Studies on the performance of geocomposite reinforced low-permeable slopes subjected to rainfall

B.V.S. Viswanadhamⁱ⁾ and Dipankana Bhattacharjeeⁱⁱ⁾

i) Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India.

ii) Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India.

ABSTRACT

Slope instability due to rainwater infiltration is a common problem in many parts of the world, and causes thousands of deaths and damages to infrastructures annually. The problem becomes severe if the soil within the slope has low permeability, and cannot dissipate the pore water pressure generated during the rainfall event. In recent times, the unavailability of good quality backfill material has led to the use of locally available low-permeability soil in reinforced slopes/walls construction. A viable alternative is the inclusion of geocomposites within the slope, to provide the drainage and reinforcement actions necessary to maintain slope stability against rainfall. In the present paper, the effect of rainfall on the seepage characteristics and global stability of slopes with and without geocomposites was investigated numerically using Geostudio (2012). For this purpose, a typical low-permeable slope having 2V:1H inclination and 7.2 m height was considered, and the change in matric suction in the slope with time was studied by subjecting it to a medium rainfall of intensity 22 mm/hr for a duration of 24 hours. It was observed that, the low-permeable slope exhibited high pore water pressures and low factor of safety under the applied rainfall intensity. However, the same low-permeable slope when provided with geocomposite layers, showed significant lowering of phreatic surface and reduced pore pressures, and was stable even 24 hours after completion of duration of rainfall. A parametric study was also conducted to determine the optimum position of placement of geocomposite layers within the low-permeable slope subjected to rainfall. The results indicated that the placement of geocomposite layers at bottom portion of the slope was found to be most effective, as compared to middle and top positions. The use of dual-function geocomposites within slopes subjected to rainfall thus eliminates the necessity of procuring expensive high-permeability fill materials, thereby economizing the project.

Keywords: geosynthetics, geocomposite, reinforced slopes, low-permeable slopes, rainfall, seepage.

1 INTRODUCTION

Slope instability is a common problem in many parts of the world, and cause thousands of deaths and severe infrastructural damage each year. Although slope failures may occur due to construction activities, many cases of failure have been reported in natural soil slopes and excavated slopes simply due to rainwater infiltrating into an otherwise stable slope. This may be attributed to the reduction in matric suction, or conversely, increase in pore water pressure within the slope when water infiltrates the unsaturated soil. The problem becomes severe if the fill material or the soil within the slope has low permeability, and cannot dissipate the pore water pressure generated during the rainfall event. Generally, cohesionless soils possessing good drainage characteristics are preferable as fill materials in soil walls or slopes due to their high strength, ease of compaction, ability to

dissipate excess pore water pressures and their inherent resistance to creep. However, the scarcity of good quality fill materials has recently led to the use of low permeable soils (Pathak and Alfaro, 2010), which results in some major difficulties including development of pore water pressures, excessive deformations, and reduction in shear strength at the interface of soil and reinforcement, as reported by Koerner and Soong (2001) and Yoo and Jung (2006).

A novel technique of providing stability in slopes with backfill soils with large percentage of fines against rainfall infiltration is the use of geosynthetics within the slope. Alternatively, it is possible to combine the drainage characteristics of a non-woven geotextile with the strength or stiffness of a stronger reinforcing geosynthetic like geogrid, thereby producing a hybrid geosynthetic, or geocomposite, as

they are commonly referred to. Various researchers like Zornberg and Mitchell (1994), Christopher et al. (1998), Koerner and Soong (2001) and Raisinghani and Viswanadham (2010, 2011) have recommended the use of permeable inclusions as an effective alternative to relieve the pore pressure build-up due to marginal soil. Christopher et al. (1998) and O'Kelly and Naughton (2008) also suggested the use of geocomposites in reinforced earth structures as a remedial measure, to provide both reinforcement and preferential drainage channels, thereby increasing the factor of safety for the slope. This design approach may even lead to the elimination of external drainage requirements (Mitchell 1995).

Till date, studies on the effect of inclusion of geocomposites in low-permeable slopes subjected to rainfall is limited. Hence, in the present paper, an attempt has been made to establish the possible use of geocomposites as a dual-function reinforcement and drainage medium to provide a solution for dissipating the excess pore water pressures generated within the low permeable soils during rainwater infiltration. For this purpose, a typical low-permeable slope having 2V:1H inclination and 7.2 m height was considered, and the changes in matric suction in the slope with time was studied by subjecting it to a medium rainfall of intensity 22 mm/hr for a duration of 24 hours using Geostudio (2012). The above study also highlights the possibility of using locally available low-permeability backfills in reinforced soil construction, thereby economizing the project.

2 SLOPE CONFIGURATION AND PROPERTIES OF MODEL MATERIALS

A typical slope geometry with height 7.2 m and inclination of 63° (2V:1H) made of low-permeable cohesive soil was adopted in the present study for studying the effects of rainfall on slope stability, as presented in Fig 1a. This slope cross-section was selected so that the unreinforced slope configuration without any rainfall had a critical factor of safety just above 1. An initial water table was maintained near the toe of the slope before the onset of rainfall, and a 1.8 m thick sand layer was provided at the slope base to act as drainage layer. The model soil was formulated by blending sand and kaolin in the proportion of 80:20 to represent the characteristics of low-permeable backfill soils. The various geotechnical properties of the model soil as determined in the laboratory are tabulated in Table 1, which were subsequently given as input values for the numerical analysis using Geostudio (2012). The geocomposite selected in the study is a combination of woven acrylic geogrid (reinforcing material) and non-woven polypropylene geotextile (drainage material), as presented in Fig 1b.

Fig. 1a. Slope configuration adopted in the study

Fig. 1b. Dual-function geocomposite used in the study

Table 1. Summary of properties of soil used in the study.

Properties	Value
Specific gravity	2.62
Sand [0.075-4.75 mm] (%)	80
Silt [0.075-0.002 mm] (%)	10
Clay [<0.002 mm] (%)	10
USCS	SM
Liquid limit (%)	Not relevant
Plastic limit (%)	NP
Maximum dry unit weight, γ_{dmax} (kN/m ³)	18.75
Optimum moisture content, OMC (%)	9
Cohesion, c' (kPa)	11.6
Angle of internal friction, ϕ' (°)	27
Co-efficient of permeability, k (m/sec)	1.54×10^{-6}

The model slope was initially subjected to a medium rainfall intensity of 22 mm/hr for a duration of 24 hours, in order to monitor the changes in soil suction of the unsaturated slope during this period. Afterwards, the effect of inclusion of geocomposites in the low-permeable slope was studied by introducing nine numbers of geocomposite layers of length 6.12 m (i.e., 0.85 times the vertical height of the slope) parallel to the slope face, along the entire vertical height of the slope, with a uniform vertical reinforcement spacing of 0.8 m. The tensile and hydraulic properties of the hybrid geosynthetic used in the study are presented in Table 2.

Table 2. Properties of geocomposite used in the study

Properties	Value
Normal coefficient of permeability (m/sec)	12.59×10^{-5}
Tangential coefficient of permeability (m/sec)	7.975×10^{-4}
Tensile load at peak strain (kN/m)	55.35
Bond skin friction (kPa)	12.49

3 RESULTS AND DISCUSSION

The performance of the selected low-permeable slope subjected to rainfall, with and without geocomposite layers, from seepage and stability point of view are discussed in consecutive sections.

3.1 Seepage analysis using SEEP/W

During seepage analysis using the finite element software SEEP/W (a product of Geostudio 2012), the flux boundary q equal to the desired rainfall intensity and duration was applied at the surface of the slope. In addition, non-ponding boundary condition was adopted in order to prevent excessive accumulation of rainfall on the slope surface. The nodal flux Q equal to zero was applied along the sides in order to simulate no flow zone, and an impermeable layer was created at the bottom of the slope to allow proper build-up of pore pressures during rainfall events. Initial hydrostatic pore-water pressure condition for the slope was taken from the water table located near the toe of the slope, with a limiting negative pore-water pressure of 50 kPa, to prevent the generation of unrealistic pore-water pressures. In addition, suitable unsaturated soil parameters in terms of hydraulic conductivity functions and volumetric water content functions were fitted in the numerical model using the Fredlund and Xing (1994) method.

The analysis was carried out with an approximate global element size of 0.25m, with 3597 nodes, and 3582 elements. The finite-element model down to 1m below the slope surface had a mesh size of approximately 0.125m in order to obtain accurate results within the infiltration zone. The mesh was generated with a pattern of quadrilaterals and triangles. A linear time increment of 10 steps was selected at 4.8 hours interval up to 48 hours. The selected time increment was related to a period of rainfall of 24 hours at the rate 22mm/hr. Figures 2(a-c) represent the seepage analysis results of the unreinforced low-permeable slope during rainfall in terms of pore water pressure contours (kPa). From Figs. 2(a-c), a rapid decrease in suction, and an increase in phreatic surface due to rainfall can be observed, which is detrimental for the slope stability.

(a) 4.8 hr after rainfall

(b) 9.6 hr after rainfall

(c) 24 hr after rainfall (Rainfall stopped)

Fig. 2. Seepage analysis results for the unreinforced slope during rainfall of 22mm/hr in terms of the pore water pressure contours (kPa)

In order to improve the performance of the low-permeable slope subjected to rainfall, nine geocomposite layers of length 6.12 m and vertical spacing of 0.8 m were incorporated within the slope. The hybrid geosynthetics were modelled as interface material model in conjunction with interface elements added to the mesh to represent the thickness of the geosynthetics. In this case, tangential (transmissivity) and normal (permittivity) conductivity values of the geocomposite layers were incorporated separately as input in the analysis (values as tabulated in Table 2), to simulate reduced flow in the cross-plane direction than in the tangential direction. The seepage analysis results of the reinforced slope in terms of pore pressure contours (kPa) at various stages of rainfall are presented in Figs. 3(a-c). From Figs. 3(a-c), it can be observed that, the geocomposite layers provided preferential drainage channels for pore pressure

dissipation, and caused negligible change in the phreatic surface during and after the rainfall event.

(a) 4.8 hr after rainfall

(b) 9.6 hr after rainfall

(c) 24 hr after rainfall (Rainfall stopped)

Fig. 3. Seepage analysis results for the reinforced slope during rainfall of 22mm/hr in terms of the pore water pressure contours (kPa)

The effectiveness of the geocomposite layers in dissipating the excess pore water pressure generated within the slope due to rainfall, as compared to the unreinforced slope is also brought out from Fig 4, which depicts the variation of pore water pressure observed at the nodal points located at the base of the slope with time due to rainfall. The pore pressure values (u) have been normalized with respect to unit weight of the soil (γ) times the height of the slope under consideration (h).

Fig. 4. Normalized pore water pressure at the base of the slope with time due to rainfall with and without hybrid geosynthetic layers

3.2 Stability analysis using SLOPE/W

The phreatic surfaces obtained from SEEP/W analyses were incorporated into SLOPE/W (Geostudio 2012), a limit-equilibrium based software, for performing stability analyses of the low permeable slope under rainfall condition, with and without geocomposite layers. The static global factor of safety for the slope under these two cases was calculated using modified Bishop's method of slices. The reinforcement function of the geocomposite layers was taken into account in SLOPE/W by feeding the ultimate fabric capacity (kN/m) and bond skin friction value (kPa) of the geocomposite layers (mentioned in Table 2) as input parameters in the analyses, along with suitable reduction factor for installation damage only. While performing the stability analysis, the reinforcement function of the geogrids was considered along with the in-plane drainage capability of the geotextiles to simulate the dual-function geocomposites, and a coupled pore-pressure analysis was carried out to arrive at the minimum factor of safety values during rainfall. The factor of safety of the slope obtained with and without geocomposite layers have been tabulated with time in Table 3, and a typical cross-section of the of the reinforced slope 48 hours after rainfall along with a circular slip surface is presented in Fig 5.

Fig. 5. Typical output of SLOPE/W analysis giving the critical FOS value at the end of 48 hours for the reinforced slope

Table 3. Variation of factor of safeties with time during rainfall in the unreinforced and hybrid geosynthetic reinforced slope

Time (hour)	Unreinforced slope	Reinforced slope
0	1.036	1.580
4.8	0.989	1.555
9.6	0.987	1.546
14.4	0.986	1.543
19.2	0.981	1.542
24	0.979	1.540
28.8	0.978	1.561
33.6	0.978	1.567
38.4	0.978	1.570
43.2	0.978	1.574
48	0.978	1.576

As can be seen from Table 3, with the progress of rainfall, failure occurs in the unreinforced slope just 4.8 hours after the onset of rainfall, whereas, the slope reinforced with geocomposite layers is stable even 24 hours after the completion of duration of rainfall.

3.3. Effect of position of geocomposite layers

The effect of relative placement of a geocomposite layer within a reinforced soil slope was studied by subjecting the low-permeable slope to a rainfall of intensity 22 mm/hr monitored for 2 days with the inclusion of a single layer of geocomposite of length 6.12m. The analysis was carried out for three different positions of the geocomposite layer, viz, at the top of the slope, middle of the slope, and at the bottom of the slope, keeping geogrid reinforcement in rest of the eight reinforcement layers. The seepage and stability analyses results thus obtained are presented graphically in Fig 6 and Fig 7 respectively.

Fig. 6. Normalized pore water pressure at the base of the slope for various positions of geocomposites

Fig. 7. Stability analysis results of the slope for various positions of geocomposites

From Figs 6 and 7, it can be concluded that the middle position is the least effective in improving the seepage and stability characteristics of the low-permeable slope subjected to rainfall, while the top and bottom positions yielded close results, with the bottom position proving to be more effective with respect to pore water pressure reduction and maintaining stability

4 CONCLUSIONS

The non-woven geotextile component of the geocomposite provided alternate drainage path for the dissipation of excess pore water pressure generated due to rainfall, and the geogrid component provided the necessary reinforcement function needed to maintain stability under rainfall. Thus, the provision of geocomposite layers caused lowering of the phreatic surface by reducing the normalized pore pressure values from 1.8 in the unreinforced slope to about 0.35 in the reinforced slope at the end of 24 hours when rainfall stopped. When monitored for a

further 24 hours after completion of rainfall, the reinforced slope recorded a value of 0.26, whereas, the unreinforced slope maintained the normalized pore pressure value of 1.8, thereby showing its inability to dissipate the pore pressures generated due to rainfall. The stability analyses indicated that the geocomposite reinforced slope exhibited higher factor of safeties compared to the unreinforced slope during the progress of rainfall, and was stable even 24 hours after completion of duration of rainfall. The numerical analyses results further highlighted that the bottom position is most effective for placement of hybrid geosynthetic layer in low-permeable slopes subjected to rainfall, followed by top and middle positions respectively.

Further work is in progress in this direction to validate numerical results with a centrifuge-based physical model tests by creating rainfall at high gravities.

REFERENCES

- 1) Christopher, B.R., Zornberg, J.G. and Mitchell, J.K. (1998): Design guidance for Reinforced soil structures with marginal soil backfills, *Proceedings of the 6th International Conference on Geosynthetics (6ICG)*, Volume 2, Atlanta, Georgia, Industrial Fabrics Association International (Pubs.), pp. 797-804.
- 2) Fredlund, D.G. and Xing, A. (1994): Equations for the soil- water characteristic curve, *Canadian Geotechnical Journal*, 31(4), 521- 532.
- 3) Geostudio 2012: SLOPE/W and SEEP/W, Ver. 7.15, User's Guide, *Geo-Slope International Ltd*, Calgary, Canada.
- 4) Koerner, R.M. and Soong, T-Y. (2001): Geosynthetic reinforced segmental retaining walls, *Geotextiles and Geomembranes*, 19(6), 359-386.
- 5) Mitchell, J.K. (1995): Reinforced soil structures with poorly draining backfills. Part II: Case Histories and Applications, *Geosynthetics International*, 2(1), 265-307.
- 6) O'Kelly, B.C. and Naughton, P.J. (2008): Technical note on the interface shear resistance of a novel geogrid with in-plane drainage capability, *Geotextiles and Geomembranes*, 26(4), 357-362.
- 7) Pathak, Y. P. and Alfaro, M. C. (2010): Wetting-drying behavior of geogrid-reinforced clay under working load conditions, *Geosynthetics International*, 17(3), 144-156.
- 8) Raisinghani, D.V. and Viswanadham, B.V.S. (2010): Evaluation of permeability characteristics of a geosynthetic-reinforced soil through laboratory tests, *Geotextiles and Geomembranes*, 28(6), 579-588.
- 9) Raisinghani, D.V. and Viswanadham, B.V.S. (2011): Centrifuge model study on low permeable slope reinforced by hybrid geosynthetics, *Geotextiles and Geomembranes*, 29(6), 567-580.
- 10) Yoo, C. and Jung, H.Y. (2006): Case History of Geosynthetics Reinforced Segmental Retaining Wall Failure, *Journal of Geotechnical and Geoenvironmental Engineering*, 132(12),1538-1548.
- 11) Zornberg, J.G. and Mitchell, J.K. (1994): Reinforced soil structures with poorly draining backfills. Part I: Reinforcement Interactions and Functions, *Geosynthetics International*, 1(2), 103-147.