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Comparison of Factor of Safety between LEM and FEM for Geotextile Reinforced Embankment on Difficult Foundation

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Abstract. Geotextile Reinforced Embankment (GRE) stability analysis by software's are widely accepted practice when slope configuration and soil parameters are known. Stability and Deformation are the two main concerns for Reinforced Soil Structures (RSS). Stability is evaluated by limit equilibrium method (LEM), locating the critical slip surface that produces the minimum factor of safety (FS), and assessment of deformation (stress strain relationships for given tensile load in reinforcement layers) through finite element method (FEM). The application of FEM to RSS is relatively recent, but it renders additional information compared to traditional LEM and has gained attention in understanding the performance of these structures. In the present study an attempt has been made to understand the difference, study the similarities and compare the results of FS calculated between these two analysis methods. An analytical GRE on difficult foundation was designed and modelled in GEO5 software. The stability analysis on the model was performed using the GEO5-LEM. Critical slip surface with FS of 1.5 for normal condition and FS of 1.0 for flooded condition was set acceptable. The same model was reanalyzed with GEO5-FEM software for deformation study. With the understanding of analysis approach between LEM and FEM, conclusions were drawn for the modelled slope geometry, soil properties, geotextile reinforcement tensile strength/stiffness properties and its spacing. This study attempts to guide the development of more accurate LEM analysis or arrive at suitable LEM procedure to be adopted in given boundary condition based on the results obtained from FEM analysis or vice versa.

Keywords: Geotextile, Factor of Safety, Embankment, LEM, FEM

1 Introduction

Embankment slope stability analysis using computers is an easy task when the slope configuration and the soil parameters are known. However, selection of slope stability analysis method is not an easy task and effort should be made to accumulate the field conditions and the failure observations in order to understand the failure mechanism, which determines the slope stability method that should be used in the analysis. Deformation and stability are the two main concerns for reinforced slopes. An accurate assessment of deformation in a reinforced slope can only be achieved through stress deformation analysis, such as finite element analysis. Stability of reinforced slope, on the other hand, can be evaluated using either a limit equilibrium method or a stress deformation analysis.

Limit equilibrium methods (LEM) are still the most common analytical approaches in recent design practices for reinforced soil slopes. They have been used extensively for many years for the analysis of natural and manmade slopes. LEM use the Mohr-Coulomb failure criterion to determine the shear strength along the slip surface. They are based on force and moment equilibrium. At failure, the shear strength is fully mobilized along the critical slip surface. The FS against slope failure is calculated as the ratio of the available shear strength to the mobilized shear strength. In LEM analysis, the sliding mass is divided into slices, determination of the shear and normal inter-slice forces is made, and appropriate force and/or moment equilibrium equations are satisfied for static equilibrium conditions. The LEM chosen for this study is Bishop's simplified method (BSM) and is mainly applied to determine the Global Stability of GRE.

The Finite Element Method (FEM) has been used to analyze different types of geotechnical structures, such as earth dams, embankments, shallow and deep foundations, slopes, and retaining walls. The application of the finite element method to reinforced soil structures is relatively recent. Reinforced soil is a complex system that involves interactions between different structural components and soil. Since the procedure itself is very sophisticated, the application to design is rare. However, FE analysis renders additional information compared to traditional LE analysis. FEM uses the soil stress-strain behaviour for slope stability modelling. FEM preserves global equilibrium until failure is reached and monitors progressive failure up to and including overall shear failure. FEM approach divides the model into a number of pieces or elements of a mesh. Stresses and strains are calculated using the constitutive laws for materials comprising of the slope stability model. Failure occurs naturally through the zones in which the soil shear strength is unable to sustain the applied shear stresses. The shear strength reduction technique enables the FEM to calculate equivalent FS. FEM has been mainly applied to predict the reinforcing stress, strains and the deformation of the GRE (internal stability).

Evaluating the stability of slopes is through determination of FS against failure under a given set of conditions. The FS is commonly defined as the ratio of the resisting forces to driving forces along a potential failure surface. FS of 1.0 means the driving and resisting forces are at equilibrium. Greater FS indicates increased stability, whereas a lower FS suggests that the slope is unstable. In the present study, an analytical GRE slope stability analysis was carried out by software using LEM and FEM. The purpose of the study was to compare the LEM and FEM analysis, compare the similarities and differences in the FS results computed using these different methods. This study attempts to guide the development of more accurate LEM analysis or arrive at suitable LEM procedure to be adopted in given boundary condition based on the results obtained from FEM analysis or vice versa.

2 Slope Geometry and Modeling

A typical analytical model of 8m high embankment, crest width 20m and having slope angles of 58° at base with berm of 1m width at 4m height was and slope angle 64° above the berm was considered. Providing berm in the embankment can increase the factor of safety of a reinforced structure [2,3,4]. The embankment was assumed to be placed over a 2m thick embankment foundation overlying a relatively soft layer of 5m thickness. A nominal height of 8m was assumed based on commonly adopted industry practice of vertical clearance required for flyover openings which is 6m as per [1]. The horizontal crest width of 20m was used considering a four lane highway each of 7.5m wide carriageway with 2m wide median at center and walkways of 1.5m on either side of the highway. The range of slopes 58° to 64° was selected by running pilot model of GRE with PET geotextile. The present study covers all practical ranges of slope angle feasible for site application from this configuration because in practice, we encounter slopes that are steeper than 26.57° (2H: 1V) or 45° (IH: 1V). The modelled embankment was reinforced by layers of geotextile, covering whole width of embankment. The vertical spacing of geotextile is varied from 0.5m and 0.4m. As suggested by [2] the placement of the reinforcement layer, with respect to the foundation soil surface, was limited to 0.3 to 0.5m. A nominal surcharge of 50 kPa has been used for modeling the traffic load as commonly adopted in practice [5]. Fig.1 shows the geometry of reinforced earth embankment modelled in software for both LEM and FEM analysis. The soil properties in embankment fill and foundation to have a realistic model are as mentioned in Table 2.

For FEM analysis, the above model was run for mesh generation GEO5-FEM software. The finite element mesh used in these analyses involved 2037 elements with 6-nodes. Fig.1 shows the assumed boundary conditions and distinguished layers according to the representative materials. The base of the foundation has been fixed at the boundary condition. Boundary conditions for right and left sides of the embankment foundation are considered to be rollers allowing only vertical deformation and were typically located at *x* = 5, 12, and 24m from the toe of the embankment (Table 1).

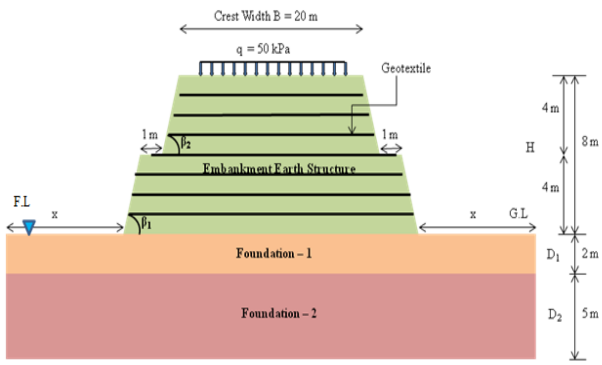


Table 1. Geometry ranges

Parameter (Fig.1)	Range of values examined
D_1	2 m
D_2	5 m
B	20 m
β_1	58°
β_2	64°
H	8 m
X	5 to 24 m

Fig. 1. Geometry of models (Reinforced Earth Embankment)

Table 2. Properties of soil material of foundation and earth structure

Properties	Type		
	Earth Structure	Foundation – 1	Foundation – 2
Unit Weight, γ (kN/m^3)	14.12	14.12	20.5
Saturated Unit Weight, γ_{sat} (kN/m^3)	19.06	19.06	25.0
Cohesion, c_{ef} (kPa)	15	15	5
Angle of Internal Friction, φ_{ef} (deg)	30	30	15
Poisson's Ratio, ν	0.30	0.30	0.42
Elastic Modulus, E (MPa)	0.8 to 16.66*	0.8 to 16.66*	3.0
Dilation Angle, Ψ (deg)	0.0	0.0	0.0
Biot Parameter, α	1.0	1.0	1.0
Material Model		Mohr-Coulomb	

*Same as the embankment fill material fill material

The geotextile in the reinforced earth embankment are considered as a bar element to allow the both vertical and horizontal deformation but not to allow the rotation. The analyses was performed for embankments reinforced with geotextiles ranging in "moduli" from 50 kN/m to 2000 kN/m (axial stiffness of a geotextile is expressed as the force per unit width per unit strain (kN/m) commonly referred to as the "secant modulus" of the geotextile). Also it was assumed that for a given model, each layer of geotextile has same tensile strength or stiffness and placed horizontally. Soil parameters of the backfill are based on lab test results [6]. Parameters of the foundation- 2 are determined by analysis based on the measured data from the literature [7, 8]. Thus in this study; the analytical modeling of earth embankment with geotextile-reinforcement was performed using the GEO5-slope stability software and GEO5-FEM software.

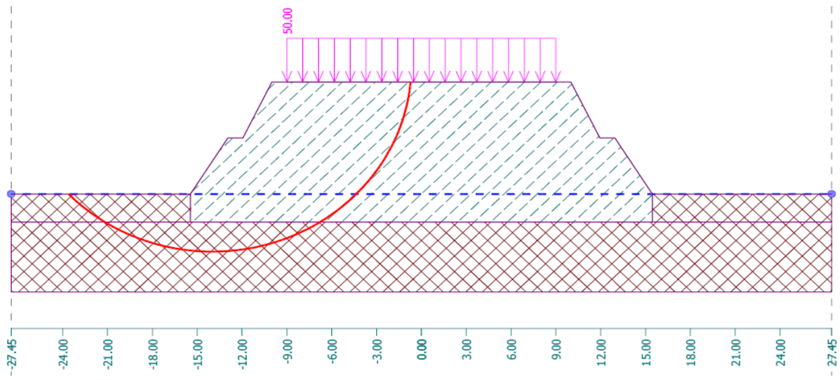
GEO5-slope stability analysis was carried out for both normal and flooded condition. FEM analysis was carried out considering worst condition, i.e. the model was analyzed for flooded condition only. Flooded or saturated condition means environmental condition considering F.L at G.L in heavy rainfall area and normal condition means non flooding condition with W.T at 8 to 10 m below the Foundation -2.

3 Results and Discussion

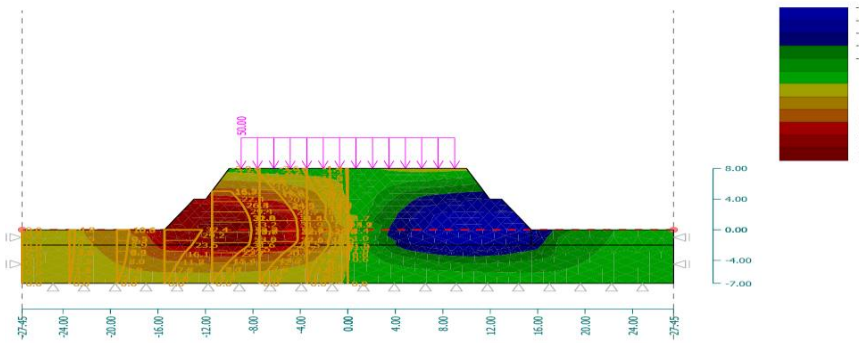
Geotechnical software's are used to analyze stability of embankment slopes. Most of these software's are designed to calculate the weakest points of the prepared model and draw a slip surface. The behavior of model is strongly controlled by the geological built up and water content especially when foundation subsoil is soft desiccated clay type deposits. In the present study GEO5 slope stability and GEO5-FEM geotechnical software packages were used to perform the analysis.

GEO5-slope stability package is based on LEM and GEO5-FEM package is based on FEM, specifically intended for the two dimensional analysis of deformation and stability in geotechnical engineering projects, to obtain estimates of factor of safety by critical slip surfaces and is built on the same original user friendly interface platform as the GEO5- geotechnical software. For better understanding of the differences and method of analysis between GEO5-LEM and GEO5-FEM, FS results obtained from both GEO5-LEM and GEO5-FEM were compared.

The weakest failure plane of the reinforced embankment model was determined, where the factor of safety had a minimum value. GEO5-slope stability software calculations were applied (Fig. 2a, Table 3). The model was considered safe at minimum calculated factor of safety of 1.5. For comparison and to understand the effect of critical slip circle, the same model was analyzed with GEO5-FEM software. The analyses with the GEO5-FEM underestimated the nature of slip surface (Fig. 2b). The nature of slip surface analyzed with GEO5-FEM was different from that analyzed with GEO5-slope stability (Fig. 2a).



(a) Model analyzed in *GEO5*-slope stability (*LEM* based)



(b) Model analyzed in *GEO5-FEM* version

Fig. 2. Nature of failure slip circle (Indicating range of movement as per colour index)

Table 3. Analysis of *F.S* for unreinforced and reinforced earth embankment by GEO5-slope stability and GEO5-FEM

Tensile Strength/Stiffness (kN/m)		10/50		10/100		10/200		20/500		40/1000		80/2000	
Unreinforced	Reinforce-ment	With FL	Without FL	With FL	Without FL	With FL	Without FL	With FL	Without FL	With FL	Without FL	With FL	Without FL
F.S (Bishops)	Model With Berm of 1m & 5.0 m Extra Margin (GEO5-Slope Stability)[a]												
$FS_{Without\ FL}$ = 1.40	S_V = 0.5 m	1.45	1.55	1.46	1.56	1.47	1.57	1.56	1.65	1.72	1.82	2.07	2.16
$FS_{With\ FL}$= 1.20	S_V = 0.4 m	1.47	1.57	1.48	1.58	1.49	1.59	1.60	1.70	1.81	1.91	2.14	2.27
	Model With Berm of 1m & 12 m Extra Margin (GEO5-Slope Stability)[a]												
F.S (Bishops)	S_V = 0.5 m	1.40	1.52	1.41	1.53	1.51	1.54	1.51	1.63	1.64	1.78	1.87	2.03
$FS_{Without\ FL}$ = 1.25 $FS_{With\ FL}$= 1.24	S_V = 0.4 m	1.43	1.55	1.44	1.56	1.45	1.57	1.55	1.67	1.71	1.86	2.01	2.15
	Model With Berm of 1m & 24 m Extra Margin (GEO5-Slope Stability)[a]												
F.S (Bishops)	S_V = 0.5 m	1.41	1.53	1.42	1.54	1.43	1.55	1.51	1.63	1.64	1.78	1.88	2.03
$FS_{Without\ FL}$ = 1.20 $FS_{With\ FL}$= 1.30	S_V = 0.4 m	1.44	1.55	1.45	1.56	1.46	1.57	1.55	1.67	1.71	1.86	2.01	2.16
	Model With Berm of 1m & 5.0 m Extra Margin (GEO5-FEM)[b]												
F.S (FEM)	S_V = 0.5 m	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
$FS_{Without\ FL}$ = 0.9 $FS_{With\ FL}$= 1.01	S_V = 0.4 m	0.90	1.11	0.90	1.11	0.90	1.11	0.90	1.11	0.90	1.11	0.90	1.11
	Model With Berm of 1m &12 m Extra Margin (GEO5-FEM)[b]												
F.S (FEM)	S_V = 0.5 m	0.73	0.90	0.73	0.90	0.73	0.90	0.73	0.90	0.73	0.90	0.73	0.90
$FS_{Without\ FL}$ = 0.81 $FS_{With\ FL}$= 0.90	S_V = 0.4 m	0.66	1.03	0.66	1.03	0.66	1.03	0.66	1.03	0.66	1.03	0.66	1.03
	Model With Berm of 1m & 24 m Extra Margin (GEO5-FEM)[b]												
F.S (FEM)	S_V = 0.5 m	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
$FS_{Without\ FL}$ = 0.90 $FS_{With\ FL}$= 0.81	S_V = 0.4 m	0.73	0.59	0.73	0.59	0.73	0.59	0.73	0.59	0.73	0.59	0.73	0.59

Note: (a): For same S_v with margin 5, 12, 24 m shows for limit state (Bishop's) analysis that F.S is constant for extra margin exceeding 12 m. F.S is maximum within margin of 5 to 12 m. **(b):** Table shows increased stiffness for same tensile strength, increases F.S of slip circle. The increase is apparent for higher tensile strength /stiffness in 20/500 to 80/2000 range.

GEO5-FEM works with combined factor of safety. Consequently a factor of safety 1.0 calculated with GEO5-FEM is equal to a factor of safety of 1.5 calculated with conventional method of GEO5-Slope stability software. [7], also observed the differences between two methodologies. Thus the FEM model was stated or considered safe with minimum calculated factor of safety of 1.0 as shown in Table 3.

Global FS of an embankment slope cannot be analyzed with GEO5-FEM software. Therefore, global stability factor was also determined using GEO5-slope stability software. This can be related to the fact that in the finite element modelling the location of the slip surface cannot be manually adjusted or determined [9].

In order to analyze the effects of boundary distance from the embankment toe on the FS, the proposed model of unreinforced and reinforced embankment adopting a berm of 1m at 4m height was analyzed by GEO5-Slope stability (Bishop's limit state stability analysis) with boundaries on either side of the of the foundation typically located at 5m, 12m and 24m from the toe of the embankment. No noteworthy influence on FS was observed for variation on boundary distance beyond 12m on either side of the toe of embankment.

4 Conclusions

The overall stability of GRE on difficult soils was analyzed with software having two different methodologies and fundamental approaches:
(i) GEO5–FEM, a model based on the Finite Element Method and
(ii) GEO5-slope stability model based on Limit Equilibrium Method.

LEM was simpler and faster whereas FEM required tedious input parameters for the same model to be analyzed. It is seen that, for analyzing FS, the critical slip circle behavior of GRE by LEM is best suited compared to FEM analysis, which is unable to give a clear cut idea about the FS and nature of slip circle analysis. Therefore LEM checked the overall safety of model whereas approximate durability and displacement of model was attempted by FEM analysis.

The LEM analysis does not evaluate the inter-slice forces, which is dependent on number of factors including stress strain deformation characteristics of the materials in GRE. The FEM is an appropriate tool for the investigations of deformation and the behavior of the GRE. The greater rigidity of the embankment and foundation fill material, greater the deformation of the embankment. But the deformation of the embankment face cannot be exactly estimated by integrating the strains of the reinforcement since these strains do not include the external factors (e.g., foundation settlement or global embankment rotation). Therefore FEM checked the local stability of the model.

The LEM and FEM methods used in this study provide fairly consistent FS. When a relatively same critical failure surface as analyzed, smaller values of FS, are related to some stress redistribution that occurs inside of the soil mass simulated by the FEM but not considered in the simplified hypotheses of the LEM. Also FEM show high concentration of strain near the toe of the slope.

With the understandings of the different analysis approaches between LEM and FEM, as well as knowing the advantages and limitations, it is suggested to use both the methods for GRE stability analysis. Both methods have their own benefits and limitations and both methods can be used to provide an estimate of safety factors and slip surfaces. GEO5-slope stability for nature of failure of circular slip surface and overall/global stability, while GEO5-FEM for deformation, strain behavior and local stability thus providing the best economical and safe design.

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