Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Slope - Reinforcement Interactions: Effect of Strength Parameters

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Abstract. Steepening of slopes for construction of rail/road embankments or for widening for other civil engineering structures is a necessity for development. Use of geosynthetics for steep slope construction or repair of failed slopes considering all aspects of design and environment could be a viable alternative to these problems. Designing geosynthetic reinforced slope with minimum length of geosynthetics leads to economy. 1.5H:1V slope reinforced with a single layer has been analysed for three different sets of soil parameters and for three depths from the top of the embankment.. Reinforcement length has been optimized from face and non-face ends of the slope. The paper presents effect of soil parameters, angle of shearing resistance and cohesion on optimized length of reinforcement and saving in length of reinforcement. Affect of adhesion between soil and reinforcement on slope stability has also been presented.

Keywords: Reinforced Slope, Geosynthetics, Soil Parameters, Adhesion, Slope Stability

1 Introduction

Analysis of earth slopes is one of the oldest geotechnical engineering problems that engineers have been dealing with using various techniques. The methods can be classified as Limit Equilibrium Methods (LEM), Finite Element Method (FEM) based on c and ϕ reduction, Finite Difference Method (FDM), combination of FEM and LEM, Limit Analysis (LA), etc. Geosynthetic reinforcement of earth slope results in reduction in the land requirement and preservation of natural resources (land and backfill requirements) apart from time and cost. Designing geosynthetic reinforced slope with minimum length of geosynthetics leads to further economy. Jewell et al. (1985), Bonparte et al. (1987), Verduin and Holtz (1989) present design methods for earth slopes reinforced with geotextiles or /and geogrids using LEM assuming different types of failure surfaces such as circular or/and bilinear wedges. Jewell et al. (1985) used Limit Equilibrium Analysis and local stress calculation for design of reinforced slope. Jewell (1991) presented revised design charts for steep slopes valid for all polymer reinforcement materials. These revised charts lead to savings of the order of 20-30% in reinforcement quantity. Leshchinsky (1992) and Leshchinsky et al. (1995) used log spiral failure mechanism to determine the required reinforcement long term strength. Zhao (1996) and Michalowski (1997) present kinematic limit analysis solutions for the stability of reinforced soil slopes. Shiwakoti et al. (1998) conducted parametric studies to investigate the effect of geosynthetic strength, soil–geosynthetic interaction coefficients, vertical spacing of geosynthetics for soil slope/wall on competent foundation. Baker and Klein (2004a, b) modified the top-down approach of Leshchinsky (1992) to obtain the reinforcement force needed for a prescribed factor of safety everywhere within the reinforced mass. Han and Leshchinsky (2006) present a general analytical frame work for design of flexible reinforced earth structures, i.e., walls and slopes. Leshchinsky et al. (2010) presented a limit equilibrium methodology to determine the unfactored global geosynthetic strength required to ensure sufficient internal stability in reinforced earth structures. Leshchinsky et al. (2014) introduced a limit state design framework for geosynthetic reinforced slopes and walls. Leshchinsky and Ambauen (2015) presented use of upper bound limit analysis (LA) in conjunction with discretization procedure known as discontinuity layout optimization (DLO) for comparison with rigorous LE Methods. DLO-LA is an effective tool for establishing a critical failure mechanism and its stability without the constraint or assumptions required in LE analysis. Gao et al. (2016) in their study considered three dimensional effects on reinforced earth structure stability and to determine required strength and length of reinforcement using limit analysis approach. The three dimensional effects are more significant for the minimum required length of reinforcement than for the minimum required tensile strength.

1.2 Problem definition

An embankment of height, H, of 6.0 m with side slopes of 1.5 Horizontal to 1 Vertical (Fig. 1) is considered. H is height of embankment. L_r is total length of

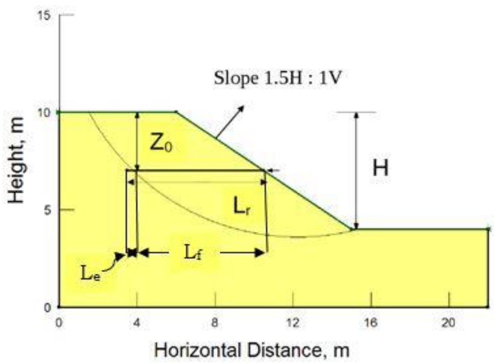

Fig. 1. Definition Sketch, H: Height of embankment, Lr: Length of geosynthetic reinforcement, L_f: Length of geosynthetic reinforcement in unstable zone, Le: Effective length of reinforcement in stable zone

Geosynthetic reinforcement L_f is length of reinforcement in unstable zone and Le is length of reinforcement in stable zone and is contributing directly to slope stability. The embankment and the foundation soil have the same soil parameters. Cohesion (c) of 5 kPa and angle of shearing resistance of soil of 23° have been considered. The unreinforced slope has minimum Factor of Safety (FS_{min}) of 1.22 which is less than the desired minimum Factor of Safety (FS) of 1.5 and hence considered to be unsafe. The slope is reinforced with a single layer of reinforcement to ensure the required minimum FS. Ultimate tensile strength (T_{ult}) of geosynthetic reinforcement is 200 kN/m and allowable tensile strength (T_{all}) 100 kN/m. The adhesion between soil and reinforcement (c_a) of 3 kPa and interface friction angle or bond resistance between soil and reinforcement (δ) of 17° have been considered for analysing the reinforced slope. The embankment with reinforcement placed at Z_0 = 3.0, 4.0 or 5.0 m from the top of embankment has been analysed for the above soil and soil - reinforcement interaction parameters. The initial lengths of reinforcement considered are 8.0 m, 7.8 m and 8.2 m for reinforcement at Z_0 = 3.0 m, 4.0 m and 5.0 m respectively. Unreinforced and reinforced slopes are analyzed using Morgenstern-Price method to obtain the critical factors of safety. Geostudio 2004 SLOPEW has been used for the analysis.

1.2 Analysis

The slope with reinforcement at 3.0 m from top of embankment analysed and reinforcement length optimized from non-face end as detailed in Akshay and Madhav (2015). The length of reinforcement after optimization form non- face end was 7.27 m (Fig. 2).

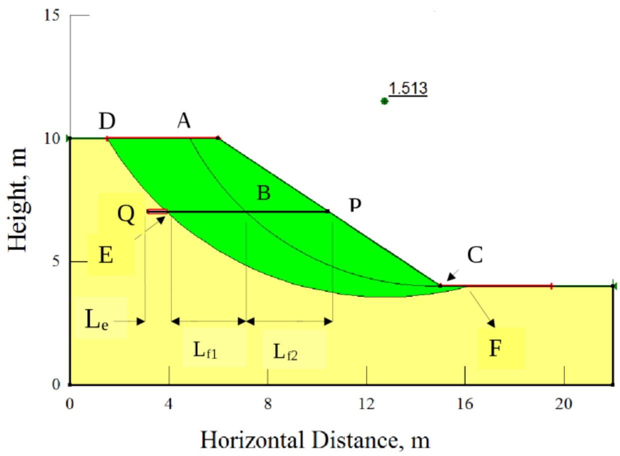

Fig. 2. Critical Slip Circle for reinforced slope for Z_0=3.0 m, FS_{min} = 1.51, L_r = 7.27 m

Above slope as in figure 2 is reanalysed by curtailing the reinforcement from the face end by moving point P inside the slope but still maintaining minimum factor of safety of 1.5. The face end optimization of length resulted in reduction in length of reinforcement to 5.08 m (Fig. 3).

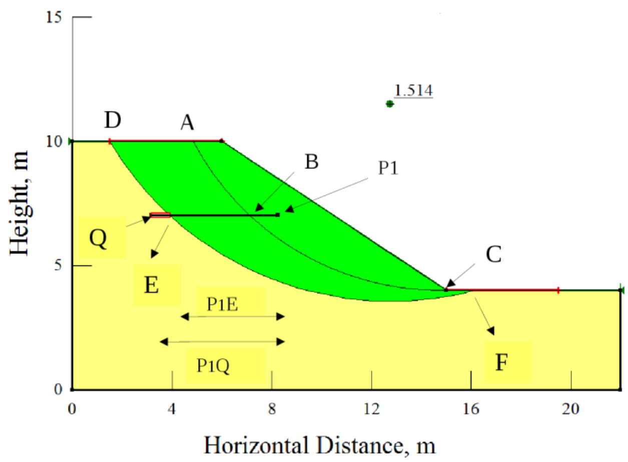

Fig. 3. Critical Slip Circle for Slope with Reinforcement Length optimized from Face end with Z_0 = 3.0 m, L_r = 5.08 m and FS_{min} = 1.51.

The face end optimization has led to further reduction in length and saving is length of the order of 30 %. Similar analysis was carried for reinforcement at 4.0 m and 5.0 m depths from the top of the embankment. The analysis was repeated with two more sets of soil parameters, c = 6 kPa & $\phi = 20^0$ and c = 4 kPa & $\phi = 26^0$. The summary of soil parameters used for analysis being as detailed in Table 1.

Table 1 Parameters of Soil and Reinforcement for Stability Analysis

S No.	Unit Weight(γ), kN/m^3	Cohesion (c), kPa	Angle of Shearing Resistance (ϕ°)	Interface friction angle between soil and rein-forcement, $\delta°$	Adhesion between geosynthetic and backfill, c_a, kN/m	Ultimate Tensile Strength of Geosynthetics (T_{ult}), kN/m
1	18	5	23	17	3	200
2	18	6	20	16	4.5	200
3	18	4	26	20	3	200

2 Effect of Soil Parameters on Factor of Safety

The effect of soil parameters on slope stability requires analysis of same slope with different sets of soil parameters.

2.1 Variation of reinforcement length with angle of shearing resistance and cohesion

As mentioned in 1.2 above the embankment slope was analysed with soil and soil - reinforcement parameters as detailed at S. No. 1, 2 and 3 of above Table 1 with reinforcement at 3, 4 & 5 m from the top of the embankment. The results of analysis for all the three cases of single layer reinforced slope as analysed in detail are summarized in Table 2.

Table 2. Summary of Results for 3 sets of soil parameters

Location of Reinforcement from Top, m	Soil Cohesion (C), kPa	Angle of shearing resistance, ϕ°	Non-face optimized length of Reinforcement, L_r, m	Optimal Length of reinforcement (L_{ropt}),m	Saving in Length of reinforcement(L_r-L_{opt}), m	Effective Length of Reinforcement(Le), m
3	4	26	6.11	3.88	2.23	0.62
3	5	23	7.27	5.08	2.19	0.76
3	6	20	8.12	5.87	2.25	1.68
4	4	26	6.15	4.15	2.00	0.22
4	5	23	7.33	5.26	2.07	0.25
4	6	20	8.56	6.50	2.06	0.29
5	4	26	6.45	4.94	1.51	0.15
5	5	23	7.64	6.04	1.60	0.15
5	6	20	9.02	7.47	1.55	0.22

2.2 Discussion of results

The saving in length of reinforcement (L_r-L_{opt}) is maximum for the reinforcement at 3 m depth from the top of the embankment for the three sets of soil parameters. For a given location of reinforcement saving in length of reinforcement increases with decreasing angle of shearing resistance and increasing cohesion. Effective length of reinforcement (Le) increases with decreasing angle of shearing resistance(ϕ) as is expected since mobilised force in reinforcement is highly dependent on ϕ. The savings in reinforcement length is maximum for Z_0 = 3 m case for all three sets of soil parameters and least for Z_0 = 5 m case.

2.2 Variation of reinforcement length with Angle of Shearing Resistance and Cohesion

Figure 4 shows variation of length of reinforcement with angle of shearing resistance of soil.

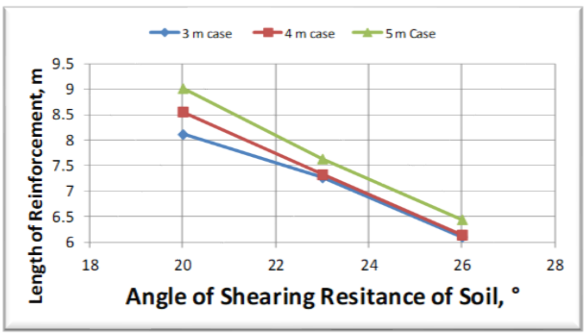

Fig.4. Variation of L_r with Angle of shearing resistance of soil

Length of reinforcement, L_r, decreases (Fig. 4) with increase of angle of shearing strength of soil. This is expected as increasing angle of shearing resistance of soil contributes more towards slope stability by way of increasing stabilizing force and moment. The variation of L_r with angle of shearing resistance is nearly the same for 4 m and 5 m cases.

The savings in length of reinforcement (difference in length of reinforcement for non-face optimized length and face optimized length) , (L_r- L_{ropt}), are nearly independent of angle of shearing resistance of soil and cohesion as shown in Figures 5 & 6. The variation of savings in length with angle of shearing resistance of soil (Fig. 5) is practically straight line for given depth of reinforcement from the top of the embankment. The possible explanation of this behaviour could be the fact that reduction in length from face end is possible only for shallow slip circle do not become critical . As depth of reinforcement from top of embankment increases the savings in length of reinforcement decreases (Fig. 5). As depth of reinforcement from the top of the embankment increases with curtailment of length of reinforcement from face end, the shallow slip circle becomes critical. Hence further curtailment of reinforcement from face gives factor of safety less than the desired value of 1.5. The variation of savings in length of reinforcement with cohesion varies in a similar fashion as with angle of shearing resistance (Fig. 6.).

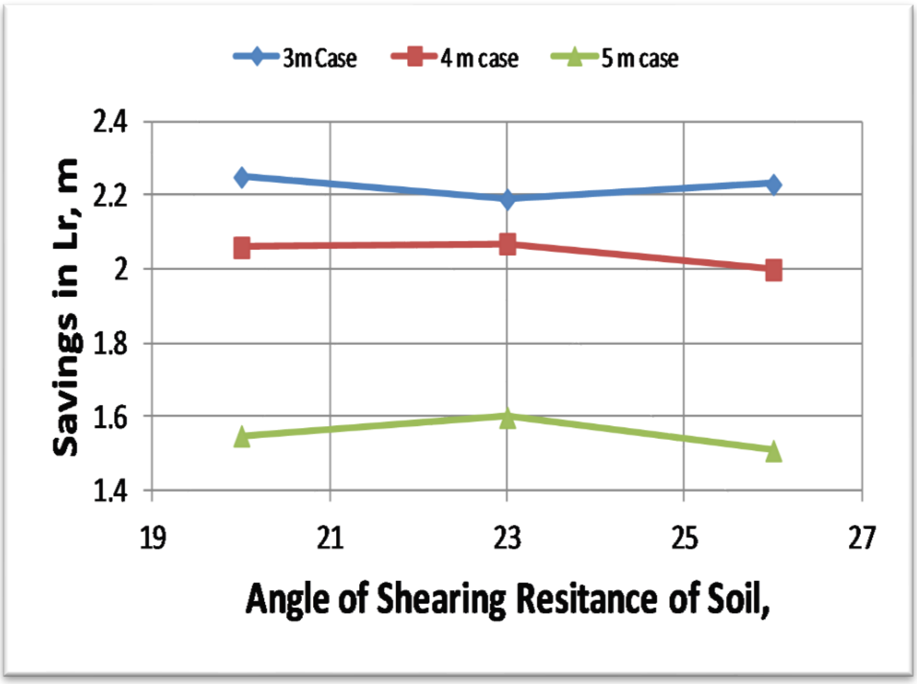

Fig. 5. Saving in Length of Reinforcement vs. Angle of shearing resistance, □

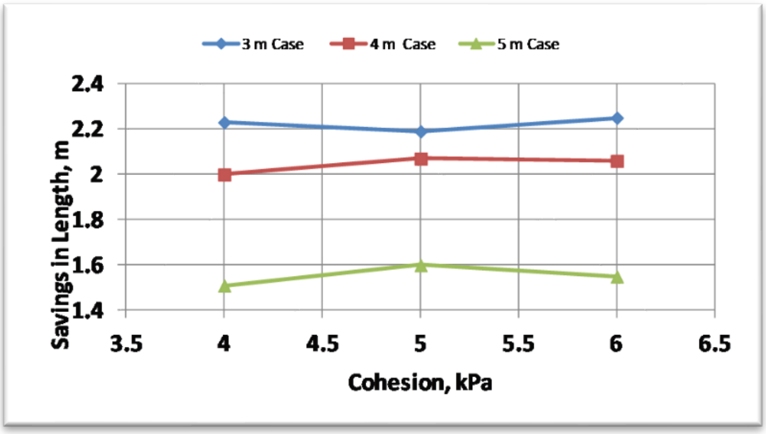

Fig. 6. Saving in Length of Reinforcement vs. Cohesion

The length of reinforcement in the stable zone (L_e) (Fig. 1) has been found to be constant for 4.0 m and 5.0 m depths of reinforcement but decreases with angle of shearing resistance for 3.0 m depth case (Fig. 7). Figure 7 indicates the effective length of reinforcement, L_e, in the stable zone is independent of angle of shearing resistance of soil for Z_0 equal to 4.0 m and 5.0 m.

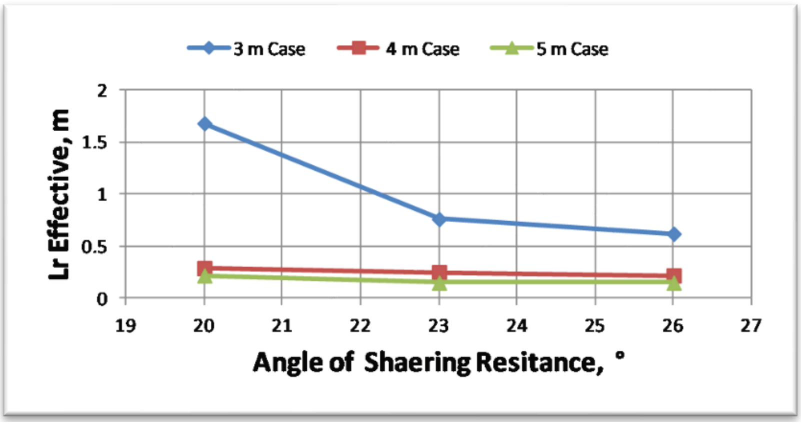

Figure 7 Variation of Effective Length of Reinforcement vs. ϕ

2.3 Effect of adhesion on factor of safety

To study the effect of interface adhesion between soil and reinforcement on slope stability, 6 m high slope 1.5H:1V with the soil parameters as detailed in 1.2 with reinforcement at 3 m , 4 m and 5 m from the top of the embankment but with zero adhesion has been re-analyzed and FS_{min} and reinforcement loads, F_r obtained have been compared with the values obtained with c_a= 3.0 kPa.

The results of analysis are summarized in Table 3. Critical study of data in the above table indicates that (i) with increasing depth of reinforcement from the top of the slope (i.e., with increasing Z_0) the effect of neglecting adhesion between soil and reinforcement (c_a) reduces marginally on Factor of Safety (FS_{min}) and significantly on mobilised force in reinforcement, F_r. FS_{min} reduces by 0.93% to 0.20% as reinforcement position from the top of embankment increases from 3.0 m to 5.0 m. Thus the contribution of adhesion is practically negligible so far slope stability is concerned. However % change of F_r reduces from 16.8 to 9.8 for the same positions of the reinforcement. Absolute change in Fr (i.e. difference of F_r with and without considering c_a) reduces from 1.85 kN/m to 0.59 kN/m as reinforcement position changes from 3.0 m to 5.0 m probably due to increase in normal stress as reinforcement load increases with increasing depth (increase in normal stress).

Table 3. FS_{min} and F_r with and without considering adhesion between reinforcement and soil

Fixed Parameters of Study: Slope 1.5H:1V, c = 5kPa, ϕ = 23°, Unit Weight = 18 kN/m^{3,} Tall = 100 kN/m

Study of Effect of Adhesion on FS_{min} and Reinforcement Load(F_r)

SN	Z_0, m	c_a (kPa)	FS_{min}	F_r, kN	FS_{min}	F_r, kN
			L_r = 7.27 m		L_{ropt} = 5.08 m	
1	3	3	1.513	19.59	1.513	19.59
2		0	1.499	16.74	1.499	16.74
	% Change in Parameters		0.93	14.55	0.93	14.55
			L_r = 7.33 m		L_{ropt} = 5.26 m	
3	4	3	1.514	8.38	1.514	8.38
4		0	1.51	7.43	1.51	7.43
	% Change in Parameters		0.26	11.34	0.26	11.34
			L_r = 7.64 m		L_{ropt} = 6.06 m	
5	5	3	1.508	6.23	1.508	6.23
6		0	1.505	5.64	1.505	5.64
	% Change in Parameters		0.20	9.47	0.20	9.47

$$\%\ \text{Change in FSmin} = \frac{(\text{FSmin with Adhesion} - \text{FSmin without adhesion}) * 100}{\text{FSmin with Adhesion}}$$

% change in F_r is also defined in similar way.

4 Conclusions

The analysis of 6 m high slope with 1.5H: 1V side slope with different sets of soil parameters show that length of reinforcement (L_r) decreases with increasing angle of shearing resistance (ϕ) as is expected (Figure 4). With varying depth of reinforcement from top of embankment for same value of ϕ, L_r is lowest for 3 m depth followed by 4 m and 5 m depth cases. Savings in length of reinforcement were found to be practically independent of c and ϕ but dependent on depth of reinforcement. Adhesion has negligible effect on slope stability.

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