

SLOPE FACE STABILIZATION FOR CRITICAL SLOPE SURFACES

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ABSTRACT

Advancements in erosion and sediment control technology have produced new and improved products, which have fostered innovative techniques for critical slope face stabilization. This paper reviews various slope stabilization techniques to address critical slope surfaces related to roadway construction. Emphasis is given to showing details and describing the different products utilized in various slope treatments while evaluating their effectiveness and cost. In the fall and winter of 1997-98, the El Niño rains in Northern California yielded at least 150% of the natural rainfall of a normal winter season. These conditions provided a rigorous test of the effectiveness of implemented slope stabilization construction techniques.

In particular, this report examines Geosynthetic Stabilized Embankments (GSE) and their resulting slope surfaces. GSE embankments are commonly used for over steepened slopes when a site presents limited right of way and construction constraints. GSE embankments have steep slope face surfaces that present challenges in the design of functional and effective slope stabilization measures. Also, an effective technique for stabilizing critical excavation slopes will be reviewed and illustrated. Given these challenges, standard conventional methods of erosion control are often insufficient. By using well-established Biotechnical Slope Protection principles in conjunction with improved erosion control products, erosion control and slope surface stability can be significantly enhanced.

KEYWORDS: slope protection; erosion control

1. SLOPE STABILITY AND EROSION CONTROL

Slope stability can be generally described as the inherent structural integrity of a slope to resist failure. Failure can occur as slides, cracks and slope movement. Erosion control is intended to provide surface slope stability to protect the face of the slope and to strengthen portions of the slope below the surface by interlocking soil particles with a complex matrix of roots. There are differences between stabilization and erosion control. The two principles have separate influence on slope integrity and should be treated individually when designing embankment slopes and recommending appropriate erosion control measures.

Slope stability, or the lack thereof, rests upon the ability of a slope to resist stress excess to what is normally acceptable for the material property of the soil or rock inherent to the construction slope. Slope movements, such as translational or rotational slope failures occur when sheer stress exceeds sheer strength of the materials forming the slope (Gray and Leiser 1982). Factors contributing to high sheer stress include: lack of lateral support, excessive surcharges, lateral pressures and removal of underlying support. On the other hand, low sheer strength, due to inherently weak materials, soil weathering (swelling, shirking and cracking) and low intergranular force due to seepage pressure, also contributes to slope instability.

Factors of safety are generally used in evaluating slope stability. The factor of safety can be defined as the ratio of the total force available to resist sliding to the total force tending to induce sliding. A stable slope is considered to be in a condition where the resisting forces are greater than the disturbing forces. Conversely, an unstable slope failure situation exists when resisting and disturbing forces are equal and the factor of safety equals $F=1$. A Limit Equilibrium condition exists when the forces tending to induce sliding are exactly balanced by those resisting sliding (Hoek and Bray, 1981).

What is important to note is that the factor of safety can be increased by modifying resisting factors, such as tension, to counteract disturbing forces. These factors include increasing and promoting free slope drainage and installing other mechanical materials to increase resistance to movement.

A thorough geotechnical assessment must be done in order to determine erosion control concerns and subsequent treatments. Only after slope stability factors and the probability for slope failure have been addressed can appropriate surface stabilization requirements be identified.

2. CRITICAL SLOPE SURFACES

A critical slope surface exists when a combination of soil and slope factors create a high potential for slope face failure and subsequent erosion. Over-steepened freshly graded or disturbed slopes are considered critical when resistance to surface erosion is low and sheer and strength resistance tolerances are exceeded. The potential for slope face failure of the slope can compound with inadequate slope face compaction under super saturated conditions. In such cases, soil movements are influenced by numerous parameters including, but not limited to, angle of repose, soil structure, slope length and erodibility. A quick look at embankment construction techniques and constraints will provide a basis for examining factors that influence slope stability.

Traditionally, embankment slopes constructed at gradients 1(Vertical): 2(Horizontal) and flatter can be built and compacted using common construction equipment. Generally, engineered embankment slopes are constructed in 203 millimeters (8 inch) layers. Each layer is compacted to a relative compaction of 90%. When constructing an embankment on existing hillsides, the existing hillside slopes are cut into a minimum of 2.73 meters (6.5 feet horizontal) as the embankment is brought up in layers. The cut into the existing hillside provides a way for 'keying' (bonding) the new embankment with the existing hillside. The slope face of a 1:2 embankment slope can be compacted by using common track laying equipment running up and down perpendicular to the slope contours. Water can be used to assist in promoting relative compaction. Due to the need to have a good growth medium at the slope face, it is not uncommon to require the placement of 'select material', material derived from the work area that has the

qualities of topsoil, at the outer portions of the embankment. Imported topsoil can be used in lieu of select material, but may be costly and only justifiable in cases that would warrant such use.

For simplicity, this paper will address common embankment slope construction gradients of 1:2, 1:1.5 and 1:1 (V:H typical) and steeper.

When working in tight areas or in wildland areas with steep terrain, embankment construction can be difficult due to limited access and room. Additionally, there may be sensitive habitat contiguous to the work area that cannot be impacted. In such cases, the use of geogrid reinforcement can be used to provide internal and external stability to allow construction of slope gradients up to 1.5:1 and greater. When slope face gradients exceed 1:2, common track laying equipment may not be appropriate for compacting the slope face due to safety issues. A sheepsfoot roller connected to a winch can be used to compact the slope face. However, the cost and feasibility may not make the use of a specialized piece of compaction equipment feasible.

2.1 Geosynthetic Stabilized Embankments (GSE)

Technological advancements in the field of embankment slope construction have fostered the use of plastic geogrids to increase slope stability. Generally, the use of geogrids allows the construction of embankments with steep slope face gradients 1:2 and steeper. With the steepening of the slope face, the erosion potential of the slope increases due to an over steepened condition that poses difficulty when compacting the slope face material. Wrapping of the slope face is always recommended when the slope angle exceeds 34 degrees. However, wrapping of the face should also be considered at lower slope gradients (26-34 degrees) when factors such as compaction constraints, steep angle of repose, soil structure of the backfill material and environmental setting necessitate slope stabilization measures in situations where erosion and pollution potential is high.

Failures of the slope face on earlier installations of GSE embankments due to super saturation and erosion at the slope face have identified a need to investigate new methods of attaining slope face stability without compromising the integrity and design of the geogrid stabilized embankments. The slope face erosion control treatment must be compatible with construction operations, practical and relatively non-labor intensive. The treatment should strive to avoid using specialty equipment and instead, use readily available construction equipment, materials and techniques to facilitate accurate assessment of the work during the bidding process and installation.

Generally, the construction application requires netting as a slope facing wrap. The netting is placed in conjunction with the installation of the primary geogrids. At the placement of the first primary geogrid, 0.6m (2 ft. vertical), the coir netting is laid down at the face of the slope overlapping the geogrid a minimum of 0.9 meters (3 feet). At the back of the embedment, plastic pipe is laid down longitudinally at the edge of the netting and secured with rebar anchors spaced 1.2 meters (4 feet) apart. The pipe and anchors are installed at the back of the netting to secure it in place and to provide bonding with the geogrid. This connection is important because the coir netting resistance to pullout is enhanced by the resistance of the geogrid that is installed the full depth of the fill. With the placement of every other primary geogrid thereafter, the netting is wrapped back over completed portions of the slope face approx. 1.9m (6.4 ft.) (slope measurements) and embedded with the primary geogrid prior to the construction of the next sections of geogrid and so on (Figure1). Steel staples 1.5 cm (6 in.) in length with a 25.4 mm (1 in.) crown are installed throughout the face of the netting in a staggered grid pattern 1.2 m (4 ft.) apart longitudinally and 1.8 m (6 ft.) apart vertically. This stapling provides additional anchoring of the netting to the slope surface. Upon completion of the embankment, the 'wrapped' slope face is hydroseeded to establish a vegetative cover.

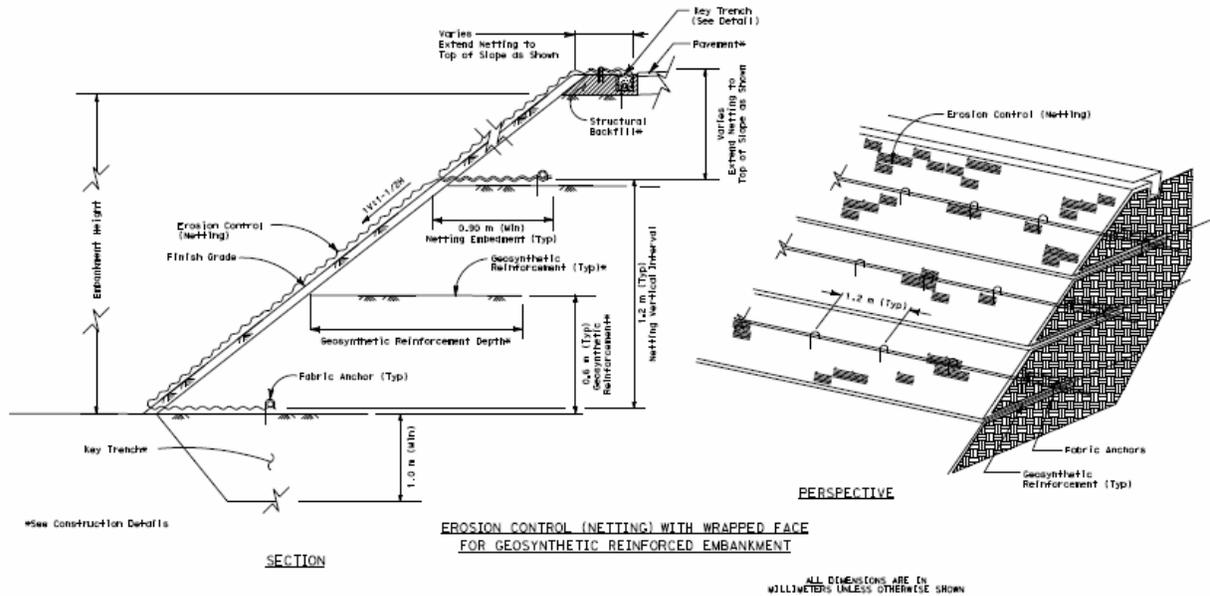


Figure 1.

Another very promising aspect of this technique is its ability to control erosion on portions of the embankment slope constructed but temporarily abandoned due to winter rains. Again, very little slumping of the slope surface occurred. Piping of the soil through openings in the netting face was minimal. This technique also significantly reduces the amount of temporary erosion control work necessary to cover and protect unfinished slopes. Unlike plastic covers, coir netting adheres to the slope surface when wet and will not detach under high winds. Essentially, the full or partial wrapping of embankment slopes with netting provides erosion control stabilization throughout the construction process.

2.2 Geotechnical Analysis of Wrapback (Wajahat Nyaz)

Surficial (or shallow) failures of fill slopes are caused by infiltration due to prolonged rainfall or uncontrolled runoff. These failures are mainly triggered by the deepening of the wetting band accompanied by a decrease in matric suction induced by the water infiltration. Additionally, if the fill soil has a significant amount of plastic clay material, cracking of surficial soils also increases the rate of moisture infiltration.

Calculations for surficial slope stability are performed assuming saturated condition. These calculations are based on analysis of stability for infinite slope seepage parallel to the slope surface or other failure mode that would yield the minimum factor-of-safety (SF) against failure. In California practice, the acceptable vertical depth of soil saturation is 1.2 meters (4 feet) and the minimum SF for surficial stability is 1.5. The soil shear strength parameters (cohesion and friction angle) used in surficial slope stability analysis should be representative of the surficial material and shall not exceed residual (ultimate) value. The GSE fill embankments are compacted to 90% relative compaction. Typically, the compacted material has an internal friction angle of 30 to 32 degrees, internal cohesion of 0 to 7.18 kilopascals (150 psf) and moist unit weight of 19.2 kiloneutons/cubic meter (120 pcf). The surficial 0.6 meters (2 feet) of embankment soil at the slope face generally have no internal cohesion due to poor compaction. Embankment soil at depth greater than 0.6M (2 feet) generally has an internal cohesion of at least 2.39 kilopascals (50 psf).

Geogrids can be used to increase surficial stability of slopes. However, to prevent erosion and sloughing of the soil between the geogrid layers, slope face confinement is often needed in slopes with inclination greater than 26 degrees (1V:2H). The wrapped face configuration can be effectively used to prevent minimize surface erosion and sloughing.

Typically, the surface erosion and sloughing in a reinforced slope is limited to the un-reinforced prism between the reinforcement (geogrid) layers at the slope face (Figure 2). To prevent this surface erosion and sloughing, the wrapped face must be anchored in stable ground to resist the earth and hydrostatic pressures that develops within this prism. Analysis of wrapback model (Figure 2) shows that the frictional resistance under full saturation condition is not sufficient to prevent instability (sloughing) of the un-reinforced prism. To prevent surface erosion and sloughing, the slope must be wrapped and the wrapping fabric (coir netting) must be anchored in stable ground to resist the earth and hydrostatic pressures that develop within the unstable prism. The coir netting exerts a force (pull) on the anchor and the anchor must be able to resist this force to prevent pullout of the coir netting.

Lateral analysis of the anchor shows that a 12.7 millimeter ($\frac{1}{2}$ inch) diameter, 457 millimeter (1.5 feet) long anchor as shown in Figure 1 and embedded in surficial soil, at depth greater than 0.6 meters (2 feet), can resist approximately 3.39 kiloneutons (763 lb) force with less than 25.4 millimeters (1 inch) of deflection (Figure 2a). The load deflection curves for the anchor are shown in Figure 2a. Deflection in excess of 25.4 millimeters (1 inch) is excessive and can lead to failure.

The analysis shows that the wrapped face system shown in Figure 1 is adequate for slopes up to 45 degrees (1:1). However, if the primary reinforcement (geogrid) vertical spacing is increased to 0.9 meters (3 feet), the anchor spacing must be reduced to 0.6 meters (2 feet) on center.

It is important to note that, although the soil is encapsulated within the wrap, surface protection in the form of vegetation is still required. It should also be noted that, over time, a geosynthetic wrapped face will tend to sag and slough because of the creep behavior of the polymer geosynthetic. Therefore, to decrease the significance of the sagging of the face of the wrap, it is important to restore the vegetative cover on the face of the slope as quickly as possible. When the inclination of a slope is significantly steeper at or greater than 45 degrees (1V:1H) and/or vegetation is difficult to establish, a more permanent rigidly formed face confinement system, such as formed welded-wire-fabric facing, is necessary.

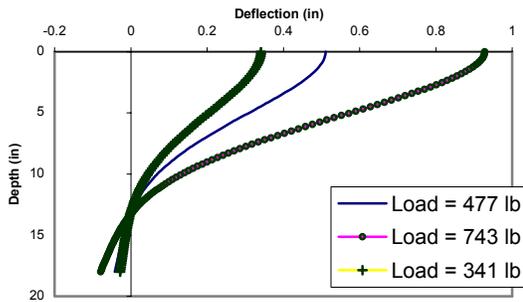
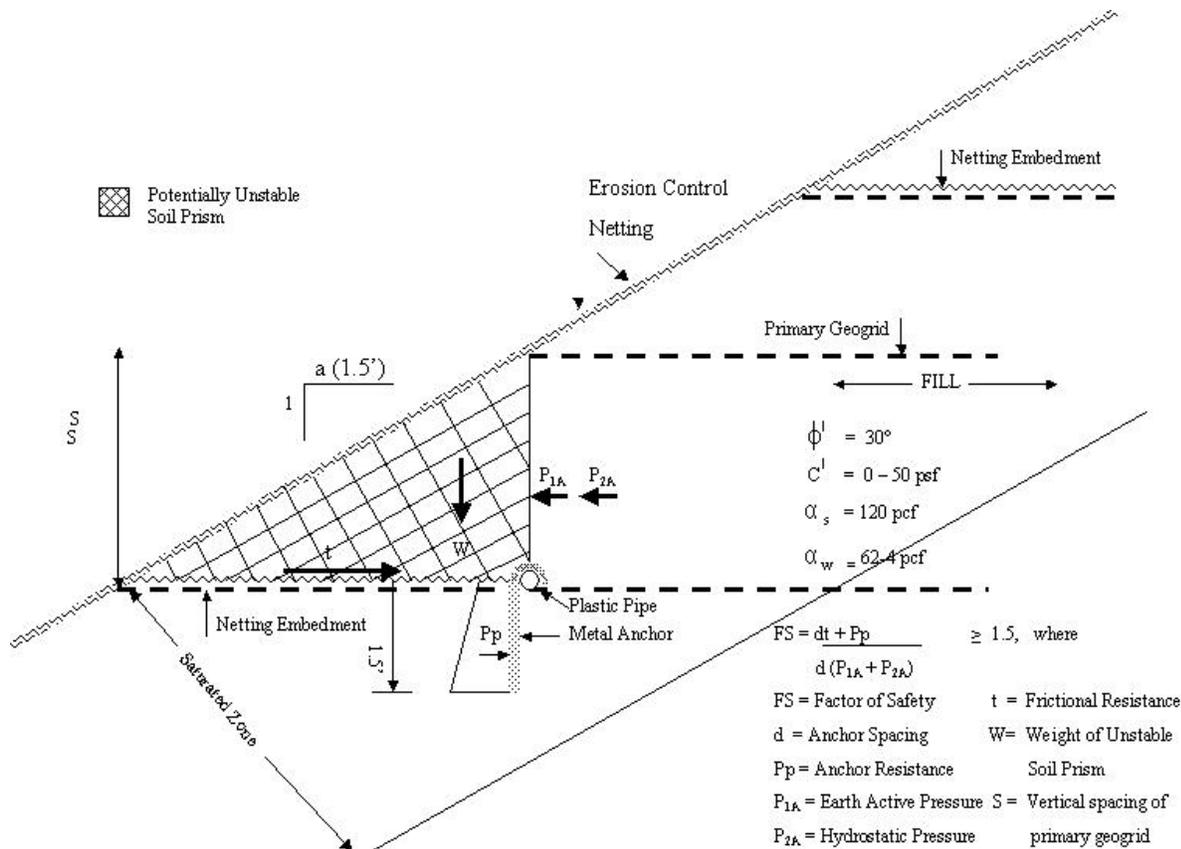


Figure 2a. Anchor Load Deflection Curves

2.3 Wrapback Installations

The District began using the wrapback reinforced embankment design in 1997-98 (Figures 3, 3A & 3B). Since then, many other installations have occurred. During early installations of this new stabilization technique, each contractor experienced a bit of difficulty at the beginning of construction due to their lack of familiarity with the new technique. However, they quickly adapted to working with the netting by using slope boards and small forms to maintain the finish gradient. By the time the slopes were midway through construction, the contractors were able to dispense the forms and construct the face of the slope close to the contract finish grade.



Figure 3. Completed 1:1.5 Wrapback constructed slope



Figure 3A. Wrapback slope with drainage down drain



Figure 3B. Natural colonization of adjacent vegetation. 1:1.5 (H:V) Slope face gradient. 04-Son-01 May 1998

At both locations on the Sonoma coast along Highway 1, severe winter rains temporarily halted construction on portions of the embankments (Figures 4,4A). Both sites showed little erosion or slumping of the face. Piping of material at the grid opening in the netting was minimal. The contractor was able to quickly cover exposed portions of the embankment at the perimeter of construction prior to anticipated rain and easily begin construction once the rains halted. This is one of the prime benefits of a wrapback face design. The slope face is essentially stabilized and protected as the embankment is constructed. If foul weather is imminent, deployment of weatherizing material can be implemented quickly. The final product is a stable and aesthetically pleasing slope that is compatible with its natural surroundings and capable of sustaining vegetative growth.



Figure 4. Wrapped face installation in conjunction with GSE embankment construction. 1:1.5 (H:V) Slope face gradient.

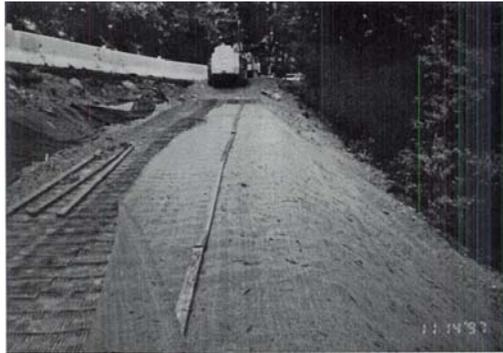


Figure 4A. Wrapped face construction abandoned due to wet grade. 1:1.5 (H:V) Slope face gradient.

A decade later, the wrapped face embankment techniques described herein have been highly successful in controlling erosion and establishing vegetative growth. There has been no noticeable slumping or deflection of the slope.

3. Other Techniques For Stabilizing Critical Slope Face Surface

Often, there is a need to stabilize excavation slopes that are over steepened. The over steepened condition creates issues with both slope stability and potential erosion. Again, standard erosion control treatments are not suitable to mitigate the threat of both surficial slope failure and erosion. The District has developed an Erosion Control (Type B) Technique that has proven to be reliable and effective. Erosion Control (Type B) combines mechanical and vegetative treatments using commonly available materials that are easily installed (Figures 5,5A & 5B).

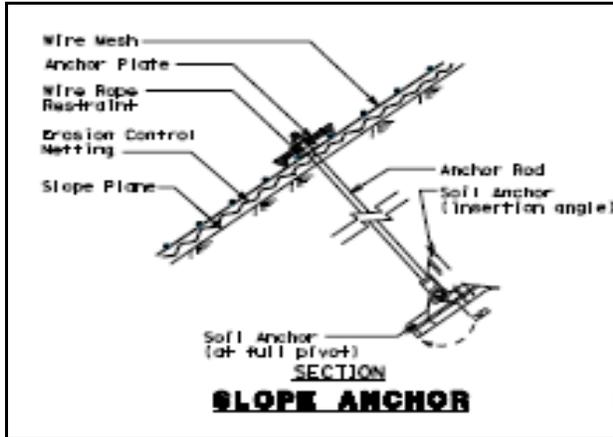


Figure 5, Erosion Control (Type B)

Figure 5A, Anchor plate over wire mesh



Figure 5B, Fully vegetated 1.5:1 Slope – Erosion Control (Type B)

3.1 Erosion Control (Type B)

Erosion Control (Type B) involves the installation of biodegradable coir netting and welded wire mesh that are anchored in place with slope anchors and anchoring plates. Hydroseeding of a slurry of fiber, seed, and fertilizer is applied as a final treatment to provide vegetation.

3.1.1 Biodegradable Netting

A biodegradable netting consisting of coir is used as a resilient, high tensile strength textile to cover bare construction slopes with slope face gradients varying from 1:1.5 and steeper. Twisted coir is chosen for its organic biodegradable properties, high tensile strength when wet, long life and effectiveness as a cover conducive to plant growth. Coir provides effective source cover with a high tensile strength capable of retaining saturated soils in the top prism of the slope surface. The coir product chosen has a tight weave of braided coir strands with a uniform grid opening of approximately 19 millimeters (3/4 inch). The coir netting has approximately 63-70% open area and is rated to have a life of at least 4-6 years. This is sufficient time to establish permanent vegetation and supplemental planting (if needed). The 63-70% opening is very conducive to hydroseeding applications. Seed is able to make it through the openings. A 50% opening was found to be too small and did not perform as well in establishing vegetation.

3.1.2 Welded Wire Mesh

Welded wire mesh is used over the coir netting. The wire mesh is proven to resist slumping material when anchored. In difficult slope conditions, coir netting alone held in place with staples is not effective at holding back saturated material. The wire mesh provides effective mechanical support while allowing the coir netting to control surface erosion. The wire mesh has a nominal opening of 0.078 millimeters (2-inch) x 0.15 millimeters (4-inch). Adjoining sections of wire are laced together with 10-gage wire. The wire mesh provides initial support and allows vegetation to develop over several years.

3.1.3 Slope Anchor and Plates

A Slope Anchor is a ductile iron or aluminum anchor designed to pivot once embedded into the ground and then stressed vertically. The maximum pivot below the ground surface achieves holding capacity and pull out resistance. A threaded anchor rod 12.7 millimeters (1/2 inch) diameter 762 millimeters (30 inch) in length is connected to the pivoting anchor.

Anchor plates can be either metal treated with a corrosion resistant coating or hardened polyethylene. The plate center has an opening to pass the anchor rod through the plate. Once the plate is placed, a washer and nut are installed to stress the plate against the wire and coir netting.

3.1.4 Vegetative Erosion Control

The other element of the erosion control treatment is a hydroseed application consisting of a slurry of water, fiber, sterile seed, fertilizer, and stabilizing emulsion applied over the netting face. The materials are applied at close range so that the slurry is well integrated into the netting face and soil surface below. Any portions of the netting displaced as a result of the hydroseeding application are repaired and anchored.

The erosion control mix generally uses native grass species in combination with a sterile cereal grain such as Briggs barley, Re-green (triticum) or California red oats. Cereal grains are effective at providing a quick cover. They germinate readily and can grow on shallow and soils with low nutrient value. Sterile cereal grains are proven in their ability to provide fast cover without becoming perpetuating pests. This is especially desirable in wildland areas where revegetation is likely to occur through natural colonization, and where there are concerns about introducing exotic plant material into a predominantly native plant community. Fiber and stabilizing emulsion are included to provide additional tackified mulch as a buffer and cover for the seed while also filling in open areas between grid openings in the netting.

Erosion Control (Type B) has proven to be effective in stabilizing steep slopes 1(V) : 1.5(H) and steeper. The use of coir netting instead of erosion control blanket allows erosion control materials to be applied as the last treatment. When using erosion control blankets, the erosion control hydroseed treatment must be applied first on the ground surface prior to the placement of the blanket material. Often, due to steep slope conditions, much of the erosion control materials is displaced, migrates and is covered during placement and anchoring of the blanket material. This results in spotty vegetative growth. The use of coir netting allows the mechanical erosion control treatment to be installed first and the

hydroseeding to occur when scheduling permits. This is a distinct advantage when stabilizing disturbed slopes at the earliest opportunity given that a general contractor can install the mechanical erosion control materials and then call in the hydroseeding contractor at a later date.

3.1.5 Embankment Confinement System

As discussed earlier, the wrapback stabilization of the slope face is appropriate for slope gradients from 34-44 degrees. However, there are instances where embankment construction may be required with slope gradients steeper than 44 degrees (1:1). Given the limitations with the wrapback technique, a stiffer confinement system that is conducive to re-vegetation is needed to accommodate slope gradients from 45-60 degrees. In such cases, an Embankment Confinement System (ECS) has been used successfully. The ECS is essentially a double twisted wire mesh containment system with an articulating front face that can be set to a desired angle (Figure 6). The bottom portion of the containment system can run the full depth of the embankment at each layer providing the same function as a geogrid. Select material is used at the face of the ECS to provide a medium for growth. Coir netting is placed inside the basket face to prevent piping of the soil through the face. The netting also allows hydroseeding through the face of the ECS. For revegetation purposes, a 60 degree incline is about the maximum slope face angle conducive to revegetation (Figures 6, 6A).

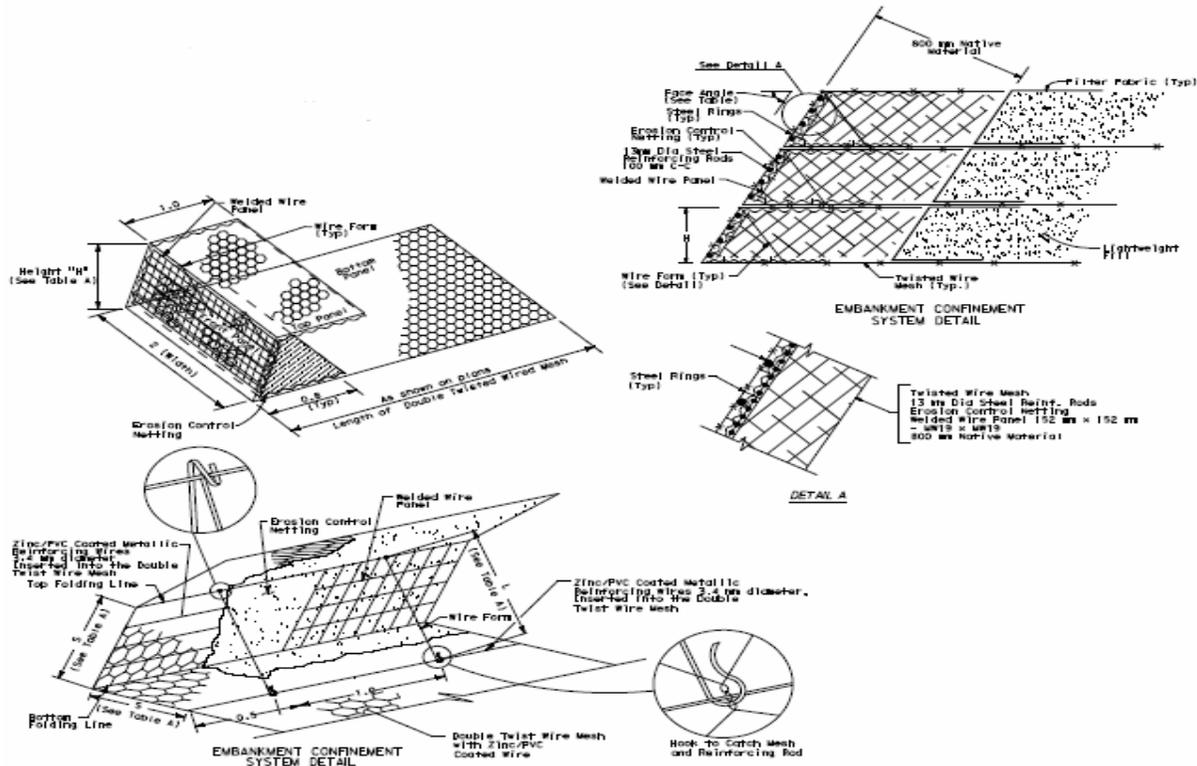


Figure 6.



Figure 6A, Fully Vegetated ECS



Figure 6B, View of twisted wire mesh and netting with vegetation

4. FUTURE IMPROVEMENTS AND ALTERNATIVES

Results suggest that the technique of combining both mechanical and vegetative erosion control treatments to stabilize critical slope surfaces is sound and practical. Familiarity with installations such as the wrapback technique should result in lower installation costs. At present, there are very few erosion control blankets that are 100% organic and biodegradable with the tensile strength comparable to coir netting. Also, the amount of open areas in the blanket and blanket thickness impedes the contact of hydroseeded materials with the soil surface. Twisted Coir netting works very well with a hydroseed application. With a high tensile strength, variable open area and being completely biodegradable, coir netting is an effective and dependable erosion control revetment. One drawback is that a nominal 3.96 meter (13 foot) long roll, which is ideal for the wrapback application for 0.6 meters (2 foot) vertically spaced geogrids (1:1.5 slope), is heavy and difficult to maneuver. Polypropylene or polyamide Turf Reinforcement Mats (TRM) may be suitable for use as a wrapping revetment in lieu of coir netting. However, due to the thickness of the material and narrow openings, there may be problems with establishing vegetation if hydroseeding is applied and expected to penetrate the mat.

Slope anchor and plate research should strive to develop strong lightweight materials that are resistant to corrosion that can easily be installed and tensioned on steep slopes. Also, anchors and plates of different sizes and shapes with the ability to connect with each other may enhance soil stability.

5. COMPARABLE CONSTRUCTION COSTS

The cost for wrapped face slope surface protection averaged \$7.20 M2 for a project in Sonoma County with 1,240 M2 of erosion control (netting). The high price was \$9.50 M2 and the low was \$4.00 M2. On a project in Santa Clara County with 900 M2 of erosion control (netting) and the same wrapping detail, the high item cost was \$19.00 M2 and low \$12.00 M2 with an average unit cost of \$14.00 M2. The Engineer's estimate was \$10.00 M2 on both projects.

Comparatively, conventional installations of erosion control blanket projects with approximately 1,000 M2 averaged between \$11.00 to \$15.00 M2. Conventional installations of erosion control (netting) averages around \$26-27.00 M2. The installation of erosion control blankets requires a more traditional technique, placing the blanket over the face of the slope perpendicular to the slope contours.

The average cost for an Embankment Confinement System (ECS) was \$110.00 M2 for a project in San Mateo County with 2,120 M2 of ECS. The price includes the placement of the ECS and backfill.

On face value, the wrapped face technique appears to be much more expensive. However,

considering the purpose of the wrapping technique as both an enhancement to slope stability and compensation for inadequate compaction, the wrapping technique serves multiple purposes beyond erosion control alone. Wrapping the face also reduces the need for difficult and costly slope face compaction operations and can reduce temporary slope stabilization measures for unfinished slopes.

6. CONCLUSION

The concept for wrapped face slope stabilization is not new and has been promoted by many companies in the geosynthetic stabilized earth industry. It is a sound and proven technique that is improved through the use of new erosion control products currently available in the market place. Hybrid or modified designs will be forthcoming as designers find that enhancing erosion control through effective anchoring techniques is justified and, in fact, crucial to successful slope stabilization for critical slope surfaces.

Interdisciplinary communication will ensure that new technology addresses multiple needs. Continued research into improving existing products and technological advances in recycled products will create more alternatives available to designers searching for solutions to challenging erosion control problems.

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