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Vegetated reinforced soil slopes

R.B. SOTIR, Principal, Robbin B. Sotir & Associates, Inc., Atlanta, USA
B.R. CHRISTOPHER, Geotechnical Engineering Consultant, Christopher Consultants, Atlanta, USA
J.W. COWLAND, Geotechnical Engineering Consultant, Hong Kong, China

ABSTRACT: Several soil bioengineering techniques use woody living vegetation purposely arranged and imbedded in the ground to prevent shallow mass movement and surficial erosion. Combining specific soil bioengineering vegetative techniques with geosynthetic reinforcement to form a composite vegetated reinforced soil slope (VRSS) system can produce a very durable, low maintenance structure with exceptional aesthetic and environmental qualities. This paper describes the use of soil bioengineering vegetative systems in conjunction with geosynthetic reinforcement along with geocomposite drains and erosion control fabrics to provide an economical and ecological method for safely constructing steep (up to seventy degree) slopes. Basic principles of soil bioengineering and the associated benefits of vegetation are presented. Pre- and post-construction conditions, environmental and aesthetic benefits, vegetation selection and design considerations are discussed. Selection requirements and design for geosynthetic reinforcement, geosynthetic drainage layers and erosion control materials, in relation to their compatibility with vegetation, are presented.

1 INTRODUCTION

Reinforced soil slope systems are often cost effective alternatives for new construction where the cost of fill, right-of-way and other considerations make a steep slope, up to 70 degrees, desirable. The conventional use of grass-type vegetation for the facing of these systems is often problematic and in some cases prone to significant maintenance.

An alternative is the use of soil bioengineering methods to establish hardier, woody-type vegetation in the face of the slope. Soil bioengineering uses living vegetation purposely arranged and imbedded in the ground to prevent shallow mass movement and surficial erosion. However, the use of woody vegetation alone is limited to stable slope masses. Combining this system with geosynthetic reinforcement produces a very durable, low-maintenance soil bioengineering structure with exceptional aesthetic and environmental qualities.

2 REINFORCED SLOPE SYSTEMS

Reinforced soil slope (RSS) systems incorporate geosynthetic reinforcements arranged in horizontal planes in the backfill to resist outward movement of the reinforced fill mass so that stable steepened slopes on the order of 45 to 70 degrees can be safely constructed (See Figure 1). RSS systems may prove a cost effective alternative for new construction where the cost of fill, right-of-way and other considerations that make a steepened slope desirable. They also provide a means of improving the safety of unstable slopes.

Slope facing requirements will depend on soil type, slope angle and reinforcement spacing. Often the slope face (outer slope profile or surface) requires wrapping to prevent sloughing and erosion. A facing wrap may not be required for slopes up to 1H:1V if the reinforcement is maintained at close spacing (i.e. every lift or every other lift, but no greater than 400 mm) and is extended to the face (Holtz et al, 1997). Additional treatments may be required on the face to shade the geosynthetic and prevent ultraviolet light exposure that may degrade the geosynthetic over time. Additional treatments are necessary to prevent unraveling and sloughing of the unwrapped soil exposed face. In either case, conventional vegetated facing treatments generally rely on grass-type vegetation, and occasionally with more costly flexible armor where vegetation cannot be established.

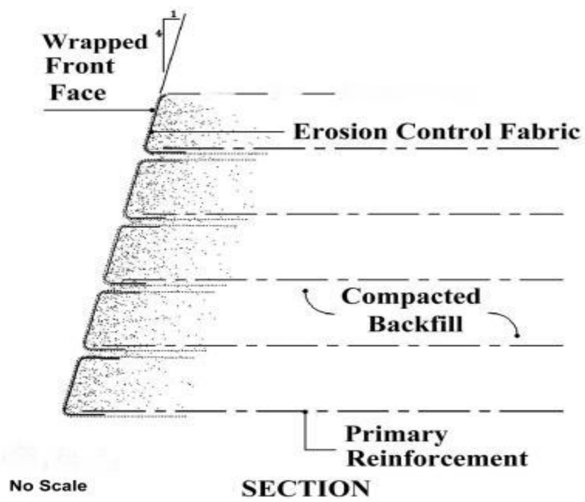

Figure 1. Reinforced soil slope system.

A synthetic (permanent) erosion control mat is normally used to improve the performance of grass cover. This mat must also be stabilized against ultraviolet light and should be inert to naturally occurring, soil-born chemicals and bacteria. The erosion control mat serves to: 1) protect the bare soil face against erosion until the vegetation is established; 2) assist in reducing runoff velocity for increased water absorption by the soil, thus promoting long-term survival of the vegetative cover; and 3) reinforce the surficial root system of the vegetative cover. Geosynthetic reinforced slopes can be difficult sites to establish and maintain grass type vegetative cover due to the steep grades and high slopes that can be achieved. The steepness of the grade limits the amount of water absorbed by the soil before runoff occurs. Due to tractive forces and velocities along waterways, grass is often an ineffective solution. Once vegetation is established on the face, it must be protected to ensure long-term survival. Considering this, it is imperative that slope protection is not left to the construction contractor's or product sales company's discretion.

Maintenance issues, such as mowing, must be carefully considered. The shorter, weaker root structures of most grasses may not provide adequate reinforcement and erosion protection. Grass is highly susceptible to fire, the heat of which can also melt the synthetic erosion control mat. Downdrag from snow loads, interface problems or upland slides may also strip matting and vegetation off the slope face.

3 SOIL BIOENGINEERING

Soil bioengineering is an integrated technology that uses sound engineering practices in conjunction with integrated ecological principles to assess, design, construct and maintain living vegetation systems to repair damage caused by erosion and failures in the land and to protect and enhance healthy functioning systems (Sotir 2001). This is achieved frequently in association with inert materials such as rock, wood, geosynthetics and geocomposites.

Appropriately applied, soil bioengineering offers a cost-effective and attractive approach for stabilizing slopes against erosion and shallow mass movement, capitalizing on the benefits and advantages that vegetation offers. The value of vegetation in civil engineering and the role woody vegetation plays in the stabilization of slopes has gained considerable recognition in recent years (Greenway, 1987; Coppin and Richards, 1990; Gray and Sotir, 1995). Woody vegetation improves the hydrology and mechanical stability of slopes through root reinforcement and surface protection. The biological and mechanical elements must be analyzed and designed to work together in an integrated and complementary manner to achieve the required project goals. In addition to using engineering principles to analyze and design the slope stabilization systems, plant science and horticulture are needed to select and establish the appropriate vegetation for root reinforcement, erosion control, aesthetics and the environment. Numerous areas of expertise integrate to provide the knowledge required for success. RSS systems require knowledge of the mechanisms involving mass and surfical stability of slopes. Likewise when the vegetative aspects are appropriate to serve as reinforcements and drains, an understanding of the hydraulic and mechanical effects of slope vegetation is necessary.

4 WATERWAYS

Slopes along streams, rivers and levees create special problems due to erosion and scour by flowing water. Geotechnical failures associated with surface and groundwater often add complexity to the problem. As velocities increase so do the erosive powers of the flowing water. Vegetation is able to reduce erosion via the branches that bend over and protect the bank face during floods and reduce the velocities along the near bank. The roots physically "knit" the soil particles together and increase the bank strength. The effects of vegetation on the structural integrity of sandy levees were investigated by Shields and Gray (1992). Their study along a six-mile channel along the Sacramento River in California concluded that woody vegetation did not adversely affect the structural integrity of a levee. The presence of plant roots reinforced the soil and measurably increased the shear strength of the surface layers. Shields (1991) investigated the influence of woody vegetation growing in riprap revetment. His investigation showed that the frequency of revetment failure was lower in vegetated as opposed to unvegetated sectors.

5 BENEFITS OF WOODY VEGETATION

The main benefits of woody vegetation on the mass stability of slopes and streambanks are root reinforcement, soil moisture depletion, buttressing and arching and surcharge. While there can be adverse effects, most of these such as windthrow and surcharge can largely be eliminated through the appropriate vegetation selection; and slope design. Selective pruning on a three to ten year rotation may also mitigate these problems. These related benefits and impacts must be carefully considered and incorporated into the overall assessment, design and construction to reach the desired project goals.

Soil bioengineered systems are often able to provide a significantly more durable facing treatment, not only protecting the outward surface but also improving the internal drainage and stability of the system. Initially, the angle at which the vegetation is installed, 10º-35º sloping down from front to back, positively affects the direction of seepage. The zone immediately around the circumference of the branches tends to be more porous, and it acts as a horizontal drain, which diverts downward flow away from the face of the slope. This improves the factor of safety. The use of deeply-installed and rooted woody plant materials, purposely arranged and imbedded during slope construction offers:

- Immediate erosion control for slopes; stream, and shoreline;
- Improved face stability through mechanical reinforcement by roots;
- Reduced maintenance costs, with less need to return to revegetate or cut grass;
- Modification of soil moisture regimes through improved drainage and depletion of soil moisture and increase of soil suction by root uptake and transpiration;
- Enhanced wildlife habitat and ecological diversity;
- Improved aesthetic quality and naturalization; and
- Additional environmental benefits including air and water quality improvements via:
  - Cleansing, filters out pollutants
  - temperature modification
  - noise absorption due to the soil mass
  - reduction in quantity and time of runoff improving stormwater management

The composite system known as a vegetated reinforced soil slope (VRSS) system (See Figure 2), while it is not suitable under all conditions, has many attributes, as previously mentioned, over the RSS system alone, including a significantly more durable facing.

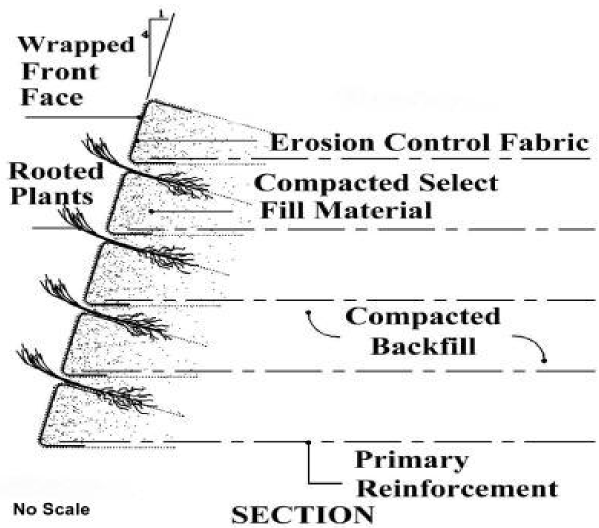

Figure 2. Vegetated reinforced soil slope system (VRSS).

6 VEGETATED REINFORCED SOIL SLOPES

Appropriately applied, soil bioengineering combined with properly designed reinforcement offers an attractive, cost-effective approach for stabilizing slopes against erosion and shallow mass movement, capitalizing on the benefits and advantages that vegetation offers. For example, one of the primary modes of failure for RSS systems is compound failure, where the failure surface passes behind and through the reinforced mass (i.e. in between the reinforcements). The soil bioengineering vegetative component assists in precluding this type of failure by producing an inherently strong face, not only in terms of protecting the outward surface but improving the internal stability of the system. The US Federal Highway Administration currently includes guidelines for its use in combination with geosynthetic reinforcement for design and construction of steep slopes (Elias et al., 2001).
The biological and mechanical elements must be analyzed and designed to work together in an integrated and complementary manner to achieve the required project goals. In addition to using engineering principles to analyze and design the slope stabilization systems, plant science and horticulture are needed to select and establish appropriate vegetation for root reinforcement, erosion control, slope aspect, aesthetics and the environment.
Figure 2 shows an example cross section of the components of a vegetated reinforced slope (VRSS) system. The design details for construction include vegetation selection, placement, and development as well as agronomic and geotechnical design issues.

6.1 *Vegetation selection, placement and development*

The vegetation used in the VRSS system is typically in the form of live woody branch cuttings from species that root adventitiously, bare root, tublings and/or container plants. Plant materials may be selected for a variety of tolerances including drought, salt, flooding, fire, deposition, and shade. They may be chosen for their environmental wildlife value, water cleansing capabilities, flowers, branches and leaf color or fruits. Other interests for selection may include size, form, and rooting rate of growth characteristics and ease of propagation. The decision to use natives, naturalized or ornamental species is also an important consideration. Time of year for construction of a VRSS system also plays a critical role in plant selection.
The plant materials are placed on the frontal section of the formed terraces. Typically 150 to 300 mm protrudes beyond the constructed terrace edge or finished face, and 0.5 to 4 m of the live branch cuttings, when used, are embedded in the reinforced backfill behind. Rooted plants are placed 300 to 1000 mm into the backfill. The process of plant installation is best and least expensive when it occurs simultaneously with the conventional construction activities, but may be incorporated later.

Figure 3. VRSS immediately after construction.

Typically, soil bioengineering VRSS systems offer immediate results from the surface erosion control structural/mechanical and hydraulic perspectives. Over time, (generally within the first year) they develop substantial top and root growth further enhancing those benefits, as well as providing aesthetic and environmental values (See Figures 3, 4 and 5).

Figure 4. Early in the first growing season.

Figure 5. VRSS 5 years after construction.

6.2 *Design issues*

In combining soil bioengineering and RSS systems, there are several agronomic and geotechnical design issues that must be considered, especially in relation to selection of geosynthetic reinforcement and type of vegetation (Sotir et al., 1998). First and foremost, the geosynthetic must be carefully selected and located to ensure structural stability. Several national design guides are available, for example the US Federal Highway Administration Manual (Holtz et al., 1997 and Elias et al., 2001) and the British Standards Institute Guide (BS 8006, 1995). Additional considerations include root and top growth potential. The root growth potential consideration is important when face reinforcement enhancement is required. This will require a review of the vertical spacing of the reinforcement based on the anticipated root growth for the specific type of plant. In addition to spacing, the selected type of reinforcements is also important. Open-mesh geogrid-type reinforcements, for example, are excellent as the roots will grow through the grid and further "knit" the system together. On the other hand, geocomposites providing both reinforcement and lateral drainage, offer enhanced water and oxygen opportunities for the healthy development of the woody vegetation. Dependent upon the species selected, aspect, climatic conditions, soils etc., dense woody vegetation can provide ultraviolet

light protection within the first growing season and maintain the cover thereafter (See Figures 4 and 5).
In arid regions, geosynthetics that will promote moisture movement into the slope such as non-woven geotextiles or geocomposites may be preferred. Likewise, the need for water and nutrients in the slope to sustain and promote vegetative growth must be balanced against the desire to remove water so as to reduce hydrostatic pressures. Plants can be installed to promote drainage toward geosynthetic drainage net composites placed at the back of the reinforced soil section.
Root penetration through the geosynthetic is anticipated to provide a composite root/geosynthetic structure with a net gain in reinforcement strength. Geosynthetic strength loss as a result of root penetration is anticipated to be minor due to the relatively high strength geosynthetics used in soil reinforcement. The roots naturally displace rather than damage or break the geosynthetic structural elements (i.e., filaments, fibers or ribs) and any strength loss should be more than offset by the strength of the root mass. It should be noted that lightweight 140 to 160 g/m^2 non-woven geotextiles are often used in tree farming to restrict root growth.
Organic matter is not required; however, a medium that provides nourishment for plant growth and development is necessary. As mentioned earlier, the agronomic needs must be balanced with the geotechnical requirements, but these are typically compatible. For both, a well-drained backfill is needed. The plants also require sufficient fines to provide moisture and nutrients. While this may be a limitation, under most circumstances, some slight modifications in the specifications to allow for some non-plastic fines in the backfill in the selected frontal zone offers a simple solution to this problem.
While many plants can be installed throughout the year, the most cost effective, highest rate of survival and best overall performance and function occurs when construction is planned around the dormant season for the plants, or just prior to the rainy season. This may require some specific construction coordination in relation to the placement of fill, and in some cases may preclude the use of a VRSS structure.

6.3 *Drainage*

Special emphasis on the design and construction of subsurface drainage features is recommended for structures where drainage is critical for maintaining slope stability. Redundancy in the drainage system is also recommended for these cases, and may involve using soil bioengineering as part of the drainage scheme. Design of subsurface water drainage features should address flow rate, filtration, placement, and outlet details. Geosynthetic drainage composites can be used in subsurface water drainage design. Drainage composites should be designed with consideration of: 1) geotextile filtration/clogging; 2) long-term compressive strength of polymeric core; 3) reduction of flow capacity with pressure and time. Procedures for checking geotextile permeability and filtration/clogging criteria as well as geocomposite design requirements are presented in FHWA *Geosynthetic Design and Construction Guidelines* (1998), as published in Holtz, et al. (1997).

7 VRSS CASE HISTORIES

7.1 *Massachusetts Turnpike*

The Massachusetts Turnpike in Charlton, Massachusetts is an example where a vegetated reinforced soil slope (VRSS) system was used to construct 1H:4V slopes to replace unstable 1.5H:1V slopes along a 150 m section of the Turnpike (Sotir et al, 1998 and Sotir and Stulgis, 1999). This slope eroded for a number of years. The erosion was widening and threatening to move back into private property beyond the right-of-way (See Figure 6). Eventually, the increased maintenance to clean up the sloughed material, the visual scar on the landscape and the threat of private property loss prompted the Turnpike Authority to seek a solution. The combined soil bioengineering vegetative treatments and geosynthetic reinforcement approach was adopted to meet the narrow right-of-way requirement, assist in controlling internal drainage, and reconstruct an aesthetically pleasing and environmentally sound system that would blend into the natural landscape. The 3 to 18 m high 1H:4V slope was stabilized with layers of primary and secondary geogrids, erosion control blankets and live cut branches in the frontal 3 m geogrid wrapped portion of the face.

Figure 6. Existing condition of slope prior to VRSS.

The soil bioengineering design is illustrated in the cross section shown in Figure 2. The primary geogrid was designed to provide global, internal and compound stability to the slope. This grid extends approximately 6 m from the face to the back of the slope. The vertical spacing of the primary geogrid is 0.6 m and 1.2 m, respectively, over the lower and upper halves of the slope. The face wrap forms a 0.9-m thick earthen terrace (See Figure 7) for face view. The live cut branches, consisting of 2 m to 3 m long willow (Salix sp.) and dogwood (Cornus sp.), were placed on each constructed wrapped terrace, extending back 3 m. The branches and geogrids were sloped back to promote drainage to backdrains placed in the slopes while providing moisture for the plants.

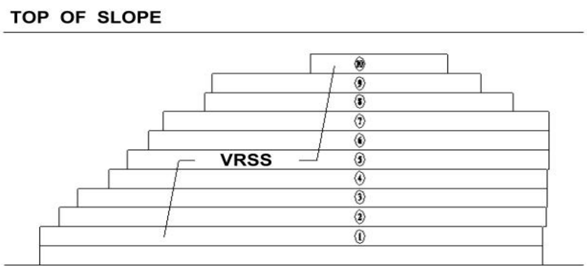

Figure 7. Illustrated face view.

The backdrain system consisted of 1-m wide geocomposite panels spaced 4.6 m on center. Design of the panels and spacing was based on the anticipated groundwater flow and surface infiltration conditions. The panels connect into a crushed-stone drainage layer at the base of the slope, extending the width of the slope (See Figure 8).
The backfill soils consisted of granular borrow, ordinary borrow, 50/50 mix and specified fill. The first three materials constitute the structurally competent core while the specified fill, consisting of fertilizers and a blend of four parts ordinary borrow to one

part organic loam by volume, was placed at the face to provide a media amenable to plant growth. This modification from the normal geotechnical specification accommodated the vegetation. The VRSS slope was constructed in the winter/spring of 1995/96 at a cost of US $270 per square face meter (See Figures 8 and 9) for construction sequence. The slope is currently in its fifth growing season. The vegetated slope face performed as intended, initially protecting the surface from erosion while providing a pleasing aesthetic look (See Figure 10). The system is blending into the naturally wooded scenic setting of the area, meeting the required long-term aesthetic and ecological goals.

Figure 8. Conditions during construction.

7.2 *Johnson Creek stream realignment*

The realignment of Johnson Creek, located in the Portland, Oregon metropolitan area, is an example where the VRSS system was used to produce a compound channel in a constricted outside meander stream reach. This is a highly urbanized watershed with land uses ranging from heavy industry to low-density residential. Johnson Creek is a third-order stream with a 100-year discharge at the project site of about 125 m³/sec. The stream was enlarged, but not straightened, during the 1930's for flood control. A survey of Johnson Creek revealed that with few exceptions, streambanks were stable, heavily vegetated, and provided excellent riparian habitat and overhanging cover for the stream (See Figure 11).

Figure 9. Immediately after construction.

Figure 10. Second growing season.

The Oregon Department of Transportation (ODOT) proposed relocating a section of Johnson Creek for bridge and highway construction. The relocated section would be about 20% shorter than the existing channel with a commensurate increase in gradient. A local committee, created because of concerns over degraded water quality and aquatic habitat and an interest in restoring an anadromous fishery, were concerned about potential impacts of the stream relocation. The stream reach is in a highly visible location, and there was concern that the proposed riprap rock channel designed by ODOT would present a stark, sterile appearance and cause loss of habitat.

Figure 11. Prior to construction.

The proposed channel design was evaluated for stability and for potential impacts to aquatic and riparian ecosystems. The review determined that the proposed channel cross-section shape and gradient were too uniform and that the floodplain berms were too high. Changes were recommended to the channel design to improve stability, water quality, and habitat enhancement value (Sotir and Nunnally, 1995). Lowering floodplain berms to alter the channel cross-section, incorporating a sub-channel sized to convey bankfull flows, and constructing a low flow channel to concentrate flows during the summer months. The sub-channel was also designed to serve as an area for nesting and rearing of waterfowl. A pool-riffle sequence was created by widening the sub-channel and raising the invert by 0.3 m in crossover reaches and by lowering the invert by 0.3 m in outside meander sections (See Figure 12).

Figure 12. Initial earthwork and foundation construction.

The VRSS system was used in contact with a reinforced earth concrete wall – a very challenging environment for vegetation (See Figure 13). The system was used to create a compound channel in this constricted reach between the upstream bridge and the downstream ramp to handle the volume and associated velocities and tractive forces during flood events. This also produced a wildlife corridor within the riverine zone.

Figure 13. After construction and a flood event.

The soil bioengineering systems were installed during the winter of 1993 and spring of 1994. During the early spring, prior to the vegetation establishing growth, the site experienced a 50 m^3/sec flood with mean velocities between 1.8 and 2.1 m/sec and maximum velocities estimated to be in excess of 3 m/sec. The soil bioengineering systems were secure as they offered surface protection and reinforcement to the reconstructed banks. In the first growing season, they were providing excellent bank protection, habitat, and aesthetic benefits after seven years of growth (See Figure 14).

Figure 14. Seven years of development.

8 CONCLUSION

Soil bioengineering when appropriately combined with reinforced soil can offer a synergistic composite design with considerable improvement over either method as a stand-alone solution. VRSS systems combine both structural and living elements to provide low cost, low maintenance, safe steepened slopes that are aesthetically pleasing, provide habitat enhancement, air quality improvement, temperature modification and flood resistance on waterway applications.

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