CREATING SUSTAINABLE VEGETATED COVERS OVER DIFFICULT SLOPES[1]

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Abstract Vegetated covers on steep slopes (greater than 1H:1V) and over geomembrane covers are highly desirable. However, challenges with both the structural stability and sustainability of those covers have prevented their extensive use. Using creative combinations of proven materials, soil-bioengineering techniques, and innovative installation methods, the highly desirable outcomes can be economically obtained. This paper reviews the materials and construction methods used in four successful applications. A vegetated cover on a 70-degree cut slope in the Amazon basin was established in the first application. In the second application, a vegetated cover over a low-pH, 60-degree rock face at over 4,300 m above sea was established. In the third application, a vegetated cover was established over a geomembrane cap in a high-rainfall area of Brazil and in the last application, an aggregate protective cover was established over a geomembrane on a 1H:1V slope in Pennsylvania.

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Problem

Water and wind caused erosion of slopes is a costly problem. The prevention of slope erosion, in the majority of situations, can be easily solved using many available standard methods. However, in the case of steep slopes and unique surfaces, the problem requires specific engineered solutions that may have high implementation cost but are cost effective in the long-term.

From the perspective of the author, costs of erosion can be grouped as follows:

- Damage to company assets
- Damage to the environment (water, land and air)
- Degradation of the company's image
- Legal costs
- Damage to other's assets

Improper solutions may be completely ineffective and most likely, amplify the problem. Erosion along or near to any structure will result in maintenance and often cause physical damage to the structure. Some damages are obvious and others are less obvious. The less obvious are those that may have high legal cost associated with them if or when they pollute the environment of others. The details and costs of erosion are discussed in the following two scenarios.

Scenario 1

A road is cut into an area to be mined. The nearly sterile, *in situ* soil is highly cohesive, therefore, to minimize earthwork, 1H:2V slopes are cut. There is a definite benefit in steep slopes as long as they have long-term surface stability. However, surface stability should not be dependent on soil characteristics only. Figure 1 shows a common lateritic clay soil found in many areas of the world.

Once surface erosion starts, the process generally progresses at an increasing rate as flows become more concentrated. Often roadside drainage ditches fill with sediment and flow through the ditches is obstructed. Over saturation of the soils causes weakening of the toe of the slope and forces water into the sub-base of the road. With a weakened toe, the slope becomes less stable and a weakened sub-base, road-surface degradation occurs. As sediment accumulates in the waterways, culverts become clogged and water flow is obstructed. With the loss of natural water storage capacity in the channels, flooding occurs at lower rainfall intensities affecting the livelihood of crop producing landowners. Maintenance cost increase as the public opinion of the erosion control practices of a particular company is affected.

Figure 1. One of many slope surface stabilization schemes which seldom works well.

Scenario 2

A tailing pile starts to produce acid runoff which subsequently pollutes natural streams and causes unexpected environmental damage. Regulatory agencies require the tailing pile to be permanently capped. A geomembrane cap, in this scenario, seems most logical but due to the 'permanent' requirement, the geomembrane will need some type of protection. Common practice would recommend re-grading the pile slopes to 3H:1V at the steepest so a protective soil cover could be placed over the geomembrane. However, space restrictions prevent re-grading and force moving large quantities of the pile to another site. Costs are extremely high but an action must be taken regardless of associated costs.

The Solution

General

The first step in any slope surface stability problem is to decide what type of protective cover is desired. Three common options are:

an armored cover provided by materials such as concrete

a non-vegetated cover such as aggregate - often used in arid climates,

a sustainable vegetated cover

In all cases, a cellular confinement system can provide an excellent solution. Success depends on proper analysis of site-specific conditions and choice of system components to produce desired results.

Steep Soil and Rock Slope Covers

General information such as slope angle and length, slope toe and crest conditions, slope surface hardness, frictional interface values, slope soil or rock chemistry, climatic conditions, and area topsoil and vegetation types should be gathered. This data determines the manufactured materials to be used for the desired protection.

Questions that can be answered from this information are:

Should geotextile separation or drainage layers be used and if so, what are the specifications for the geotextile?

What is the optimal cell size and depth of the cellular confinement material? Factors influencing this are slope angle, infill material type, and materials that influence surface stability of the infill material.

Does the cellular confinement material need to provide permanent or temporary confinement?

What anchoring scheme is required and / or best; stakes, tendons, both, others?

Is the anchoring scheme temporary in nature or does it need to be permanent? If temporary in nature, must anchoring stakes provide support for a few weeks or several years?

What is the best way to develop vegetation sustainability when vegetation is desired?

Designs should be done by experts who understand how the uniqueness of each situation influences the whole problem-to-solution process. The purpose of this paper is to provide an overview of well-tested solutions and alternatives for slope stabilization. Successful extreme slope surface stabilization solutions are very sensitive to proper understanding and treatment of unique details. Figure 2 and Figure 3 illustrate the typical components of cellular confinement systems.

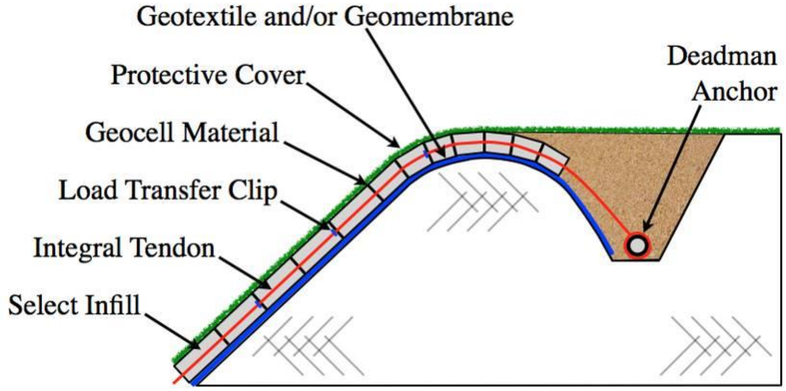

Figure 2. Cellular Confinement over a geomembrane.

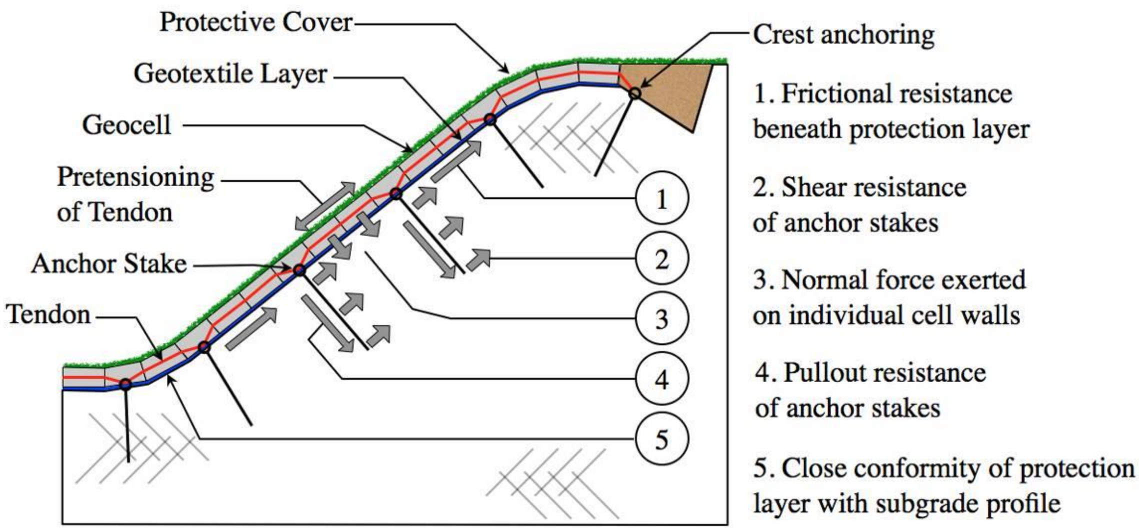

Figure 3. Cellular Confinement over a soil or rock surface.

Geomembrane Covers

Protective cover types over geomembranes are the same as those used over soil and rock slopes. Generally, interface friction angles between a geomembrane and cover materials are low relative to those over soil and rock faces. Many times, the design interface friction between the geomembrane and the protective cover is considered to be zero for calculating down-slope loading. Since geomembrane penetration is unacceptable, stake anchoring is not used. Crest anchoring via tendons passing through the cellular confinement material is the desired anchoring scheme and must be considered as permanent anchoring. A geotextile layer both under and over the geomembrane is absolutely necessary in some situations and optional in others. One factor influencing the selection of the geotextile is the roughness / angularity of both base and fill materials. Cell content influences the depth on the cell. A good rule-of-thumb for cell depth is:

75-100 mm for concrete infill - flexible, hard-armor protection

100-150 mm for aggregate infill

150-200 mm for topsoil infill when sustainable vegetation is desired

Creating Sustainable Vegetation

Phytoremediation science and techniques have produced some significant success stories. Understanding the inter-relationships between native plant species, soil chemistry, soil biology, and climatic conditions is important. Reproducing these relationships using site-specific materials (soils, bacteria, other micro-organisms, plants, etc.) is becoming more common and economical. When natural conditions are successfully incorporated into a slope stabilization problem, natural sustainability is essentially guaranteed. When the natural growth-supporting components are enhanced within the soil during the construction phase of the solution, healthy, rapid vegetation growth will occur. Making application of inorganic nutrients and non-native plant species is unnecessary. Using natural phytoremediation techniques, vegetation germination is 50%-90% faster and natural vegetation density reaches 100% within the first growing season. Introduction of chemical fertilizers or use of irrigation systems is not necessary to produce sustainable vegetation in most cases.

Overview of Case Studies

The following case-studies summarize the beneficial uses of cellular confinement system on steep slopes and the results obtained.

Iquitos-Nauta Road - a steep natural soil slope (Senf et al., 2009)

During the construction of the highway between Iquitos and Nauta, Peru, many cut/fill areas were required through the native, lateritic clay soil. Standard practice is to cut steep slopes with angles from 65-75 degrees so the highway footprint is kept to a minimum. Cut depths were up to 18 m. The resulting soil erosion produced a considerable number of slides, which obstructed the ditches, overfilling them, and impounding water. This forced the water to flow outside of the ditch and to saturate the slope toe. This in turn resulted in soil loss and new slides finally causing flooding which damaged the highway structure. Figure 4 illustrates the problem.

Figure 4. Damages from an unprotected slope along a highway road cut between Iquitos and Nauta, Peru.

To demonstrate the performance of a vegetated geocell stabilization system for steep slopes, two test sites were chosen; one on the west side and one on the east side of the highway. Both slopes were 16 m +/- in height with a 70-degree +/- slope angle. Over the slopes, a 100 mm depth textured perforated geocell was placed. It was then anchored at the top of the slope using tendons and a mix of wooden and steel stakes. The cells were filled with on-site organic soil containing seed propagules and seedlings. Use of on-site soils and vegetation ensure greater survivability of the system since nature already selected these species for the site-specific varying climatic conditions. Figure 5 depicts the west slope after installation of the system.

Figure 5. The completed installation of the west slope system on a highway road cut in Peru.

In addition, at the time of the installation, bacteria were harvested from the soil and bacteria rich water solution was applied to the soil within the geocell. As the organisms colonize the soil, the plant roots feed upon them and create favorable conditions for their mutual survival through a biological and chemical process. When the system is created correctly, the result is the development of a sustainable new ecosystem.

From the moment that micro- and macro-organisms start colonizing of the underlying slope soils over which the system is placed, these soils start biological activities that Pb to a release of nutrients, and biochemical reactions that lead to the formation of organic soils.

This activity demonstrated that the vegetated geocell system and the underlying slope soils are interrelated by means of the vegetation. In this phase of development, the system is anchored to the slope via vegetation establishment, and concurrently the slope soil is continually being modified, increasing its capacity to support vegetation. Root strength increases resulting in plant development and strength. Foliage becomes denser resulting in greater slope protection. Over time, the strength of the system increases and the slope stabilization further improves. Figure 6 shows the slope eight months after the original installation.

Figure 6. The system as it becomes mature.

The objective to create a fully self-sustainable vegetated cover over a steep, laterite-clay slope using both site-specific soils and vegetation was completely accomplished.

Peru Mine - a steep rock face slope (Schmalbach et al., 2010)

Developing a structurally-scaleable support system to permit sustainable vegetation cover over steep irregular rock faces for open-pit mines while protecting the rock surface from rainwater induced degradation is challenging. Figure 7 shows the rock face where a geocell / geogrid structure holds topsoil in place so a sustainable vegetation cover can be developed.

This particular open-pit mine is located in the Peruvian Andes at over 4,300 m above sea level. The open-pit walls have slopes greater than 1H:1.75V and an average height of 8 to 10 m. Site temperatures fluctuate between -7 and 21° C.

One project requirement was to develop a system where no additional slope grading was necessary before the placement of the soil containment system. After reviewing site conditions, a structural containment system, consisting of a high-strength geogrid structurally connected to the geocell cellular confinement material, was developed. This combination permitted the section to have excellent conformity to the irregular slope surface as well as a secure method to develop the needed crest anchoring system.

Figure 7. One of the typical rock faces requiring sustainable vegetation.

Sections were pre-assembled on a flat work area, rolled up, and carried to the top of the slope. Once there, the upper geogrid portion of the section was anchored in a trench and then rolled down the slope. Figure 8 shows the section expanded down the rock face. Once anchored and expanded down the slope, the sections were filled with local topsoil as show in Fig. 9.

The open pit mine exposed soils have low pH and provide little support for vegetation development. In addition, negative factors such as acid rains, dry winds, low relative humidity, and low temperatures contribute to the harsh environment. Therefore, a solution of on-site soil bacteria was developed and applied to the soil infill. The vegetation develops quickly and becomes sustainable. The results are shown in Fig. 10.

Figure 8. The geocell / geogrid system ready for soil infilling.

Figure 9. Irrigation of the soil-filled system with a bacteria-rich water.

Figure 10. Sustainable local vegetation established over the rock surface in Peru.

<u>Brazil Paper Mill - a soil covered geomembrane slope (Abramento et al., 2008)</u>

A pulp paper mill plant in the Northeastern region of Brazil, has used a single area to dump residue for several years. Residue included organic materials, lime, contaminated soils and other non-organic materials. Figure 11 shows the dumpsite in 2003.

Figure 11. The residue dumpsite in 2003.

Due to increasing pressure from regulatory agencies and existing environmental issues, the dumpsite was required to be covered and confined in 2006.

The following objectives were desired from the geotechnical confinement of the dumpsite:

to prevent dispersion of residues and contaminants due to rain and wind actions

to prevent infiltration of water and consequent transportation of contaminants into the aquifer

to prevent contact of personnel and animals with contaminated residues, and

to promote landscape integration.

Geotechnical analyses determined that in order to guarantee the stability of the residue and allow for the construction of a new landfill over it, the residue had to be re-graded to a stable 3H:1V slope. The cover consisted of a 0.60 m of soil fill over a geotextile-protected geomembrane.

In mid-June 2006, after a heavy rainfall, the residue cover completely failed at the geotextile-geomembrane interface. At some points along the slope crest the geotextile tore. Figure 12 shows the typical failure.

Figure 12. Typical failure of the slope-cover system.

The failure was caused by the combination of a relatively low friction angle at the geotextile-geomembrane interface (even though a textured geomembrane was used), increased load from the saturated soil, and seepage forces due to water flow within the 0.60 m thick soil cover. The failure involved 1,200 m^3 of cover soil and 1,800 m^2 of geotextile. Fortunately, the geomembrane remained in place and was not affected by the soil movement.

For the repair, the following details were considered important for the design of the soil cover:

- varying slope heights (from 20-35 m)
- slope angle 3H:1V (18.4°)

- the critical interface for sliding between the sand and geomembrane, with a 15° angle of shearing resistance
- an overall desired factor of safety of 1.5.

The repaired system consisted of a sand-infilled, tendon reinforced, perforated geocell layer 75 mm deep, with a cell area of 1200 cm^2 installed directly over the HDPE geomembrane. In between the soil cover over the geocell layer and the geocell layer, a 200 g/m^2 non-woven geotextile was used for separation and as a filter. The main advantage of the geocell layer was to allow a sand layer to be placed directly over the geomembrane. The perforated geocell material acted as "formwork" and prevented sand flow during installation during periods of rainfall as well as to allow drainage of the sand infill. The use of a sand layer had two advantages: 1) increasing the friction angle at the critical interface with the geomembrane; and 2) providing a structural drainage layer. Figure 13 illustrates the installation process.

Figure 13. The tendoned geocell system ready for infilling.

The system has now been through three rainy seasons (2007, 2008, and 2009) without seeing movement to the vegetated geomembrane protection system. The system's vegetation is healthy and sustainable. Figure 14 shows the system after sod was placed over the soil surface.

Figure 14. The vegetated system protecting the geomembrane.

I-99 - a steep geomembrane covered slope (Filshill et al., 2008)

The I-99 / State Route 6220 Project, extending form the Village of Bald Eagle in Blair County, Pennsylvania to the Mount Nittany Expressway (U.S.322) in Centre County, Pennsylvania, involved the construction of a four-lane limited access highway approximately 29 km long. During construction, large volumes of pyrite-bearing sandstone were exposed to air and rainfall, creating acid rock drainage containing elevated concentrations of heavy metals and sulfates. A typical pyrite vein is shown in Fig. 15. The acidity caused by the reaction of sulfuric minerals with oxygen and water threatened the quality of two adjacent, exceptional-value trout streams and local residential water wells.

Figure 15. A pyrite vein exposed by the excavation.

The remediation program consisted of two major areas / sources of contaminants: 1) movable material and 2) immovable material. The estimated 600,000 m^3 of movable material was encapsulated in a double-lined landfill constructed along the right-of-way of the project.

The immovable material required the encapsulation of approximately 100,000 m^2 of exposed rock slopes. A geosynthetic cap of a high-density polyethylene (HDPE) geomembrane protected by two heavyweight non-woven geotextiles and a geocell filled with crushed stone.

There were several immovable slopes ranging in length from 9.0 meters to 110 meters with inclinations from 3H:1V to 1H:1V. The most severe slope was the large cut face shown in Fig. 16. Both slope lengths and slope inclinations strongly influenced the reinforcement demand while the topography of the crest of slope influenced the practical anchor types and dimensions.

Figure 16. One of many cut faces needing encapsulation.

Three project-specific requirements created unique design challenges: 1) no penetrations through the liner system were allowed on the slope face, 2) no frictional resistance to sliding on the slope face was allowed, and 3) limited upslope area was available for anchor construction. These constraints demanded significant engineering consideration to arrive at an economical design for each section.

The geosynthetic liner system consists of three layers: 1) a 540 g/m^2 non-woven geotextile bottom cushion, 2) a 1.0 mm HDPE geomembrane, and 3) a 540 g/m^2 geotextile top cushion. The bottom and top geotextile cushions were selected to protect the geomembrane against damage by irregularities in the slope surface and by the crushed stone selected for the protective cover.

The geocell cell size and depth was chosen to provide macro stability to the crushed stone. On the longer steep slopes, stainless steel wire rope reinforcement of the geocell was used. Sizing of the wire rope and anchorage was based on stability considerations.

The type of anchor selected for each section depended upon the load demand and the available space. The project used several anchoring schemes. The longest, steepest slopes had the greatest load demand and used ground anchors as shown in Fig. 17. Installation of the geocell is shown in Fig. 18.

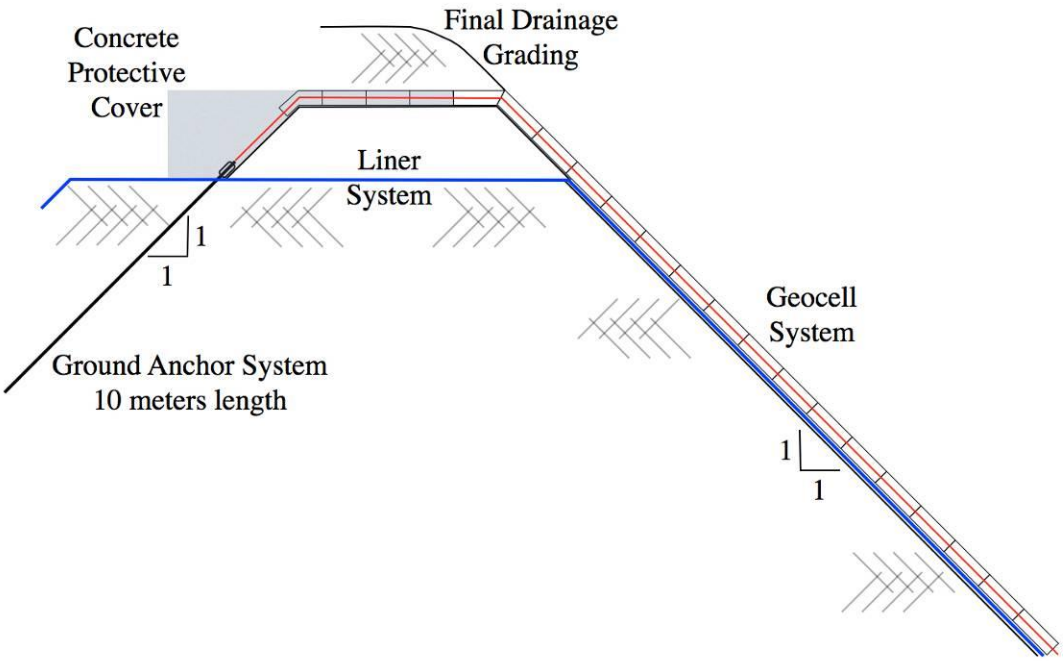

Figure 17. Cross section of the slope protection scheme for long steep slopes.

Figure 18. Installation of the geocell on a long steep slope.

Conclusions

The establishment of naturally sustainable vegetated or other protective covers over steep slopes requires in depth knowledge of structural containment systems, a variety of anchoring schemes, soil chemistry and biology where vegetation is desired, and unique construction techniques. In addition, to obtain sustainability of a vegetated cover in extreme conditions, it is necessary to create a symbiosis between plants and the soil so that auto-sustainability of the micro- and macro-systems results.

Successful installation of the geocell cover system involves close coordination between the installer and the design engineer. Many of the construction challenges of a project are driven by practical construction constraints in the field. These constraints can cause frustration resulting in delays and cost overruns or they can stimulate creative thinking that results in unique methodologies for successful implementation of the protection system.

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