Analysis of a Slope Failure in Los Canales Road in Carolina Puerto Rico after the Tropical Storm Irene

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Abstract *— Natural slopes are susceptible to instability due to different factors. This study investigates the factors that contributed to the Los Canales slope failure. The main factors that could contribute to the slope failure are slope saturation due to rainfall infiltrations as consequence of the tropical storm Irene and slope profile change due to cutting of the slope toe. The soil type and properties were determined through laboratory tests on a soil sample. A preliminary analysis using stability charts was performed to compute the factor of safety and locate the origin of the potential failure surface. The failure surface was assumed as circular due to a visual inspection of the slope failure. The limit equilibrium method was used with the computer software SLOPE/W to find the critical surface failure. This study intends to provide slope restoration considerations for the failed slope reducing the existing vulnerability in the site.*

Key Terms *— Slope Restoration, Slope Saturation, Slope Toe Cutting, Stability Analysis.*

INTRODUCTION

After the Tropical Storm Irene in the past month of August in 2011, a slope failed covering the road of Los Canales in Carolina, Puerto Rico. A community was isolated for two days due to this event. A few weeks before the storm, a gutter was constructed at the side of the road removing a toe portion from the slope. This study is intended to consider the influence of the disturbance due to cutting of the toe and the soil saturation effect due to the storm rainfall. The precipitation data for that period will be evaluated for determination of its contribution. To perform an accurate analysis and modeling, a disturbed soil sample was used to find the soil properties through several laboratory tests. The software SLOPE/W was used to model the slope and perform a limit equilibrium analysis. Recommendations for the slope restoration are given based on the analysis results. This study intends to assess the remedial measures for a suitable slope restoration reducing the existing vulnerability in the site.

SCOPE

The scope of this study covers the contribution of the following factors: analysis of the rainfall infiltration and disturbance effect due to cutting of 24 inches of the toe slope. The precipitation data for the month of August in 2011 was compared to the average total precipitation for that area to evaluate the effect of the rainfall infiltration that lead to saturation of the slope soil. This study pretends to determine the contribution of each factor to the slope failure. This analysis is fundamental when selecting the appropriate slope restoration technique. This is a case history for the slope situated in the road Los Canales in Carolina P.R., and the final recommendations of this study apply to this particular case.

BACKGROUND

Natural slopes are considered as any soil mass of natural deposits that has an angle with the horizontal. It's essential to identify and characterize natural slopes behavior, parameters and properties to adequately perform a slope failure analysis. The soil mass in a slope has a natural predisposition to slide under the influence of gravitational forces. The shearing resistance of the slope soil must balance these forces to prevent landslides. Slope failures occur mainly when the shearing resistance cannot counterbalance the forces tending to cause movement along any surface in the slope. A common terminology to describe the features of a landslide is illustrated in Figure 1.

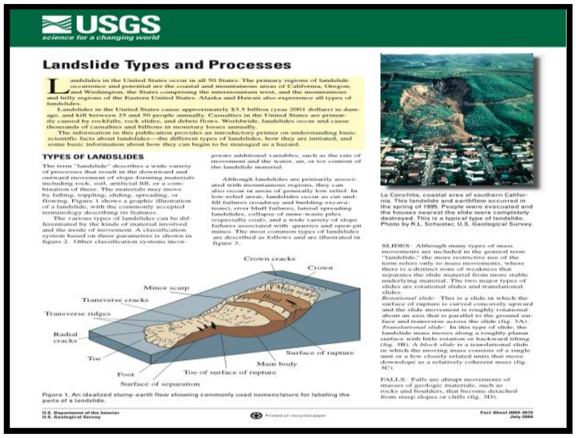

Figure 1
Landslide Parts Labeling [1]

Slope failures may arise different type of movements. The basic type of slope movements are slides, falls, topples, flows and spreads.

Slides may involve planar or rotational sliding of the soil mass. A planar slide is distinguished by a parallel displacement of a soil mass, as shown in Figure 2-B. These slides often occur due to movement along planar discontinuities or a parallel plane of weakness. A rotational slide has a concave curved upward surface of rupture and its slide movement is rotational about an axis, as shown in Figure 2-A. Block sliding also falls under this category, consisting of a translational movement in which the moving mass moves downslope, as shown in Figure 2-C. Falls are sudden movements of soil masses or rocks that separate from a steep wall or cliff, as shown in Figure 2-D. This detachments can occurs due to discontinuities in the layers of the soil mass. Toppling failures are characterized by a frontward rotation of a unit due to gravitational forces, forces exerted by adjacent units or by fluid in soil fissures, as shown in Figure 2-E. Flows are continuous movements where the soil mass behaves as a viscous flow. They are commonly categorized as Debris flows (Figure 2-F), Debris avalanche (Figure 2-G), Earthflow (Figure 2-H), Mudflow and Creep (Figure 2-I). These categories differentiate generally by the materials, causes, shape and velocity of movement of the flow.

Spreads are another type of movement that usually occur on level soil or nearly flat slopes (Figure 2-J). This slope movement is caused by liquefaction phenomena of underlying material.

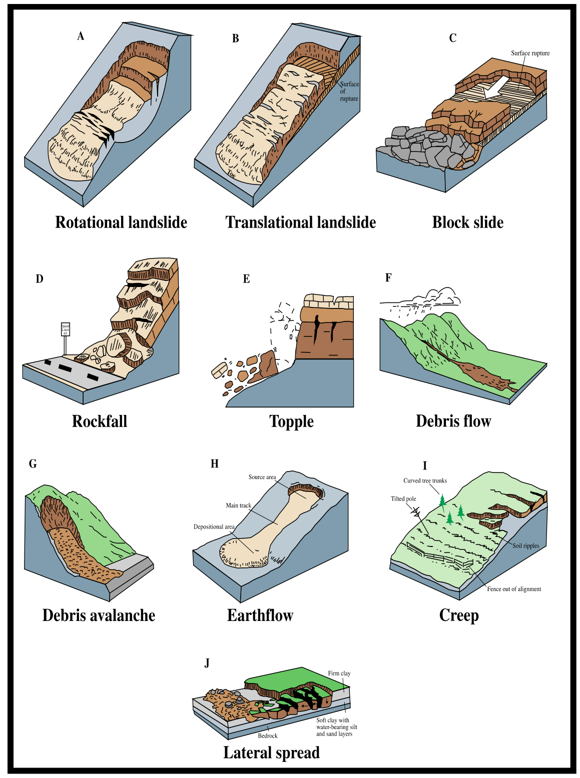

Figure 2
Slope Movements Types [1]

SITE DESCRIPTION AND SLOPE GEOMETRY

The slope is located on a mountainous area to the south of Carolina near road PR-853. The slope is at an elevation of 530 ft. from the sea level and has a height of 30 ft. The incline length and horizontal length are approximately 76 ft. and 70 ft., respectively. The slope inclination makes an angle with the horizontal of 23 degrees.

After a visual inspection of the failure, a rotational soil movement type was assumed creating a circular failure surface. Figure 3 shows the landslide movement over the road. In Figure 4 the slip surface is shown through a portion of the slope's crest side-view.

Figure 3
Landslide Movement (Front View)

Figure 4
Slope Side-view of the Failure Surface

MATERIAL TYPE AND PROPERTIES

To find the soil properties a soil sample was used and several laboratory tests were performed. A grain size distribution test [2] was performed to determine the size range of particles in the soil; the results are shown in Figure 5. A soil-washing laboratory was performed to identify the amount of fines. The amount of soil passing the sieve #200 was 84 percent, which means the material is cohesive with a small amount of coarse particles. The grain size distribution for the soil-washing results is show in Figure 5.

A hydrometer test was performed to identify, through sedimentation of soil particles, the amount of particles size smaller than 0.075mm. Results are show in Figure 5. Clay particles are generally defined as particles smaller than 0.002mm [3]. The amount of cohesive particles smaller than 0.002 mm is 17.8%, this indicates the soil is mainly compose of silt.

The consistency limits were determinate performing the liquid limit, plastic limit and plasticity index tests [4]. The results for the liquid limit test are shown in Figure 6. For a 25-blow count the liquid limit value obtained was 48%.

The results obtained for the plastic limit test are shown in Table 1. The plastic limit value obtained was 29.2%. The difference between the liquid limit and the plastic limit represent the plasticity index and the value obtained was 18.8%. With the Atterberg limits and the grain size distribution we can classify the soil using the unified soil classification system (USCS) [5]. The soil was classified as inorganic silt with sand. Based on the soil classification the unit weight value of 92.5 pcf was chosen for this soil type [6].

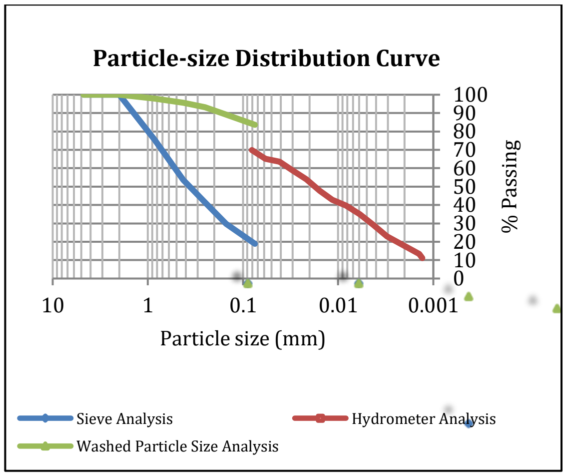

Figure 5
Laboratory Test Results

Table 1
Plastic Limit (PL) Test Results

W(gr)	PL-1	PL-2	PL-3
Cup No.	78	41	96
W cup+moist	45.1	44.7	44.5
W cup+dry	43.2	43	42.7
W cup	37	36.7	36.7
w(%)	30.6	27.0	30.0

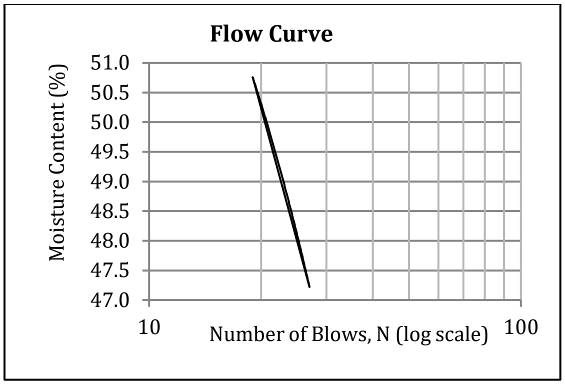

Figure 6
Liquid Limit Test Results

MATERIAL PARAMETERS

To perform a slope stability analysis the angle of friction and cohesion parameters are indispensible. These shear strength parameters were obtained performing a direct shear test [7] on the soil sample. The results are shown in Figure 7. The test was performed applying vertical stresses of 5, 10, 15 psi to three remolded soil samples. The angle of friction is the tangent of the slope for each curve. The peak angle of friction (ϕ_p) was 30 degrees and the residual angle of friction (ϕ_r) was 13.3 degrees. Since the material was a cohesive one a cohesion of 205.35 psf was obtained for the peak analysis.

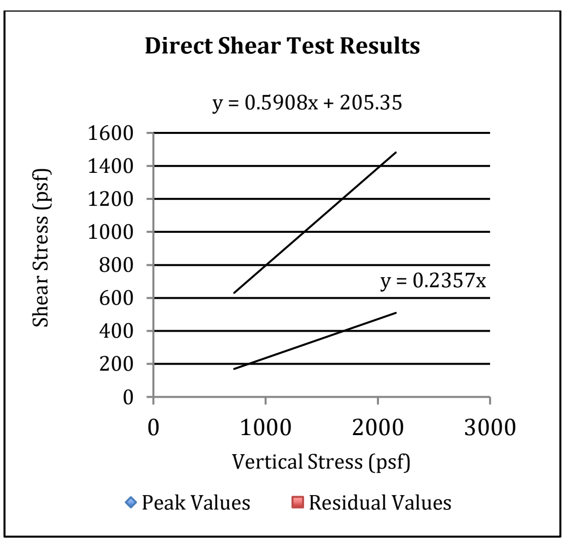

Figure 7
Plot of Direct Shear Test Results

For slope stability analyses on slopes that have already failed, residual values are commonly considered for angle of friction. The shear strength along the defined slip surface is reduced to a residual value due to the large deformations and displacements in the slip surface. The slip surface its assumed to have a reduce shear strength when performing the limit equilibrium analysis since the mass along the sliding surface develops great deformations and displacements. Since the slope being analyzed had failed residual values were used.

STABILITY ANALYSIS

Many engineers have studied slope failures and develop numerous methods based on the different failure surfaces assumed. In this case history the failure surface is known to be a circular one. Circular failure surfaces commonly occur when the landslide movement of the soil mass is rotational. For this type of failure surface the limit equilibrium analysis is used.

For this analysis two major types of procedures are used: mass procedure and method of slices. The Mass procedure takes the soil mass as unit assuming a homogeneous soil. This procedure is useful when performing a quick preliminary analysis. The method of slices instead divides the soil mass into several vertical slices. This method accounts for nonhomogeneous soils, pore water pressures and variation of the normal stresses along the potential slip surface.

Preliminary Analysis

Stability charts are a mass procedure method that can be used to perform preliminary analyses. For this analysis Janbu charts [8] were used for a soil with an angle of friction greater than zero. A preliminary factor of safety of 1.26 was computed and the coordinates of the critical center were x=22.5 and y=50.7. This critical center was used in the software SLOPE/W as reference for the critical slip surface.

COMPUTER SOFTWARE ANALYSIS

Many approaches or advances on the method of slices had been developed during the last years. For this analysis the method of Morgestern-Price was used since it includes all the inter-slice forces and satisfies all the static equations. The computer software SLOPE/W [9] was used to perform the analysis. Three models were selected for the analyses to clearly distinguish the contribution of the soil saturation and disturbance due to cutting of the toe.

Model 1: Original Conditions

The first model represents the original dry conditions of the slope before the storm and toe removal. For this model the peak value of the angle of friction was used since the model intended to represent the stable condition of the slope before failure. After performing the analysis a factor of safety (FS) of 2.33 was obtained. For slope stability analyses a factor of safety greater than 1.5 is considered stable. Figure 8 shows the slip failure surface and the origin of the radius.

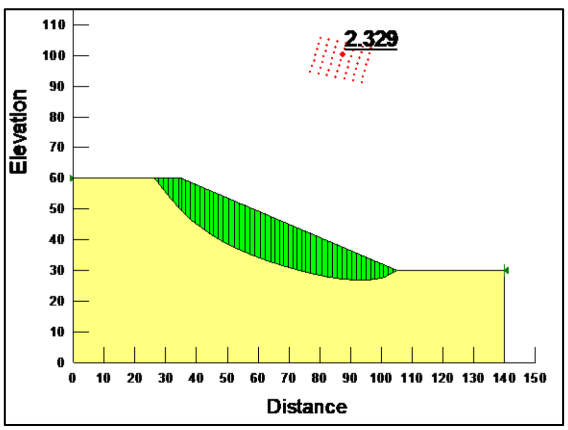

Figure 8
Model 1 Analysis Results

Model 2: Soil Saturation Analysis

The second model represents the slope at failure after the storm. This model considers the effect of soil saturation but not toe removal. A piezometric line was added along the slope face to the model to saturate the soil. A residual value for the angle of friction was used since the model represents the conditions at failure.

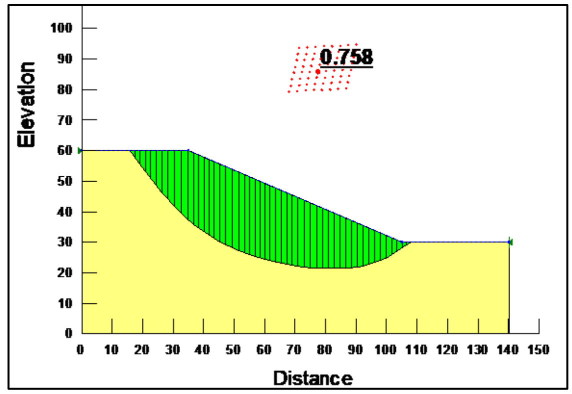

Figure 9
Model 2 Analysis Results

Figure 9 shows the failure surface, the factor of safety and the origin of the radius for model 2. A factor of safety of 0.76 was obtained, which was less than 1.5, indicating slope failure.

Model 3: Soil Saturation with Toe Removal

The third model considers a piezometric line representing the soil saturation as well as the 24 inches removed from the slope's toe. Figure 10 shows the critical center and the failure surface. A factor of safety of 0.75 was obtained. This value is less than the minimum factor of safety therefore the slope is at failure.

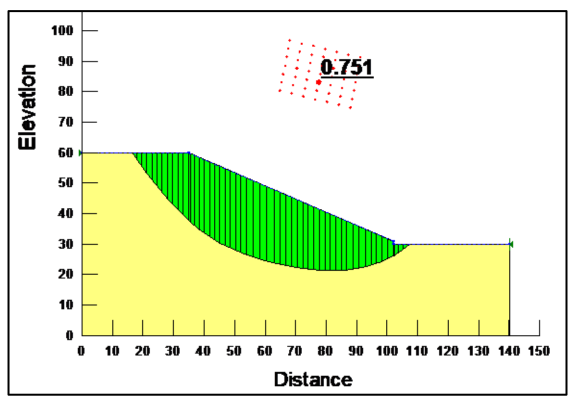

Figure 10
Model 3 Analysis Results

ANALYSIS OF RESULTS

Table 2 shows the results obtained from the analyses performed for each condition. Model 1, explained before, represents the original dry conditions of the slope and the factor of safety was 2.33 approximately. Model 2 analyzes the effect of the rainfall through saturation of the soil and the factor of safety obtained was 0.76, this value indicates instability or failure of the slope. Comparing Model 1 with Model 2 there is a decrease in the shear resistance and a notable increase in the mobilized stress. This change in stress is a triggering factor to landslide development. Is due to heavy rainfalls that pore water pressures within the slope increase and therefore the shear strength of soils decreases compromising the stability of the slope. Model 3 considers the soil saturation and the portion of the toe removed. The factor of safety obtained for this model is 0.75, which indicates slope failure. However this value it’s not too different from the value obtained in the analysis performed in Model 2. Therefore it can be concluded that the removal of the toe did not cause the slope failure.

A stability analysis using the ordinary method of slices was performed by hand calculations. A comparative table with the SLOPE/W results is presented in Table 3. For Models 1 and 2 the factor of safety obtained by hand calculations is smaller than the obtained by the computer software. This could be due to the limited amount of slices that are used in hand calculations. Also the computer software method used, Morgestern-Price, considers all the forces in the slices and the ordinary method does not consider the inter-slice forces. However both values for Model 1 imply a stable slope and for Model 2 both results imply instability or slope failure. For Model 3 both results are similar. Due to the difference in methods and the computer software results the factor of safety by hand calculation expected for Model 3 should be smaller than the factor of safety by hand calculation of Model 2. This value was affected by the geometry of the slope, the critical slip surface and the vertical slices width. The results of the hand calculation analysis for this model show that disturbance of the slope geometry is difficult to represent through this analysis.

Table 2

SLOPE/W Analyses Results

Model	FS	Shear Resistance Stress (psf)	Shear Mobilized Stress (psf)
1	2.329	194.39	83.48
2	0.758	150.39	198.47
3	0.751	147.90	196.97

Table 3
Factors of Safety of Performed Analyses

Model	FS (Hand Calculation)	FS (Software)
1	2.07	2.33
2	0.51	0.76
3	0.74	0.75

The total precipitation during the month of August for the slope location was 18.56 inches and the greatest precipitation in a 24-hour rain was 5.91 inches during the days 21 and 22 (storm strike) [10]. The total precipitation for the summer months is presented in Figure 11. This data shows that the rainfalls during the 2011 summer were exceedingly great compared to the previous years. This figure also shows heavy rainfalls during the months of June and July in 2011 prior to the storm.

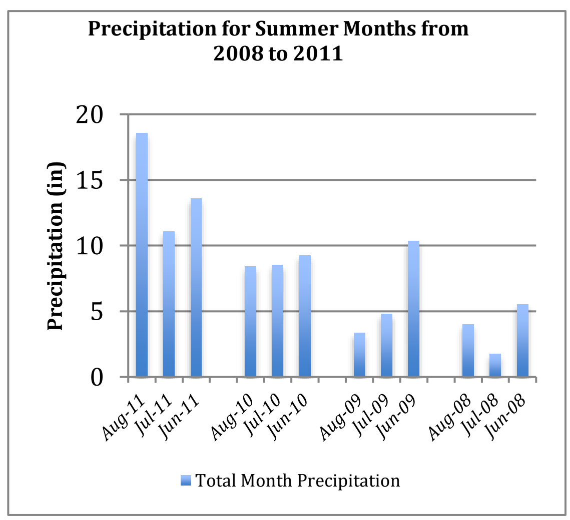

Figure 11
Summer Precipitation from 2008 to 2011

This contributed to the process of saturation of the slope and a gradual decrease of the soil shear resistance. Finally in August 2011 the storm rainfall ultimately drove the slope to failure.

CONCLUSIONS

After performing the analyses the following conclusions were drawn:

- The slope was stable at the original dry conditions
- The heavy rainfalls during the summer of 2011 contributed to the slope instability
- The rainfall caused by the storm was the triggering factor for the slope failure
- The toe portion removed did not affect significantly the instability of the slope compared to the soil saturation effect

As conclusion for this study, the main factor contributing or causing the failure of Los Canales slope was the saturation of the soil due to the heavy rainfalls.

RECOMMENDATIONS

Although a detailed subsurface exploration is recommended some suggestions are given in this section, as corrective measures to consider, for the slope restoration.

Based on the analysis results, the soil properties and slope geometry, soil nailing is highly recommended for the slope restoration. This in-situ reinforcement is appropriate since the space at the toe is limited. Figure 12 shows a cross-section of a typical soil nailing design to improve slope stability due to a road widening. This technique is also suitable for sites with difficult access like the site being addressed in this study.

The soil nailing technique involves installation of closely spaced steel reinforcing bars, which are inserted in pre-drill holes and then grouted in place. Nails holes are commonly drilled with four to five foot spacing. The nail length is designed to extend beyond the possible failure surface, roughly 75 to 100 percent of the slope height. The grout function is to transfer the stresses from the ground to the nail as result of a frictional interaction with the soil particles. The grouting also provides protection to the soil nails to prevent corrosion. The temporary facing function is to support the exposed soil during the drilling process. The material used is commonly reinforced shotcrete. The permanent face is placed over the temporary facing after the soil nailing process has finished and the nail caps have been tightened. The material used for permanent facing varies form reinforced concrete to prefabricated panels. Through this technique the soil strength is improved due to the development of the tensile forces in the nails.

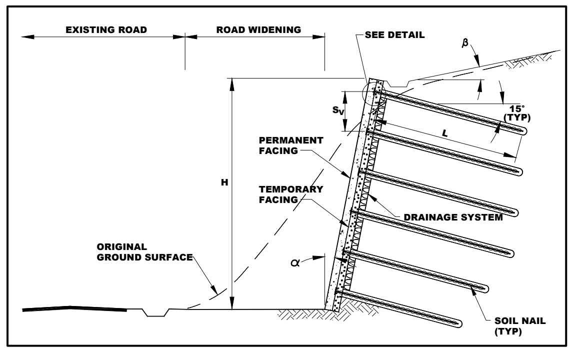

Figure 12
Soil Nailing Design [11]

Compared to other techniques soil nails cause less environmental impact. For the restoration of this particular slope soil nailing can be more efficient than a conventional concrete gravity wall, which will involve excavation of the slope base below the failure surface to provide the appropriate width for the base of the wall. An appropriate refill material must be used combined with this technique. The selected material must account for proper reinforcement and high permeability to avoid and prevent future landslides due to saturation of the slope mass.

Another recommended slope restoration technique is the use of geosynthetics. These are widely used in geotechnical engineering applications. Among the different types of geosynthetics are geotextiles, geomembranes, geogrids, geonets and geocomposites. They are manufactured with polymer materials and their main applications are separation, reinforcement, filtration and drainage in soils. For the restoration of this particular slope, geogrids can be used to provide reinforcement on the slope. Geogrids are reinforcement elements that develop tensile forces in the soil contributing to the slope stability. The geogrids sheets are embedded horizontally between the granular backfill layers transferring the shear stress of the soils to the geosyntethic sheet as tensile force through friction.

For drainage applications geonets are widely used since they can channel water quickly from the soil. Their main function is to provide a drainage layer avoiding saturation in soils of low permeability. This is highly recommended for the restoration of this slope since the main contributing factor for the failure was the saturation of the soil mass. Figure 13 shows the geonets structure. The construction procedure of geosynthetics is simpler than soil nailing since they can be placed during the construction of the backfill.

Is highly recommended that when selecting the backfill material, a granular soil with a high permeability and greater angle of friction be used to improve the strength of the soil. Increasing the soil resistance, permeability and the factor of safety.

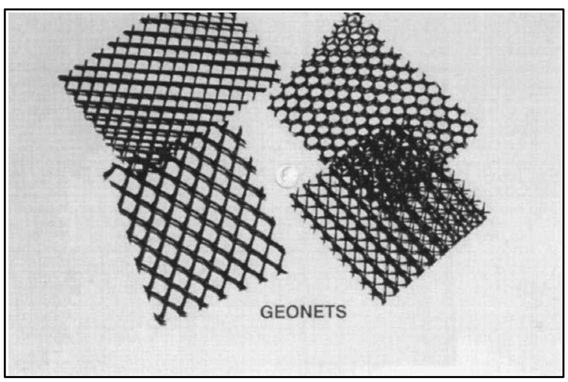

Figure 13
Geonets Used as Sheet Drains [12]

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