Slope stability analysis of steep reinforced soil slopes using finite element method

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ABSTRACT: Recently, use of geosynthetics has gained widespread popularity & has been increasingly used as reinforcing element in several engineering practices of earth retention structures like reinforced earth walls, reinforced slopes etc. Often the required soil type of requisite characteristic soil properties considered for design are not available locally, hence the available soil type has to be used. With that under consideration, present study deals with the analysis of a steep soil slope embankment reinforced with geogrids under different soil backfill properties. The steep slope is basically designed to widen & elevate the existing natural ground in order to provide road pavement over it. Initial design consideration included conventional limit equilibrium method along with classical earth pressure theories. The design is further modeled & analyzed meticulously according to the staged construction sequence undertaken at site, in a geotechnical finite element analysis software i.e. PLAXIS. Present study mainly investigates the effects of use of different types of soil backfill on stability of slope. Effect of variation of soil parameters i.e. cohesion & angle of internal friction on steep slope embankments of different heights (6m, 12m, 18m, 24m & 30m) are studied through this analysis. Since very steep and very high slope embankments were considered for the study, tiered structure i.e. provision of berm was considered. The effect of width of berm was also considered as a parameter and corresponding effect on the stability of slope was studied. The observed trends of results were further compared with available literatures and previous studies. The results suggested that with increase in soil parameters like cohesion (c') & angle of internal friction (Φ) the factor of safety for the global stability further increased. From the study it was observed that the most optimum soil type was found to be the soil with low cohesion and high angle of internal friction, because upon increasing the cohesion of soil, although increase in global stability was observed, it also led to increase in horizontal displacements and axial forces acting over the geogrids. From the results it was also observed that use of tiered structure or provision of berm increased the factor of safety for global stability marginally and reduced the forces and horizontal displacements significantly on the lower tier. It was concluded that in case of non-availability of recommended granular soil, the available soil fill be utilized only for low height embankments. For high embankments, only recommended granular soils should to be used.
KEYWORDS: Plaxis, Slope Stabilization, Reinforced Soil Slope, Geosynthetics, Geogrids

1. INTRODUCTION

Use of geosynthetics has become a widespread engineering practice & is increasingly used for different purposes such as reinforcement, drainage, separation etc. Present study deals with analysis of steep soil slope reinforced with geogrids using 2-D finite element analysis i.e. Plaxis 2D. Often the required & characterized design soil backfill i.e. recommended granular soil is not locally available. Hence through this study, effects of use of different soil parameters as soil backfill on the slope stability were analyzed. Slope of different heights i.e. 6,12,18,24 & 30m heights were considered in the study. Because of consideration of steep slopes & very high structures, provision of berm or tiered construction was considered, thereby making the structure a tiered structure. Provision of berm was selected at every 6m interval. The width of the berm was also considered as a parameter & its effect was studied.

Although the spacing of reinforcement can be varied, for simplicity it has been considered fixed as 0.6m. The preliminary design analysis for the slope is done using Limit Equilibrium method. The designs are then modeled using Plaxis. The working site conditions were modeled very closely for analysis. The designs have been analyzed according to the under construction site of Central University of Jammu, Samba, Jammu. The ground water table as per site condition was well below the ground level, hence its effect of water table was not considered.

2. EARLIER STUDIES

Since earlier times, limit equilibrium method has been used for analysis of slope stability. Initially slope stability analysis was mainly done using Swedish slip circle method. This method was further upgraded by Bishop which is used even today. Stability of slope is usually expressed as Factor of safety which is basically ratio of resisting forces & driving forces. Later Morgenstern-Price & Janbu further incorporated methods which included non-circular slip analysis. Calculations for slope stability analysis involve complex iterative procedures which are more suitable computationally. Recently many advanced numerical methods are used for slope stability analysis. Amongst the computational methods, finite element analysis is commonly followed. Few earlier studies have been made for slope stability analysis using finite element methods. **Seyed Abolhasan et.al. (2015)** studied & compared the effects of using steel & geogrid as reinforcements using finite element analysis [10]. **Nejan Huvaj et.al. (2014)** compared the results of limit equilibrium analysis & finite element analysis on a 70 degrees slope[5]. **Mirmoradi.S et.al. (2013)** studied the behavior of soil slopes with different facing type's i.e. concrete blocks & wrap-around facing [9].

3. DESIGN ANALYSIS & CONSIDERATIONS

The procedure for design of reinforced slopes involves use of conventional limit equilibrium analysis. A circular or wedge shaped potential failure pattern is assumed & the Factor of safety is determined. In this study, the stiffness of reinforcements was considered using classical theories of earth pressure. Maximum axial force acting over the reinforcement (T_{max}) were calculated using equation (1) and the stiffness of reinforcements were provided accordingly.

$$Tmax = Ka.\gamma.H \quad + \quad Ka.Q \qquad (1)$$

where, Ka = Earth pressure co-efficient
γ = Density of soil (kN/m^3)
H = Height at the given level (m)
Q= Surcharge (kN/m^2)

Partial material reduction factors according to BS: 8006-2010 were considered for the long-term design strength (LTDS) of the reinforcements [10]. The embedment lengths of the reinforcements must be sufficient to offer adequate resistance & hence considered according to Jewels Chart recommended by BS-8006-2010[1]. For ease in construction methodology, uniform allowed spacing between the reinforcements was considered as 0.6m. The design considerations were further analyzed using finite element technique.

4. FINITE ELEMENT MODELLING & ANALYSIS

Plaxis allows users to define geotechnical problems in a realistic way. With provision of staged construction analysis, stability of structure during and after construction can be analyzed. Present study deals with modeling and analysis of high steep embankments of 70 degrees slope. The heights of the embankments considered are 6, 12, 18, 24 & 30m. The basic purpose of the embankments is to widen and elevate the existing slopes.

In this study, the geometrical prototype is modeled closely in accordance with the construction methodology & construction sequences. The typical geometry considered for analysis is shown in Fig.1. In this study, the soil parameters such as cohesion (cohesion) & angle of internal friction (Φ) of soil have been varied and their corresponding effects on the stability of slope embankments of various heights have been studied.

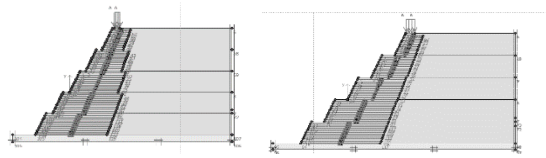

Fig 1. Typical geometry model (a) 30m height with 1.5m berm width (b) 30m height with 3.0m berm width

Construction methodology adopted for the construction was bottom-to-up technique which involved use of a facing (welded wire mesh) on the slopes. The primary reinforcements adopted were geogrids (geosynthetics), which are flexible tensile reinforcing elements. The stiffness of the geogrids has been calculated using classic earth pressure theories. With due consideration to the partial material factors, the axial stiffness of the geogrids were modeled & corresponding reduction factor was applied accordingly [4] [8] [1].

The study dealt with the effect of variation in soil backfill parameters i.e. values of cohesion (c) & angle of internal friction (Φ) on the deformation & displacement of the slope. For stability analysis in Plaxis, phi-c reduction calculation type was used, which reduces the values of cohesion (c) & angle of internal friction (Φ) in steps until the soil body fails. The following equation is used:

$$\Sigma Msf = \frac{tan(tan\Phi input)}{tan(tan\Phi reduced)} = \frac{cinput}{creduced} \qquad (2)$$

The parameters considered for the study are mentioned in Table.1. Although soil properties were varied, default properties considered are mentioned.

Since the slopes considered for analyses were very high and the slope angle very steep, provision of berm or tiered structures was considered. For simplicity, tiered structure was considered with provision berm at every 6m was considered. For example, 18m height was modeled as 3 tiered structures with every tier being 6m in height. Similarly 12, 24 & 30m structures were modeled as 4 & 5 tiered structures with height of every tier being 6m. The considered berm width was a parameter and was varied as 1.5 and 3.0 m.

Corresponding effect of the variation of berm width was studied.

Table.1 Input Parameters for finite element modeling

Parameter	Value	Unit
Soil Backfill Parameters		
Cohesion	0.5	kN/m^2
Angle of internal friction (Φ)	30	Degrees
Unit weight of soil backfill, (γ)	20	kN/m^3
Modulus of elasticity(Esoil)	2.00E+04	kN/m^2
Reduction factor	0.7	
Cohesion ($c_{\text{-foundation}}$)	10	kN/m^2
Angle of internal friction, $\Phi_{\text{foundation}}$	30	Degrees
Reinforcements		
Tensile Strength (kN/m)	Elastic Stiffness	Unit
250	1250	kN/m
200	1000	kN/m
150	750	kN/m
120	600	kN/m
100	500	kN/m
Vertical Spacing	0.6	M
Facing		
Axial Stiffness	2.00E+06	kN/m
Bending Stiffness	2.00E+04	kNm^2/m

The Plane strain model of 15-node elements was used in the analysis. The coarseness of mesh was considered as fine. Since water table was not considered for the analysis, the soil fill was modeled using Mohr-coulomb criterion and plastic staged construction was adopted for analysis. The facing type was modeled using plate. The facing & geogrids were modeled with 5-node line. Axial & bending stiffness for the facing were input accordingly. The stiffness & lengths of geogrids were modeled according to the results of analytical methods of limit equilibrium [4] [8] [1]. In order to consider long-term assessment of geogrids, reduction factor was considered for soil-geogrid interaction & long-term design strength of geogrids. Traffic loads according to traffic conditions were modeled.

4. Results & Discussions

4.1 Axial Forces

The typical trend of the axial forces acting over geogrids obtained through finite element analyses in context with variation in cohesion, friction angle & berm widths with respect to increase in height are graphically represented in Fig2. It was observed that acting horiztontal thrust or axial forces increased with respect to the height. It was also observed that the axial forces acting over the geogrids increased with increase in cohesion of soil. The observed trend is in good agreement with the theoretical trend of horizontal thrust or axial forces or tensile forces over geogrids obtained using classical Rankine Equation or the equation suggested by FHWA Design Manual.

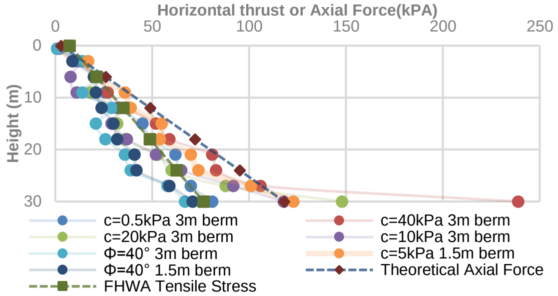

Fig.2 Graphical Representation of observe trend of acting axial forces over geogrids with respect to height (30m)

The observed trend can be attributed to the fact that the acting stress due to overburden & surcharge are function of height and they increase with increase in height, hence acting axial forces increase accordingly.

4.2 Horizontal Displacements

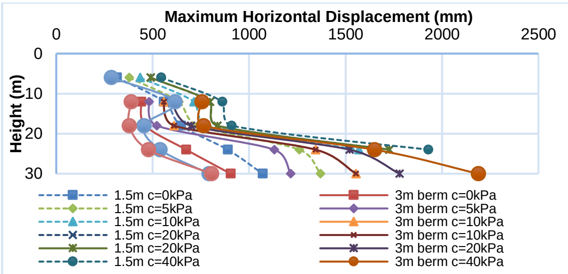

Fig.3 Graphical Representation of maximum horizontal displacement on facing at failure (c-phi reduction phase) with respect to height

Observed trend for maximum horizontal displacements at failure (c-phi reduction phase) are shown in Fig.3. It was observed that with increase in cohesion, the horizontal displacements increased. Optimum results were observed for soils with low cohesion and high friction angle. The observed trend are in agreement with earlier studies and previous literatures [9]. In order to reduce the acting axial forces and to minimize the horizontal displacements, the code recommendations suggest use of granular soil (non-cohesive) soils. Existence of ground water table further develops excess pore pressure in cohesive soils, which would increase in acting axial stresses and horizontal displacements.

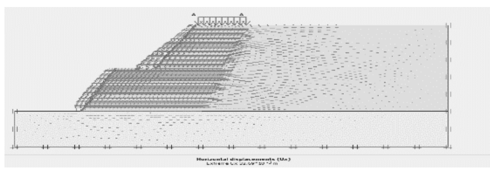

Fig.4 Screenshot: Typical Observed Trend for Maximum horizontal displacement (After staged construction analysis)

Fig.4 represents typical trend of horizontal displacement observed after plastic analysis. Observed trends are similar with the theoretical correlations provided by FHWA-NHI-10-024 & results presented in earlier studies[9][4]. Fig.3 depicts observed maximum horizontal displacements at failure (c-phi reduction phase), hence relatively higher range of values. This portrays the flexible nature of reinforcements which allow structural deformation at relatively higher strains.

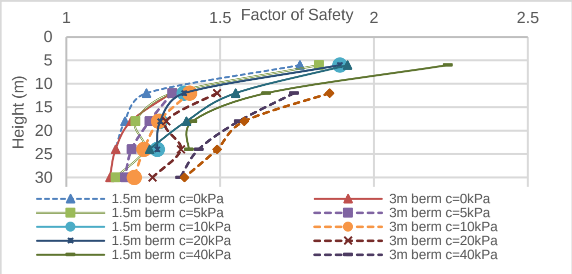

Fig. 5 Graph depicting trend of factor of safety w.r.t height of slope embankment.

Fig.5 represents the trend of variation of Global Factor of safety with different heights and different berm widths upon variation in corresponding soil parameter i.e. cohesion & angle of internal friction. The observed trend with variation in geotechnical parameters was comparable with the results of limit equilibrium analyses. It was observed that on increasing the cohesion & friction angle of soil, the factor of safety increases. This can be attributed to the fact that shear strength of soil is a function of cohesion & friction angle, which can be represented by following equation. Where τ denotes shear strength of soil & σ denotes normal acting stress on soil.

$$\tau = c + \sigma\,(\tan(\Phi)) \qquad (3)$$

For present study with finite element analysis of the slope, maximum displacement & incremental shear strains gave a better understanding for the results & possible failure shear surfaces (slip circles) of the slope. A typical plot for maximum displacements & possible shear surfaces are shown in Fig.6.

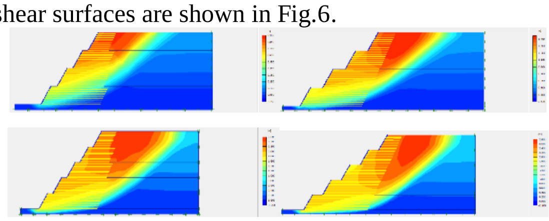

Fig.6. Typical graphical plot of total maximum displacements (shear surface or slip circles) (a) 24m 1.5m berm, (b) 24m 3.0m berm, (c) 30m 1.5m berm, (d) 30m with 3.0m berm

It can be inferred from the above Fig that with increase in berm width, the displacements and axial forces on the lower tiers reduced marginally. This can be attributed to the simple load distribution theory. With increased berm width, structure offered relatively supplementary area for the load to be distributed, hence the acting stresses reduced, hence the subsequent reduction in displacements.

5. Conclusions

Following Conclusions were drawn from the analyses:

- Factor of safety of slope increased with increase in cohesion & friction angle of soil. Soil body collapsed for friction angle less than 20 degrees.
- Axial forces and horizontal displacements acting over the geogrids & facing are directly correlated with cohesion of the soil, as they fuerther increased with increase in cohesion of soil.
- Optimum results were attained for soil with low cohesion values (<10kPa) & high friction angle (=>30°), as the observed axial forces and horizontal displacements were minimum.
- A general trend observed was that horizontal displacement & axial forces increased with increase in height & hence reduced the factor of safety with increase in height.
- Provision of increased berm width significantly reduced the acting axial forces and corresponding displacements on the bottom tier. This led to further increase in Factor of safety.
- From the study it can be suggested that in case of non-availability of recommended granular soil, the available soil fill be utilized only for low height embankments. For high embankments, only recommended granular soils should to be used.

6. References

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