Numerical Analysis of a Stabilized Natural Slope

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ABSTRACT
Marginally stable slopes coupled with heavy rainfall represent a common challenge to rapid urban development in hilly terrain. These conditions lead to landslides that can be disastrous causing significant damage to nearby properties and loss of lives. In this paper, the stabilization of a 60 m high natural slope is analyzed using finite element and limit equilibrium methods. The contribution of the post-tensioned ground anchors and face plates used for slope stabilization is considered in the analysis. The strength reduction finite element analysis was able to capture the behavior of the slope before the stabilization and its performance after stabilization. The factors of safety obtained with two different approaches are compared and discussed in this paper.
Keywords: Slope Stability, Landslides, Limit Equilibrium, Finite Element Analysis, Ground Anchors.

RÉSUMÉ
Les pentes marginalement stables couplées à des fortes précipitations représentent un défi pour un développement urbain rapide en terrain vallonné . Ces conditions conduisent à des glissements de terrain qui peuvent être désastreux, causant des dommages importants aux propriétés et beaucoup de pertes en vies humaines. Dans cet article, la stabilisation d'une pente naturelle de 60m de haut est analysée en utilisant des éléments finis et les méthodes d'équilibre limite. L'analyse considère la contribution des ancrages au sol par post-tension et des plaques frontales utilisées pour la stabilisation de la pente. L'analyse par éléments finis a permis d'examiner le comportement de la pente avant et après la stabilisation. Les facteurs de sécurité obtenus avec les deux approches sont comparés et discutés dans le présent document .
Mots-clés: stabilité des pentes , glissements de terrain , équilibre limite , analyse par éléments finis , ancrage au sol.

1. INTRODUCTION

Marginally stable high slopes can lead to disastrous damage to nearby properties or even loss of lives. To mitigate failures associated with marginal slopes, flattening of the slope, construction of retaining walls at the toe, stabilization with ground anchors, and the combination of these approaches is commonly implemented.

It is well known that the use of ground anchors is an effective method to stabilize marginally stable high slopes, especially when solutions such as flattening of slopes or construction of retaining walls are not feasible due to site constraints.

The stability of a slope can be assessed either by limit equilibrium approach (LEM) or finite element method (FEM). In the LEM, to simplify the problem, the slope is divided into a number of slices. There are a number of methods proposed in LEM based on the different assumptions made regarding inter-slice forces and the way in which overall force and moment equilibrium equations are satisfied. On the other hand, the finite element method (FEM) is a general-purpose method that has many desirable characteristics, which are not accounted for in the traditional limit equilibrium method. FEM is capable of modeling: (1) stresses, movements, and pore pressures in embankments and slopes; (2) the conditions during construction and the construction sequence; (3) the soils response under such conditions as nonlinear stress-strain behavior and non-homogeneous conditions.

The strength reduction technique of the finite element method is a popular and powerful tool which has been used for analyzing slopes reinforced by soil nails, e.g. ground anchors. It has been demonstrated by Griffiths and Lane (1999) that the FEM is a more powerful alternative to LEM when assessing stability in their study of unreinforced slopes and embankments. Cheuk et al. (2013) studied the influence of soil nail orientations on the behavior of the ground nail-facing system. The present study also has carried out similar analysis, but these results are not presented in this paper. Cai and Ugai (2000 and 2003) used three-dimensional elasto-plastic shear strength reduction FEM to evaluate the stability of homogeneous slope reinforced with piles or ground anchors. Their research shows that it is the soil-nail interaction that affects the stability of slopes, and that the factor of safety obtained from FEM approach is close to that obtained by the Bishop's simplified LEM.

In the research works cited in previous paragraph, either the slopes involved are homogeneous in nature, or the height of slope is less than 30 meters. In addition, the research work cited above mostly pertains to idealized cases to carry out a parametric study. When compared to the previous studies, in this paper, a case study of a high slope located in China is presented. The subject slope which was stabilized with ground anchors was analyzed using LEM and FEM approaches.

2. FEATURES OF THE SLOPE

The particular slope considered in this study is shown in Photo 1. It is located in Fujian province, southeast China. There are hundreds of residents living within 14 meters from the toe of the slope. These residents migrated from their original village due to construction of a hydraulic power station. The slope is 200 meter long, 40-55 meter high, and with 40º-50º inclination. The considered slope has experienced shallow slides during rainy season in 2005. These shallow slides continued developing in the following years also. The circled area in Photo 1 shows typical shallow slide.

Photo 1. The front view of the slope

Figure 1 shows the cross-section of the slope, with four distinct soil layers and the soil properties are listed in Table 1 below.

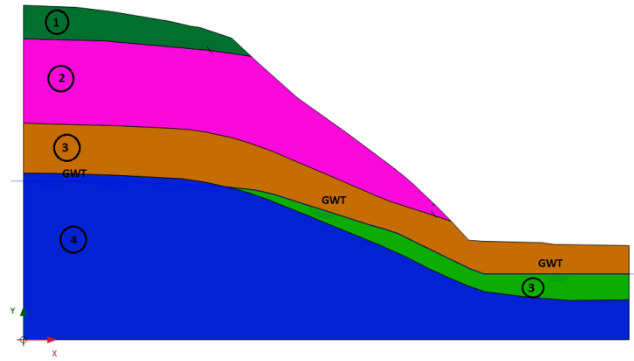


Figure 1. The cross-section of the slope

Table 1. Considered soil properties

Apellation of soil layers			Talus gravelly clay ①	Eluvial sandy clay ②	Fully weathered alkali feldspar granite ③	Strongly weathered alkali feldspar granite ④
Water content	w	%	21.6	21.1	19.1	/
Unit weight	γ	kN/m^3	18.6	18.2	18	/
Dry unit weight	γ_d	kN/m^3	15.3	15.05	15.1	/
Satuarated unit weight	γ_{sr}	kN/m^3	19.7	19.5	19.5	/
Specific gravity	Gs	—	2.72	2.71	2.71	/
Void ratio	e	—	0.78	0.8	0.79	/
Liquidity index	I_L	—	-3.90	-0.37	-0.44	/
Compression modulus	E_{s1-2}	MPa	20	30	36	*35
Drained direct shear test*	c	kPa	32	40	35	110
	φ	°	20	24	30	40
Undrained direct shear test*	c	kPa	25	25	25	/
	φ	°	17	20	24	/
SPT	N	blows	14	14	25	45
Soil anchor ultimate	q_s	kPa	/	50	75	160

**Drained direct shear test data used for the normal condition. Undrained direct shear test data used for the heavy rainfall condition.*

3. SAFETY ANALYSES OF THE SLOPE

The original stabilization design for this slope was conducted in China utilizing the limit equilibrium method aiming a factor of safety of 1.25. The design used four ground anchors on each ramp except for the lowest two ramps near the toe, where only two anchors were used. Various ramp surface angles were used from the toe to the crest. This design was intended to retain the soils at the toe and to remove the soil on the top as much as possible. In addition, one small retaining wall at the toe of the slope was built to increase the overburden at the toe, which is beneficial to the stability of the lower part of the slope. The spacing of the anchors in the horizontal direction was 4 meters. To prevent the soil on surface of the slope from being washed away by rainfall, turf was planted on the ramps to reduce the effect of rainfall on the upper 4 meters of soil, drainage tubes were installed into the slope 5 meters deep

Two dimensional finite element models were built using the FE software PLAXIS 2D (2012) and strength reduction technique was employed to validate and perform additional optimization of the design.

The factors of safety of the original slope before stabilization were calculated using LEM and FEM. The results obtained from the two methods are presented in table 2. The results presented for LEM analysis are for Morgenstern Price method. The special case corresponds to heavy rainfall condition. As the slope is located in a rainy area, the top 4 meter of soils at the top and along the slope were assumed to be saturated.

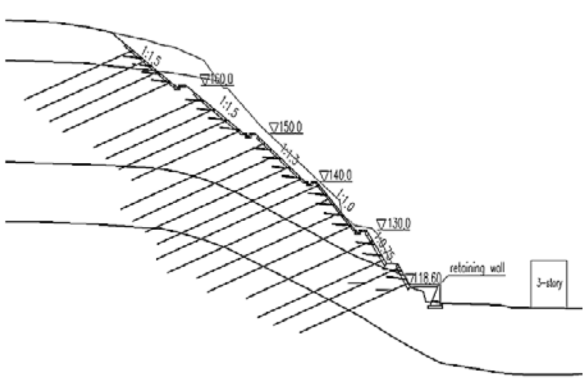


Figure 2. Schematic drawing of the original design

Table 2. Factor of safety of the original slope using LEM and FEM

Cases	Analysis Method	Factor of safety
Normal Case	***LEM(Morgenstern and Price)***	1.077
	FEM	1.048
Special Case	***LEM(Morgenstern and Price)***	1.048
	FEM	1.004

As shown in Table 2, the slope is at best marginally stable. In fact, for heavy rainfall conditions the slope has a factor of safety of only 1.004. According to the FEM analysis carried out in the present study, a deep slip surface is predicted as shown in Figure 3. In addition, two shallow failure of the slope could be identified. The nature of one of the shallow slides shown in Figure 3 is very similar to the slide depicted in Photo 1.

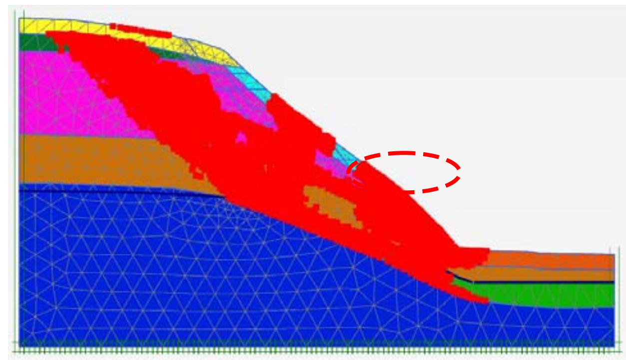


Figure 3. Failure points that occurred during the heavy precipitation event: original slope

From Table 2, it is noted that the overall factors of safety obtained by the LEM and the FEM are of comparable magnitude. In addition, failure surfaces obtained by the two approaches are similar as it can be seen in Figure 4. The failure surfaces shown are for normal case (the natural slope case).

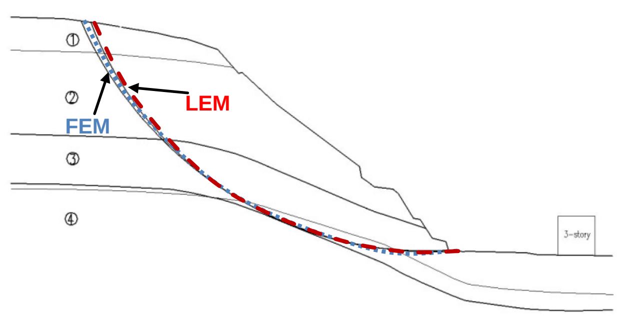


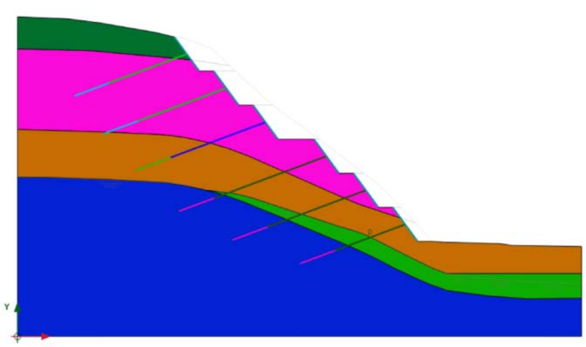
Figure 4. The failure surfaces from the LEM and the FEM

In Figure 4, the lower slip surface was obtained from the FEM, strength reduction method, while the upper one was obtained from the LEM. After establishing the fact that the slope was marginally stable even under normal condition, various slope stabilization alternatives were considered. The conventional option of flattening the slope was ruled out due to site constraints. The option of a retaining wall at the toe was also ruled out considering the height of the slope and cost of a counter fort retaining structure. In the final analysis, slope stabilization concept of excavating the slope in 6 benches and using soil anchors was considered to be the most practical and economical alternative for this site. As a first step, factor of safety for just benching of the slope was evaluated by using several FEM models for different design options. The obtained factors of safety for the considered cases are presented in Table 3 below. It can be seen that the option that considers only bench excavations could not meet the required factor of safety of 1.25 used in the original design carried out in China.

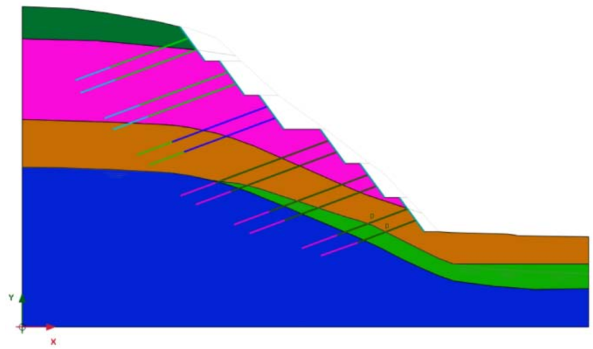
Table 3. The factor of safety of the slope with various number of anchors on each bench for normal case

Number of Benches	no anchors	1 anchor	2 anchors	3 anchors	4 anchors
0	1.048	1.048	1.048	1.048	1.048
1	1.070	1.061	1.062	1.077	1.079
2	1.096	1.088	1.101	1.112	1.108
3	1.134	1.136	1.149	1.158	1.169
4	1.144	1.161	1.187	1.207	1.232
5	1.137	1.162	1.203	1.242	1.286
6	1.089	1.179	1.214	1.267	1.340

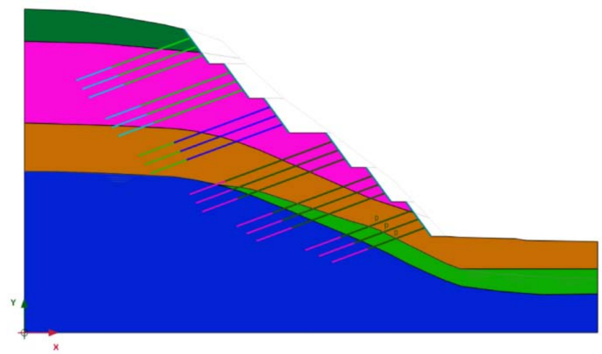
To achieve the required factor of safety, ground anchors were considered to stabilize the slope. To investigate the effect of installing ground anchors, the grouted portion of the anchors, 10 meters long, was assumed to develop bond resistance of 27, 45 and 85 kN/m based on the ultimate bond values given in Table 1 above, which corresponds to prestressing forces of 270, 450 and 850 kN applied on different ground anchors installed in ○,2, ◯,3 and ◯,4soil layers. The number of anchors installed into each bench was varied from one to four, and the FEM analysis also investigated the construction sequence. The arrangement of the anchors for the different considered cases is shown in Figure 5.



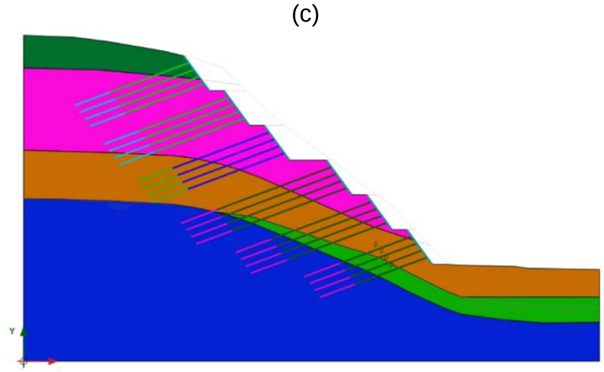
(a)



(b)



(c)



(d)

Figure 5. Arrangement of ground anchors on each bench for the considered cases: (a) one anchor; (b) two anchors; (c) three anchors; (d) four anchors

When the soil above each bench was removed, the ground anchors on the ramp were activated, and the corresponding safety factors were computed. The results are shown in Figure 5.

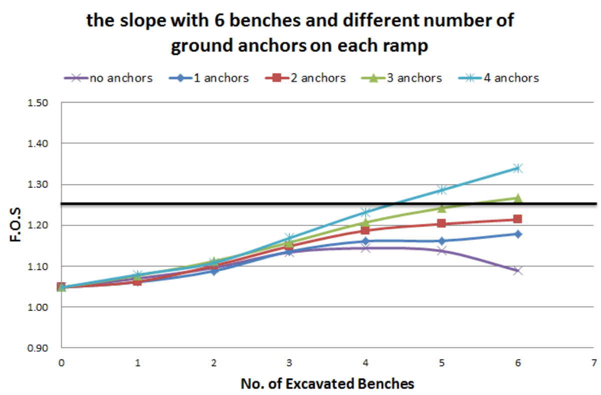


Figure 6. The safety factors of the slope reinforced with different number of ground anchors on each bench

4. DISCUSSION AND CONCLUSION

The finite element method and the conventional limit equilibrium method yielded similar results for the stability analyses of the original slope. In the final design which was carried out in China, the slope needed four anchors to be installed into upper four ramps and two anchors in the bottom two ramps to achieve a factor of safety of 1.25 based on the results of limit equilibrium analysis for the normal case. In the FEM analysis carried out, the configuration of the slope is slightly different from that in China: the height of the each ramp is constant at 8.9 meters, so is the bench face angle, 53^{o}. According to the results of FEM analysis presented in this paper, three ground anchors would be needed to reach the same value of factor of safety for the normal case. These results are contrary to the work of Cai and Ugai(2000), in which for an idealized slope with just one anchor, it was concluded that the stabilized slope yielded comparable factors of safety obtained by LEM and FEM analysis.

While carrying out FEM and LEM analysis of the subject slope, it was noticed that limit equilibrium method could compute the stability of the slope even though the factor of safety was less than 1.0. However while using PLAXIS, the factor of safety of the slope had to be greater than 1.0 so that the initial stress field could be generated and the calculation for factor of safety could proceed. In other words, PLAXIS can only analyze slopes, including the marginally ones as long as the safety factor is greater than 1.0.

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REFERENCES

Cai, F. and Ugai, K. (2000). "Shear strength reduction FEM evaluating stability of slopes with piles or anchors. *Proceedings of the International Conference on Geotechnical & Geological Engineering, GeoEng2000, Melbourne, Australia, 19-24 November, Vol.2: Extended Abstract, pp.447, CD-ROM PF0420*.

Cai, F. and Ugai, K. (2003). " Reinforcing mechanism of anchors in slopes: a numerical comparison of results of LEM and FEM". *International Journal for Numerical and Analytical Methods in Geomechanics, Vol. (27), p.p. 549-564*.

Cheuk C.Y., Ho, K.K.S., and Lam, A.Y.T. (2013) “Influence of soil nail orientations on stabilizing mechanisms of loose fill slopes.” Canadian Geotechnical Journal. Vol. (50), p.p. 1236–1249.

GRIFFITHS, D. V. and LANE, P. A. (1999) “Slope stability analysis by finite elements.” Géotechnique, Volume 49, Issue 3, pages 387 –403.

Sabatini, P.J., Pass, D.G., and Bachus, R.C., Office of Bridge Technology. “Ground Anchors and anchored systems.” Geotechnical Engineering Circular No. 4.

PLAXIS 2D (2012). PLAXIS BV, Amsterdam, Netherlands.