Front. Struct. Civ. Eng. 2017, 11(1): 56–65
DOI 10.1007/s11709-016-0380-8

RESEARCH ARTICLE

Geosynthetics used to stabilize vegetated surfaces for environmental sustainability in civil engineering

Jie HAN[*], **Jun GUO**

Department of Civil, Environmental, and Architectural Engineering, the University of Kansas, Lawrence, KS 66044, USA
[*]*Corresponding author. E-mail: jiehan@ku.edu*

ABSTRACT Geosynthetics, factory-manufactured polymer materials, have been successfully used to solve many geotechnical problems in civil engineering. Two common applications are earth stabilization and erosion control. Geosynthetics used for earth stabilization include but are not limited to stabilized slopes, walls, embankments, and roads. Geosynthetics used for erosion control are mostly related to slopes, river channels and banks, and pond spillways. To enhance environmental sustainability, vegetation has been increasingly planted on the facing or surfaces of these earth structures. Under such a condition, geosynthetics mainly function as surficial soil stabilization while vegetation provides green appearance and erosion protection of earth surfaces. Recently, geosynthetic or geosynthetic-like material has been used to form green walls outside or inside buildings to enhance sustainability. Geosynthetics and vegetation are often integrated to provide combined benefits. The interaction between geosynthetics and vegetation is important for the sustainability of the earth and building wall surfaces. This paper provides a review of the current practice and research in the geosynthetic stabilization of vegetated earth and building surfaces for environmental sustainability in civil engineering with the emphases on geosynthetic used for erosion protection, geosynthetic-stabilized slopes, geosynthetic-stabilized unpaved shoulders and parking lots, and geosynthetic-stabilized vegetated building surfaces.

KEYWORDS erosion, geosynthetic, stabilization, sustainability, vegetation

1 Introduction

Geosynthetics, factory-manufactured polymer materials, include geotextile, geogrid, geocell, geonet, geomembrane, erosion control mat, geosynthetic clay liner, and geocomposite. They are mostly planar or two dimensional; however, geocell is three dimensional and has honeycomb shape packets. Geosynthetics can be used for at least one of the following functions: separation, filtration, drainage, reinforcement, stabilization, barrier, and erosion protection. In the past, reinforcement and stabilization were considered as the same function. Recent research has shown that reinforcement is different from stabilization. Reinforcement adds force or resistance to soil while stabilization maintains soil mass unchanged or undeformed. Tensile strength is more important for reinforcement while tensile stiffness at small strain is more important for stabilization. Detailed discussion on reinforcement and stabilization can be found in the paper by Han [1]. Woven geotextile, geogrid, and geocell are mostly used for reinforcement and/or stabilization. Nonwoven geotextile is mainly used for separation and filtration. Geonet and geocomposite are mostly used for drainage. Geomembrane and geosynthetic clay liner are mainly used as barriers. Erosion control mat is used for erosion control. Geosynthetics have been successfully used to solve many geotechnical problems for different applications in civil engineering. The common applications include slopes, walls, embankments, and roads [2–7]. Recently, geosynthetic-like material has been used to form green walls outside or inside buildings to enhance sustainability.

For slopes and walls, in addition to internal, external, and global stability, facing stability is also important for their performance. Since slope facing is exposed to rainfall and runoff, they are more likely damaged. The common failure modes of slope facing are surficial failure and erosion. The surficial failure often results from low overburden stress, poor compaction, reduction of soil

Article history: Received May 22, 2016; Accepted Oct. 28, 2016

strength due to saturation, freeze-thaw, etc., increase of weight by water, and seepage force [8]. The surficial failure typically happens within a depth of 1.2 m. Soil erosion is the detachment and the transportation of soil particles by water or wind. Water can cause more soil erosion on slope facing than wind. On the slope facing, the rate of water flow is increased with an increase of a slope angle. The water at a high flow rate induces a high shear stress on the slope facing so that more soil particles are removed by water.

Shoulders are constructed next to rigid and flexible pavements to provide space for vehicles to stop during an emergency, increase road safety, and provide structural support for the roadway. Shoulders can be paved or unpaved. Unpaved shoulders including aggregate and turf shoulders are commonly constructed in rural areas. In the rural areas, when there is significant agricultural presence, slow moving vehicles including combines, tractors, and grain wagons may use unpaved shoulders to allow other vehicles to pass. Shoulders may also be subjected to run-off-the-road crashes. However, unpaved shoulders are often not designed to support heavy trucks. Heavy vehicles on unpaved shoulders may result in excessive rutting. Water run-off from pavements to the shoulders may cause soil erosion. Since pavements typically have small slope angles, the speed of water run-off is relatively slow so that soil erosion by water on unpaved shoulders is not that serious as that on slopes. However, trucks traveling at high speeds can induce high wind speeds, which cause soil erosion. Figure 1 shows the typical rutting and erosion problems of unpaved shoulders.

Vegetation has been successfully used to protect slope facing and unpaved shoulders and parking lots from soil erosion by water and wind because vegetation can reduce the rate of water flow and the wind speed. In addition, vegetation can offer the other advantages: 1) natural looking, 2) sustainable, and 3) increase of surficial soil strength. However, it takes time for vegetation to be established, vegetation may not survive all year round or for a long-time period, and the increase of soil strength by roots is limited.

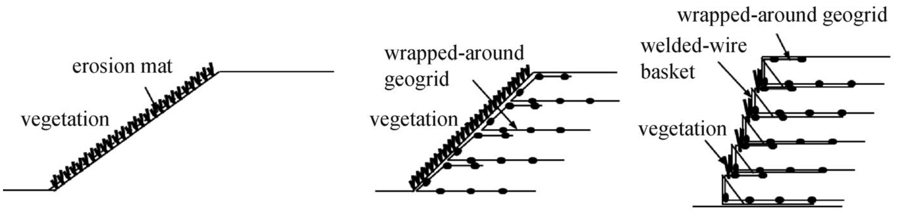
To minimize soil erosion before vegetation establishment or during the vegetation die-off period, provide suitable conditions for vegetation estalishment and survival, and increase soil strength to maintain surficial soil stability and increase load-carrying capacity of unpaved shoulders and parking lots, geosynthetics can be used in combination with vegetation as shown in Fig. 2. The erosion mat placed on the slope (Fig. 2(a)) reduces impact of rain drops and slows down water flow on the slope. The wrapped-around geogrid used near the slope facing (Fig. 2(b)) enhances the surficial slope stability. The welded-wire baskets in Fig. 2(c) are often needed for constructing steep slopes or walls. The geocell placed on the slope surface (Fig. 2(d)) is to retain soil and prevent surficial slope failure. Geocell can also be used to stabilize base courses to provide more support for vehicles as shown in Figs. 2(e) and 2(f). Recently, geosynthetic-like material has been used to form green walls outside or inside buildings to enhance sustainability. The current practice and research on these geosynthetic-stabilized vegetated earth and building surfaces will be discussed in the following sections.

2 Slope stability

Slopes may fail in different modes at different locations as shown in Fig. 3. Global failure often results from weak foundation soil and high embankments. This failure mode can be prevented by ground improvement of foundation soil and/or use of geosynthetics within or below the embankment. The toe failure happens above the foundation soil; therefore, it has nothing to do with the foundation soil but results from lack of shear strength of the embankment fill. The toe failure can be prevented by geosynthetics under a fill condition or by insitu ground reinforcement (e.g., soil nailing, ground anchoring) under a natural or cut condition. Surficial and local failures happen near the slope facing; therefore, they can affect the stability of vegetated facing. Surficial and local failures are most likely triggered by water due to the saturation and


(a) (b)

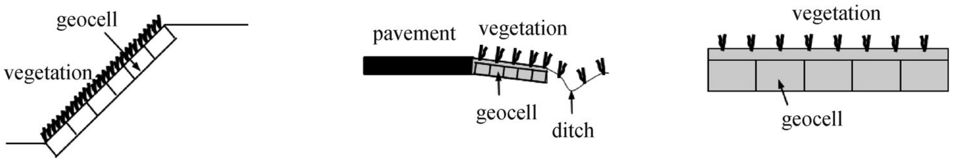
Fig. 1 Rutting and erosion of unpaved shoulders. (a) Rutting; (b) erosion



(a) slope facing protected by erosion mat

(b) slope facing stabilized by wrapped-around geogrid

(c) slope or wall facing stabilized by welded-wire basket and wrapped-around geogrid



(d) slope facing stabilized by geocell

(e) unpaved shoulder stabilized by geocell

(e) unpaved parking lot stabilized by geocell

Fig. 2 Examples of geosynthetic-stabilized vegetated earth surfaces (modified from Han and Guo [9])

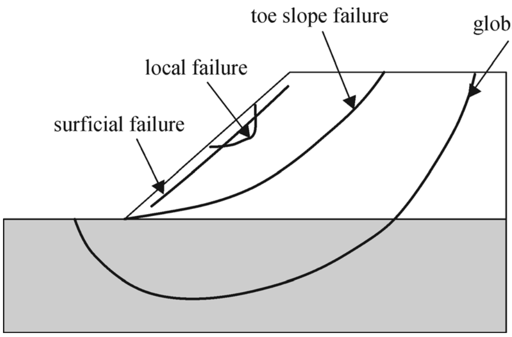


Fig. 3 Slope failure modes [8]

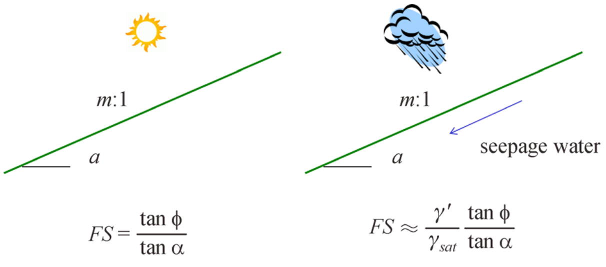


Fig. 4 Stability of infinite slope. (a) Dry condition; (b) saturated condition

weakening of the soil and the development of seepage force in the soil. Local failure may result from non-uniform soil, local variation of slope angle, and/or local water seepage. Since surficial failure happens at a shallow depth as compared with the length of the slope, it is often treated as an infinite slope for analysis.

Figure 4 shows the stability analysis of an infinite slope under a dry condition and a saturated condition. Cohessionless soil under a dry or saturated condition typically does not have cohesion. Cohesive soil can lose its cohesion due to dry-wet cycles, freeze-thaw cycles, etc. in long term. Therefore, analysis of surficial slope stability for long term should not consider soil cohesion. In Fig. 4, α is the slope angle, ϕ is the soil friction angle, γ' is the effective soil unit weight, and γ_{sat} is the saturated soil unit weight. A typical soil has the effective to saturated soil unit weight ratio of approximately 0.5. For a typical soil with a friction angle of 30 degrees, a 2(*H*): 1(*V*) slope with a slope angle of 26.7 degrees is stable under a dry condition (i.e., the factor of safety, $FS > 1.0$). However, this slope will not be stable under a saturated condition with seepage force (i.e., $FS < 1.0$). A 4(*H*): 1(*V*) slope at a slope angle of 14.0 degrees is stable under a saturated condition.

3 Soil erosion and vegetation effect

Morgan and Rickson [10] indicated that the detachment and the transportation of soil particles are the mechanisms for soil erosion, which can be caused both by wind or water. Vegetation cover is regarded as one of the most effective methods to control wind or water-induced soil erosion. The effectiveness of vegetation as a protection for soil against wind or water-induced erosion has been extensively studied. However, depending on the species, the vegetation cover can take up to two to three years of growth to be effective. A bare soil surface just after excavation or fill placement can be a harsh environment for the vegetation to establish and consequently is vulnerable to erosion.

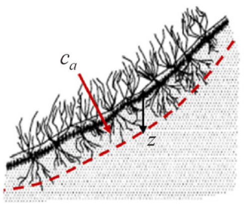
Soil erosion by wind is often accompanied with air pollution due to suspended fine soil particles. Unpaved shoulders along highways are often subjected to turbulent air flow that is caused by vehicles with large size and/or poor aerodynamic traveling at high speed and results in dust emission [11]. Li et al. [12] conducted a three-year study on soil erosion and soil nutrient loss by wind. Their study showed that wind-induced erosion was up to 25% of total organic carbon and total nitrogen loss in the upper 50 mm soil. The loss of nutrient (i.e., organic carbon and nitrogen) reduces the survival rate of vegetation.

Numerous studies have been conducted to investigate the effectiveness of vegetation on controlling wind-induced erosion and dust pollution. Van de Ven et al. [13] concluded that vegetation protects soil against erosion by wind in three ways: 1) the soil surface covered by vegetation is sheltered from the erosion force; 2) the near ground wind speed is reduced due to the obstruction of vegetation, and 3) soil particles transported by wind can be trapped by vegetation. A scaled wind tunnel study indicated that rows of vegetation parallel to the dominant wind direction reduced the mass transport by wind [14]. The wind tunnel experiment conducted by Udo and Takewaka [15] found that the mean wind velocity decreased within the space occupied by vibrating leaves and consequently reduced the sand transport rate. Lancaster and Baas [16] conducted a series of field studies and found that sand flux decreased with vegetation cover exponentially. Munson et al. [17] had 20-year monitoring of climate and vegetation and found that climate change resulted in the reduction of vegetation cover in grasslands and dwarf scrublands so that dust emission from wind-induced erosion increased.

Water-induced soil erosion often appears on coastal fronts, river channels and banks, highway cut and fill, newly constructed slopes, and mining sites. Vegetation has been regarded as one of the most effective ways to control runoff-induced erosion. A significant number of studies, both field and simulated studies, have been conducted on runoff-induced erosion and vegetation effects [16,18,19]. These studies demonstrated vegetation cover effectively reduced water-induced soil erosion. Styczen and Morgan [20] attributed the benefits of vegetation to three effects: 1) hydrological effect, such as reduction of soil moisture, interception of rain drops, and improvement of soil hydraulic conductivity; 2) hydraulic effect, such as increase of surface roughness, reduction of runoff quantity, reduction of soil detachment rate, and filtration of soil particles; and 3) mechanical effect, such as formation of a composite material through interaction of roots and soil. Gyssels et al. [21] summarized the benefits of root-soil interactions as stabilization of soil particles, improvement of infiltration capacity, increase of soil shear strength, and changes of soil texture, organic content, composition, and bulk density. Gyssels et al. [21] also concluded that an increase of root density reduced soil erosion by concentrated flow exponentially. In addition to root density, Baets et al. [22] found that fine roots are more effective in erosion control.

Coppin and Richards [23] concluded that the magnitude of soil strength increase by plant roots depends on their density, tensile strength, tensile modulus, length/diameter ratio, surface roughness, alignment, and orientation. The increased soil shear strength by plant roots is often considered as apparent cohesion of soil (also referred to apparent root cohesion). Based on shear tests, Endo and Tsuruta [24], Ziemer [25], and Gray and Sotir [26] found that the apparent cohesion increased approximately linearly with root biomass. The typical strength increase by plant roots ranges from 3 to 15 kPa per kg/m^3 biomass. Typical values of apparent soil cohesion ranges from 1 to 17.5 kPa [23]. The maximum root depth for a specific plant depends on existence of bedrock, soil porosity, soil moisture, soil structure, soil consistency, and soil fertility [27]. Typical tree root depth on slopes ranges from 0.3 to 1.2 m while typical grass root depth on slopes ranges from 0.05 to 0.15 m. Since the root density decreases with depth, the apparent cohesion of the root-stabilized soil decreases with depth down to the maximum root depth. Tree roots, because of their greater depths, can increase surficial slope stability while grass roots, because of their smaller depths, are mostly used to minimize soil erosion near surfaces.

Plant roots can also minimize surficial slope failure due to the increased shear strength. Figure 5 shows the calculation of the factor of safety of the surficial slope considering the apparent cohesion of the root-stabilized soil, c_a, and the depth of the root-stabilized zone, z. For a typical soil with a friction angle of 30 degrees and a saturated unit weight of 18.9 kN/m^3, assuming the depth of roots is greater than 0.6 m and the apparent cohesion of the root-stabilized soil zone is 5 kPa, the calculated factors of safety of the surficial slope at the depth of 0.6 m are 1.65 considering the apparent cohesion of the root-stabilized soil zone and 0.55 without considering the apparent cohesion. This calculation demonstrates the benefit of root stabilization of soil near the slope facing in increasing the surficial stability.



$$FS \approx \frac{2c_a}{\gamma_{sat} z \sin 2\alpha} + \frac{\gamma'}{\gamma_{sat}} \frac{\tan \phi}{\tan \alpha}$$

(under seepage)

Fig. 5 Root-stabilization of surficial slope

4 Geosynthetic erosion control mats for slope protection

The properties of vegetation cover against soil erosion and instability highly depend on the level of vegetation establishment. For example, the root density and vegetation cover percentage increase as the establishment process of vegetation. Civil engineering projects often disturb or completely remove native vegetation cover and leave soil surfaces difficult for vegetation establishment. High temperature and low moisture more likely occur on compacted soil than friable soil surfaces and have negative impact on vegetation development [28]. During the period from the completion of a project to the development of vegetation, bare soil surfaces are vulnerable to erosion and instability. Rickson [29] pointed out that this vulnerable period can be extended longer by extreme temperature, high rainfall intensity, soil toxicity, or excessive trafficking. The lack of protection in this vulnerable period can cause severe soil erosion and instability and make vegetation establishment even more difficult as seeds and seedlings are vulnerable to surface runoff and high winds. Based on 16-year monitoring of vegetation dynamics on slopes, Espigares et al. [30] indicated that soil erosion had negative effects on vegetation.

To avoid the above problems, adequate protection of the surfaces of unpaved shoulders or slopes is required. Temporary or permanent erosion control mats as shown in Fig. 2(a) and Fig. 6 may be used to minimize soil erosion on their surfaces. Temporary erosion control mats (also called erosion control blankets) are often composed of natural or polymer fibers. Geosynthetic erosion control mats (also called turf reinforcement mats) are typically manufactured from polypropylene, polyester, and polyethylene with service life over 25 years [31]. Temporary erosion mats can be used for shoulders and flat slopes before the establishment of vegetation while permanent erosion mats are used for steep slopes before and after the establishment of vegetation. Temporary erosion control mats degrade within a couple of years while permanent erosion mats are expected to last during the service period of the surfaces. Collin [32] suggested that permanent erosion control mats are needed for slopes with angles greater than 35°. Steep slopes are difficult to retain water; therefore, it is hard for vegetation to grow. Under such a condition, permanent erosion control mats play an important role in minimizing soil erosion. Some geosynthetic products can aid the establishment of vegetation by containing small compartments filled with fertilizer [33]. Other systems may have both seeds and fertilizer adhered [34].

Fig. 6 Geosynthetic erosion mat-protected slope (photo taken by J. Han)

Rickson [29] found that erosion control mats were more effective in reducing rain splash on easily erodible soil under high intensity rainfall and affected the hydrology and hydraulic properties of flow thus reducing soil erosion. The ability of various geosynthetic erosion control mats to minimize soil erosion has been investigated over different slopes, soil types, and climate conditions using both field and laboratory tests. Sutherland [35,36] reviewed numerous studies conducted up to the 1990s and nearly all the results from these studies demonstrated the ability of erosion control mats to minimize soil erosion.

Design of channels for erosion control is based on peak flow velocity and site conditions (e.g., soil type, slope angle, etc.). Typical approaches to prevent soil erosion include the use of vegetation, riprap, and geosynthetic liners or mats. Two types of design methods are available, which are based on: 1) the maximum permissible velocity (i.e., predicted mean flow velocity < maximum permissible velocity) and 2) the tractive force or shear stress (i.e., predicted shear stress < maximum allowable shear stress). The shear stress induced by water flow can be calculated as

$$\tau = \gamma_w \cdot d \cdot s, \tag{1}$$

where τ is the shear stress, γ_w is the unit weight of water, d is the depth of water flow, and s is the channel slope.

The maximum allowable shear stresses for typical unreinforced vegetation, erosion control blanket, and turf reinforcement mat are 0.14, 0.14, and 0.38 kPa, respectively. Colorado State University [37] evaluated the turf reinforcement mat over the textured/perforated geocell section infilled with topsoil at a $2H{:}1V$ slope angle. In this study, Kentucky bluegrass as vegetation was established through the turf reinforcement mat over a 14 week period. Flow tests showed that this erosion protection system survived under the shear stresses up to 0.76 kPa at the average velocity up to 8.1 m/s with the peak velocity over 8.8 m/s. This maximum allowable shear stress is about twice that of the typical turf reinforcement mat and almost the same as that for articulating concrete blocks (i.e., hard facing).

5 Geosynthetic-stabilized vegetated slopes

Even though erosion control mats can effectively minimize soil erosion, they cannot stabilize surficial soil because they have quite low tensile strength. Surficial slope failure is the most common slope failure mode because the surficial slope has low overburden stress, poor compaction, reduction of soil strength due to saturation, freeze-thaw, etc., increase of weight by water, and seepage force [8]. The surficial failure typically happens within a depth of 1.2 m. When the stability of the surficial soil becomes a concern, geogrid or geocell, which has relatively high tensile strength, can be used as reinforcement to stabilize the surficial soil as shown in Figs. 2(b)–2(e). When geogrid is used, long primary reinforcement is used to prevent deeper slope failure while short secondary reinforcement is used to prevent surficial slope failure as shown in Fig. 7. Collin [32] proposed a method to calculate the factor of safety against surficial slope failure using geosynthetic layers as follows:

$$FS = \frac{c'H + (\gamma_{sat} - \gamma_w)Hz\cos^2\alpha\tan\phi' + T_g(\cos\alpha\sin\alpha + \sin^2\alpha\tan\phi')}{\gamma_{sat}Hz\cos\alpha\sin\alpha} \tag{2}$$

where c' is the soil effective cohesion, ϕ' is the soil friction angle, H is the slope height, T_g is the summation of geosynthetic resisting force (controlled by pullout or rupture), and other parameters are previously defined.

Collin [32] also suggested that wrapped facing or hard facing should be used to maintain the surficial slope stability when the slope angle is greater than 45°. Figure 2(b) shows a typical cross section of a stabilized vegetated slope by wrapped-around geogrid. Figure 8 shows the actual application of this technology for the geogrid-stabilized vegetated slope. The left picture shows that vegetation was well established on the slope. The right picture shows the exposed wrapped-around geogrid with some overlap. Uniaxial geogrid was wrapped around in the project as shown in Fig. 8; however, biaxial geogrid is more commonly used in the United States for the wrapped-around facing.

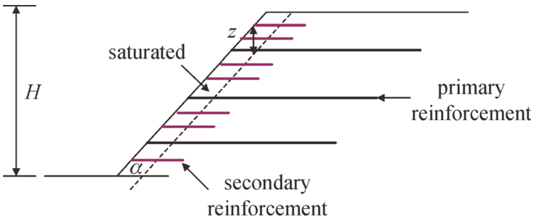


Fig. 7 Geosynthetic stabilization of surficial slope

On a steep slope, vegetation is hard to grow on the facing due to poor moisture retention. When the steep slope is constructed with welded-wire baskets stacked together with an offset, the offset can serve as a platform for vegetation to grow. Figure 2(c) shows a typical cross section of a steep slope with welded-wire baskets and wrapped-around geogrid. Figure 9 shows the actual application of this technology for a stabilized steep slope with an inclination up to 70°. This picture clearly shows the well-established vegetation on the facing of the steep slope.

Instead of wrapped-around geogrid or welded-wire baskets with wrapped-around geogrid, geocell infilled with soil can be used to stabilize the slope facing as shown in Fig. 2(d). DePasquale et al. [38] reported the application of geocell-stabilized earth walls as part of the flood protection system on Molly Ann's Brook in New Jersey. The 120 m long geocell-stabilized wall was 4.2 m tall at the highest point. Geocell of 200-mm high was used to construct the 1H: 4V earth wall. Each layer of geocell was set back 50 mm from the face of the underlying geocell. To prevent loss of material due to constant flow, the outer five cells of the first layer was filled with 19-mm stone while the rest of cells were filled with native silty sand and gravel. The wall was constructed over a 100-mm high geocell layer filled with concrete to avoid scour along the toe of the wall. The 50-mm setback on each layer was filled


(a) (b)

Fig. 8 Stabilized vegetated slope with wrapped-around geogrid. (a) Vegetated slope; (b) wrapped-around geogrid (photo taken by J. Han)

Fig. 9 Stabilized vegetated steep slope with welded-wire baskets and wrapped-around geogrid (courtesy of tensar international)

with topsoil and planted with Virginia Creeper.

Kelsey [39] reported a storm water channel reconstruction project. In this project, multiple geosynthetic materials were utilized. A PVC liner was placed under the channel area. Geocell was installed both on the $3H$: $1V$ channel slope and the channel bottom and then filled with soil. Grass seeds were applied on each bank. A turf erosion control mat was installed over the exposed soil for protection. The field performance showed that the vegetation was established well and the geosynthetics effectively prevented soil erosion and maintained the stability of surficial soils.

Figure 10 shows geocell-stabilized slope facing and concrete blocks used in the same slope project in Harbin, China. This photo clearly shows that both systems have performed well. However, clearly the geocell-stabilized slope facing is more cost-effective, environmentally friendly, and sustainable than the concrete blocks.

Fig. 10 Geocell-stabilized slope facing *vs.* concrete blocks (photo taken by J. Han)

6 Geosynthetic-stabilized vegetated shoulders and parking lots

Unpaved shoulders including aggregate and turf shoulders are commonly constructed in rural areas. Aggregate shoulders are stronger than turf shoulders. However, vegetation is hard to grow on aggregate shoulders but it can grow on turf shoulders. Therefore, turf shoulders are often green and sustainable. Unfortunately, unpaved shoulders are typically not designed to support heavy trucks. As a result, many aggregate or turf shoulders require maintenance by placing more material with re-grading and compaction. This solution is considered temporary and does not address the factors causing the problem; therefore, the problem often recurs.

Guo [40] and Guo et al. [41] conducted an experimental study on geocell-stabilized vegetated shoulders. This study included two parts: 1) the investigation of the effects of geocell, top soil, and soil mixture on the density of vegetation on unpaved shoulders and 2) the investigation of the effect of geocell stabilization on the increased strength and stiffness of base courses. The vegetation study was conducted outdoor as shown in Fig. 11, which includes unreinforced and geocell-stabilized sections. Three materials were used for the top soil: turf soil, 50/50 mixture of turf soil and aggregate, and well-graded aggregate. Two materials were used for the base courses: turf soil and 50/50 mixture of turf soil and aggregate. All the test sections had 50 mm thick top soil and 150 mm thick base course. The seeds of vegetation (primarily ryegrass and tall fescue) were uniformly spread over the 4%-slope soil surfaces of test sections. The vegetation density, leaf blade length, and collected biomass were monitored over a one-year period. The vegetation study indicated that the inclusion of geocell had no effect on the establishment or the growth of vegetation. The type of the top soil had an effect on the early establishment of vegetation and but did not have any apparent effect on the later vegetation growth because the roots penetrated through the base courses.

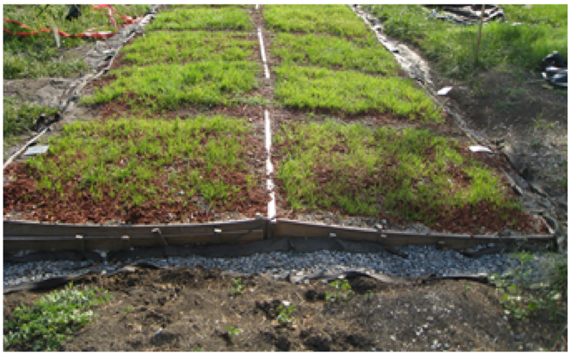


Fig. 11 Geocell-stabilized unpaved shoulders [42]

In addition to the vegetation study, a series of large-scale cyclic plate loading tests were conducted in a geotechnical test box on the same test sections as those in the vegetation study to investigate the effect of geocell stabilization of base courses [40]. The cyclic plate loading tests showed that the geocell stabilization could effectively reduce the permanent deformations of the unpaved shoulders under cyclic loading thus can extend the service life of the unpaved shoulders. This research confirmed that the combination of geocell stabilization and vegetation could be a viable option for vegetated unpaved shoulders.

Geocell has also been used to stabilize unpaved parking lots. Figure 12 shows geocell-stabilized gravel parking lots and geocell-stabilized vegetated parking lots, which were located at close distance. Geocell was exposed in the gravel parking lot under repeated traffic loading while no geocell could be found in the vegetated parking lot. Clearly, the geocell-stabilized vegetated parking lot is more sustainable than the geocell-stabilized gravel parking lot.

7 Geosynthetic-stabilized vegetated building surfaces

Vegetated building surfaces outdoor and indoor are often referred to as green walls, which include green facades and living walls [43]. Green facades are formed by climbing plants along the walls while living walls include a system (materials and technology) to support different types of plants. Living walls can be formed by plants on continuous lightweight screens or inside modular units (trays, vessels, planter tiles, and flexible bags) supported by a structure or fixed directly on the vertical or sloped surface [43]. Modular trays are often formed by several interlocked components, made of lightweight plastic material (e.g., polypropylene or polyethylene) or metal sheets (e.g., aluminum, galvanized steel or stainless steel). Modular trays and flexible bags are similar to geocells. Most modular units require supporting elements, growing media, vegetation, irrigation, and drainage. Growing media must be lightweight to reduce the weight of the system.

Figure 13(a) shows the award-winning building- the One Central Park building located in Sydney, Australia for its structural ingenuity and sustainability measures. This building includes vertical hanging gardens, in which plants, flowers, and vines are stretched over 50 m high. It is also considered the world’s tallest vertical garden (Wikipedia, accessed on May 22, 2016). Individually designed planter boxes supported by floor slabs were used to contain plants. No soil was used inside the boxes, instead, a mechanical system was installed to provide light, carbon dioxide water, and nutrients to the plants to maintain their growth and survival. Even though geosynthetic or geosynthetic-like material was not used in this building, it has been used in other buildings to create similar vegetated surfaces as shown in Figure 13(b). Geocell-like pockets were used to contain growing media and plants to form a green slope on a frame inside the building and this green slope is movable.

8 Summary

This paper reviewed the current practice and research in the geosynthetic stabilization of vegetated earth and building surfaces for environmental sustainability in civil engineering with the emphases on geosynthetics used for erosion protection, geosynthetic-stabilized slopes, geosynthetic-stabilized unpaved shoulders and parking lots, and geosynthetic-stabilized vegetated building surfaces. Vegetation is effective in minimizing soil erosion induced by wind and water. Before the establishment of the vegetation, protection of bare soil surfaces is necessary and important. Geosynthetic erosion control mats can effectively protect surficial soils and seeds from erosion. The type of erosion control mats (temporary or permanent) depends on the slope angle and duration of service. Stabilization of surficial soils on slopes and unpaved shoulders and parking lots requires geosynthetic, such as geogrid or geocell. Wrapped-around geogrid can effectively stabilize surficial soils on slope facing when the slope becomes steep. Geocell infilled with soil can also effectively stabilize surficial soils and unpaved shoulders and parking lots. The inclusion of geocell in unpaved shoulders did not have any effect on the vegetation establishment and


(a) (b)

Fig. 12 Geocell-stabilized gravel versus vegetated parking lots (photo taken by J. Han). (a) Gravel parking lot; (b) vegetated parking lot


(a) (b)

Fig. 13 Vegetated building surfaces (photo taken by J. Han). (a) Outdoor; (b)indoor

growth. Geosynthetic-like material has also been successfully used to stabilize vegetated building surfaces. Geosynthetic stabilization of vegetated earth and building surfaces can provide a viable solution for environmental sustainability in civil engineering.

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