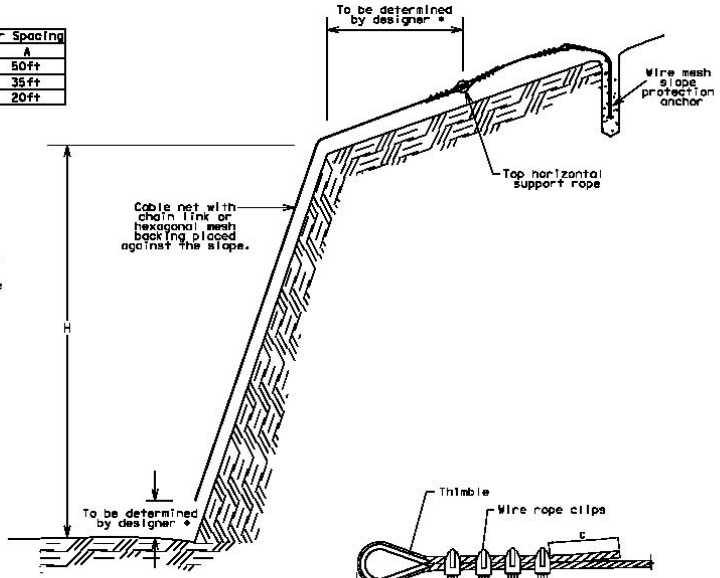
1. Maximum anchor spacing (A) for debris and impact loads required as per table for a minimum allowable anchor capacity of 20,000lbf. Systems subjected to snow loads may require narrower maximum spacing.
2. * See chapter 7 design guidelines.

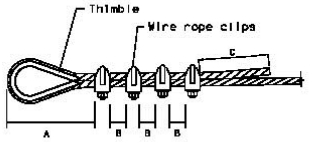
Cable Net Slope Protection



FRONT SLOPE ELEVATION

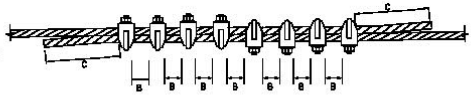
Maximum Anchor Spacing	
H	A
0-100ft	50ft
100-200ft	35ft
200-300ft	20ft





WIRE ROPE DETAIL "AA"

Distances A,B,C and torque to comply with manufacturer's specifications



WIRE ROPE DETAIL "BB"

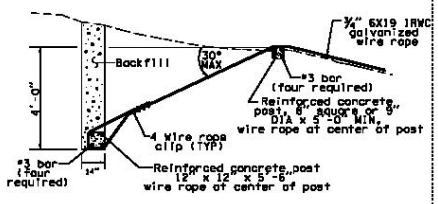
WIRE ROPE SPLICING

NOTES

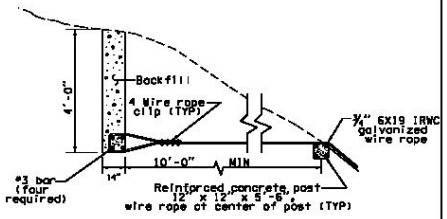
1. Maximum anchor spacing (A) for debris and impact loads required as per table for a minimum allowable anchor capacity of 20,000lbf. Systems subjected to snow loads may require narrower maximum spacing.
2. Net to be seamed with 5/16" wire ropes through each square of net.
3. Ends of seam ropes are to be terminated with (2) 5/16" wire rope clips.
4. Chain link or hexagonal mesh backing must be fastened to the cable net prior to placement on the slope.
5. * See chapter 7 design guidelines.

Wire Mesh/Cable Net Anchors

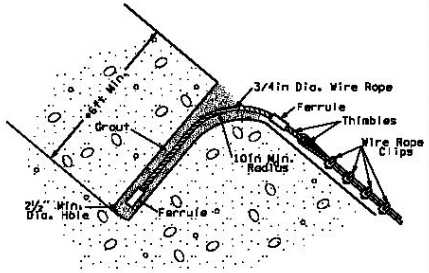
Soil Anchor Details



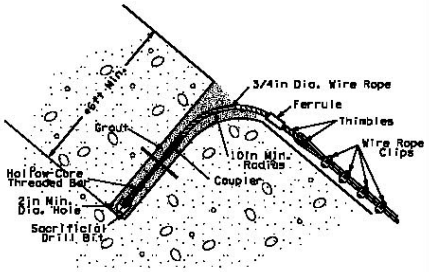
Deadman Type 1
(for use in soil)



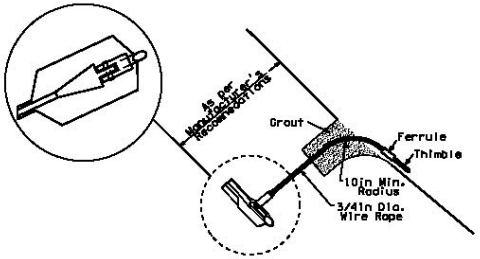
Deadman Type 2
(for use in soil)



¾" Wire Rope
(for use in soil)



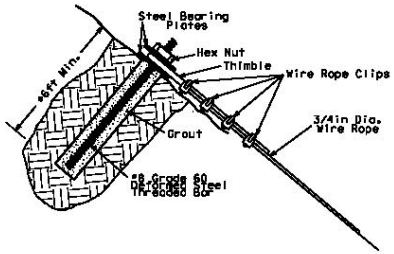
Drillable-Groutable
(for use in soil)



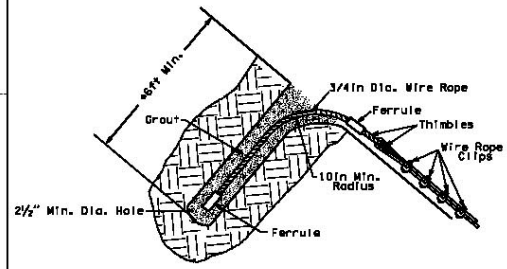
Manta Ray®
(for use in soil)

* Suggested minumum depth

Rock Anchor Details



Deformed Steel Threaded Bar
(for use in rock)



¾" Wire Rope
(for use in rock)

* Suggested minumum depth