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Numerical study of reinforced natural slope by retaining wall with prestressed anchor

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Abstract. The slope design under geological and hydraulic conditions has always been a different geotechnics problem. There have been potential main landslide and an undisturbed thin layer of saturated clays soil under the slopes in urban construction development area of Miliana city province of Algeria; its terrain is mountains. The landslide was framed by gravity creeping of thin layer of alluvium and mares cracks along steep clays. The favorable sliding surface larger than 2500 m² had destroyed the foundation of the building. In order to learn from the comparison between stabilized and non-stabilized slopes with different improvement, the authors also investigated the slopes reinforced by retaining wall with prestressed anchor and discussed their behavior parameters. Based on finite element method, the analysis of slope stability under natural conditions is discussed first, then the support structure of retaining wall and anchor reinforced and their effect of slope stability are analyzed, and also the slope stability of each case is able to be compared. The results show that the stability of slope was significantly improved after reinforcement, and anchor reinforced with retaining wall has obvious reverse anchoring effect on soil. By comparing the factor of safety, stress level and displacement field before and after slope reinforcement, it is found that better reinforcement results can be achieved if strong reinforcement is applied upon the regions with high sliding surface. Furthermore, the increase in stress level at the zone dangerous is more favorable of improving the safety of the critical region.

Keywords: slopes; prestressed anchor; retaining wall; factor of safety; Plaxis

1. Introduction

Due to the impact of regional geological structure and hydraulic conditions that are relatively strong, numerous landslides in Miliana city province of Algeria are induced. The authors investigated into various influential factors on the slope stability of landslides in site of building structures in Miliana center, such as high slopes, angle slopes, hydraulic conditions and rock brittle materials. It is often for geotechnical engineering to meet slope treatment in urban construction development area project. Especially in Miliana city, slope failure is the most outstanding problem when constructing buildings in a mountainous area, where high and angle slopes are found. It

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threats the safety during construction and excavation operation. Because of precipitation and external disturbance, it is easy for site of constructing buildings in Miliana high slope to lose its stability which seriously affects the safety of the existence of buildings. So reinforcement treatment of Miliana city slopes was considered. According to security and feasibility, it is important for Miliana slope to study improvement and reinforcement optimization for the region by using a different techniques of reinforcement. The slope design under complex geological conditions has always been a difficult geotechnical engineering problem. the finite element method is a principal tool that permit to discuss and to analyse the slope stability under natural conditions with and without reinforcement element, and also the slope stability under each conception step are analysed comparatively. Numerical methods have become very popular in recent year for geotechnical studies and stability analysis of slopes. They are completed the limit equilibrium methods, which means that the comparison of different reinforcement of the slope is difficult. The finite element software of Plaxis is exactly applies for the stability analysis of slope. Furthermore, in these methods slope geometries and building structures materials can be handled and ground water flow can be completed. In these methods stress level, displacement field and factor of safety in each step can be calculated and various modulus relations can be employed.

From the literature review, it has also been observed that researchers (Griffiths and Lane 1999, Zheng *et al*. 2009, Fawaz *et al*. 2014) employed the strength reduction method of finite element to obtain the factor of safety. The displacement-based finite element code Plaxis (Huang and Jia 2009, Brinkgreve *et al*. 2016) enables the definition of the factor of safety means of effective friction angle φ' and effective cohesion c'. The precision of the factor safety is a function of type of constitutive soil model selected, type and size of the element, discretized mesh, node location for displacement curve and tolerance allowed for non-linear analysis (Abioghli and Branch 2011). The change in size of the mesh in the model has a consequent effect on the results obtained. Therefore, the mesh size in a variety of software Plaxis, the mesh size is very coarse, coarse, medium, fine and very fine, is interested. An additional benefit is that the groundwater level could be lowered within drainage trenches that increase the slope stability especially during rainfall (Cai *et al*. 1998, Valli 2000, Pinyol *et al*. 2008, Fawaz *et al*. 2014). The increase in internal circulation of water flow can affect the balance of natural geological slope by dissolution of gypsum, so the establishment of a drainage system contributes greatly to the stability of the slope (Benamara and Belabed 2011).

Numerous researches have been conducted on the optimal position reinforcement and space of the anchor rods in soil. Researchers (Desai *et al*. 1986, Hryciw 1991, Briaud and Lim 1999, Cai and Ugai 2003, Zhu *et al*. 2005) have extensively studied the behaviors of anchor rods and soil-anchor interactions. For example, Cai and Ugai (2003) used 3D zero-thickness elasto plastic interface elements to simulate the soil anchor interactions. In fact, there is a close relationship among stress field, displacement field, and stability of the slope (Huang 2008).

Considering that the stress and displacement can be obtained by numerical methods such as finite element method (FEM), many scholars attempted to obtain the optimal reinforcement by analyzing the stress and displacement fields of the slope. Benamara and Belabed (2011) presented a numerical analysis of the behavior of the retaining wall anchored proposed for stabilization of the slope sliding movement below the highway. The calculations presented were carried out taking into account the hydromechanical coupling, the impact of changes in groundwater and the soil-bar (anchor). Liu *et al*. (2012) presented that the prestressed rods were improved to be quincunx arrangement which long rods alternating with short ones in this paper, which increasing the spacing between the anchor segments when rods have same burial depth. The optimum layout decreases the tensile stress superposition around the anchoring ends in rock, which is helpful to keep the anchorage system stable. The publications (Yuan 2014, Yang *et al*. 2015) are realized reinforcement of anchor cable by surface loading and are pointed out that a better reinforcement using anchor cable effect can be achieved when more reinforcement is applied to the position characterized by high stress level of sliding zone (or large displacement). For instance, by increasing the prestress or extending the length of anchor cable, it can provide larger resistance in this area. Hosseinitoudeshki *et al*. (2015) reported that the stability of rock slopes is affected on the spacing of anchor bolts and that the reduction of the spacing of anchor bolts can improve the rock slope stability. The maximum factor of safety can be obtained for the anchor bolts perpendicular to the slopes.

During the last three years, there have been many studies carried out on reliability analysis, which considers the geotechnical uncertainties in a rational manner and evaluates the slope safety by failure probability (or equivalently, reliability index). This latter has numerous applications in the geotechnical field (Liu *et al*. 2019, Wang *et al*. 2019). It is well known that the unsaturated slope failure risk is considerably influenced by the spatially variable void ratio, and the single exponential autocorrelation function in geotechnical engineering tends to underestimate the failure risk in the unsaturated slope risk assessment. Many researches have investigated the influence of unloading path and rate on the evolution of crack and strain of soil slope induced by toe excavation (Gao *et al*. 2019, Wang *et al*. 2019, 2020c). Wang *et al*. (2020a) have proposed a probabilistic stability analysis to evaluate the probability of earth slope failure with satisfactory accuracy and efficiency. They found that, among the hydraulic parameters, the coefficient of variation of the saturated hydraulic parameter has an influence on the failure probability of earth slope. Therefore, the failure probability of earth dam slope is significantly affected by the water level fluctuation velocity and by the coefficient of variation of the effective friction angle.

Although probabilistic stability analysis has been widely applied to the safety assessment of geotechnical structures. Some studies have been performed to investigate the effects of water level fluctuations on earth dam slope stability taking into account uncertainties of soil parameters. Wang *et al*. (2020b) has developed an extreme gradient boosting based on the reliability analysis for earth dam slope stability. It was noted that the earth dam slope failure probability is affected by the spatial variability of soil properties. Also, the results of this study indicate that the proposed approach is able to predict the failure probability of studied earth dam slope with satisfactory accuracy and efficiency, which reveals a new possibility of facilitating the probabilistic stability analysis of earth dam slope in geotechnical practice by integrating multivariate adaptive regression splines.

On the other hand, Chen *et al*. (2020a, b) have reviewed the different failure modes in over-dip rock slope against bi-planar sliding, discussing the key factors that affect their stability. Based on the analysis of this slope type, they have introduced a numerical approach to analyze the different failure modes using geomechanical model of this slope type, they proposed a classification for failure modes associated with failure zone. The slope stability was estimated using the Limit Equilibrium Method with a changed sliding surface. The equivalent slope model is suggested as a mechanism explanation for the slope factor of safety under various combinations of sliding surface geometrical and mechanical parameters. They showed design charts as a fast method for calculating stability for an over-dip rock slope against bi-planar sliding, and determining the related failure mode. They have concluded that the slope factor of safety declines when strength parameters decrease. This is due to the low strength of the sliding surface, which leads to the more unstable slope. According to all stability patterns, bi-planar sliding is more likely to occur in over-dip rock slope when the bi-planar sliding surface is composed by gentle-dipping structural planes with high and steep-dipping structural planes.

Among the most used techniques of reinforcement of the slopes in geotechnical engineering practice, it is the inclusion of the piles in the ground constituting the slope (Zhang *et al*. 2017, Chen *et al*. 2020c). Chen *et al*. (2020c) have analyzed the soil slope reinforced with pile for calculating the safety factor taking into consideration the pile location and pile length based on limit equilibrium method. The optimal reinforcement scheme was determined by comparing the results of deterministic with probabilistic analyses. They have found that the effect of soil spatial variability would generally result in a lower failure probability. Thus, they have shown using parametric analyses that the failure probability is significantly influenced by the pile location, the pile length, the spatial variability of soil, the scale of fluctuation and the coefficient of variation of cohesion and friction angle. Therefore, it is essential to investigate the influence of soil spatial variability on the slope reinforced with pile.

The main objective of this study is to investigate the different methods of improvement or reinforcement of the site contributing to the stability of the slope triggered by a landslide and to know the most effective solution. In addition, a comparative study was performed to investigate the stability of the slope by lowering the water level, the constructing of embankment and the retaining wall with prestressed anchor. In order to study the effect of retaining wall and anchor reinforced on the stability of slopes, the slopes with different soil layers and with anchor reinforced were modeled. Finally, the general relationship between the stress level, displacement field and safety factor of retaining wall with prestressed anchor is obtained by comparing the effects of different improvement procedure.

2. Engineering situation

There is an ancient slope located in east of Miliana city, province Ain Defla southwest Algiers. The slope design under complex geological conditions of the presence of rocky outcrops, saturated soil and high angle slope about of 20%. The landslide region covers an area of about 2500 m², so the foundations of the last building are destructed at the bottom of the slope, because its sliding was induced significantly under the existing conditions such as high slope and precipitation (100 mm per month and which manifests in the winter). The landslide was formed by gravity of three layers of alluvium silty clay, gray marls cracks and Marl bedrock. The geological section of the slope is presented in Fig. 1.

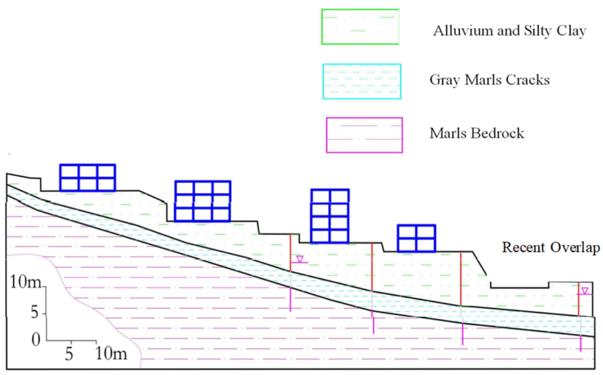
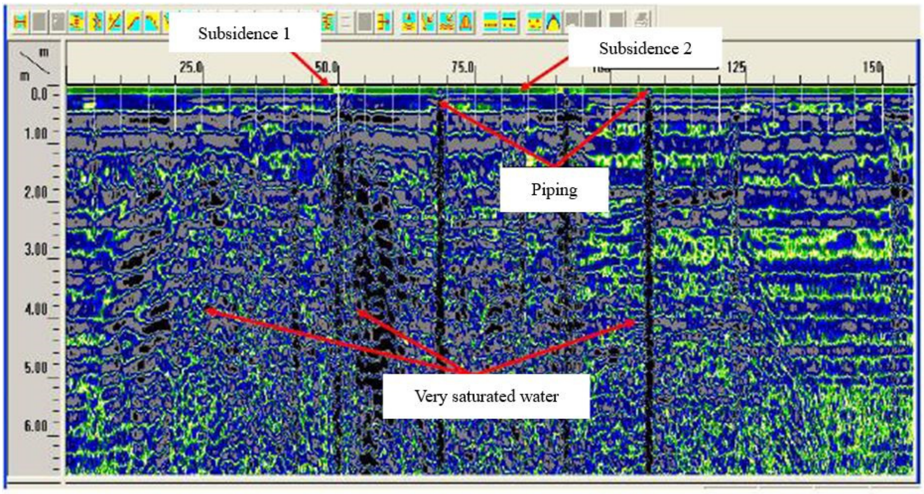


Fig. 1 Geological section of the slope



Profile 005 (length: 155 ml)

Fig. 2 Ground Penetrating Radar (GRR) central profile of soil

In this study, the geophysical parameters of the slope were obtained using Ground Penetrating Radar (GRR) systems. Theses parameters are presented in Fig. 2. The Ground Penetrating Radar (GRR) systems show that central section of soil is very saturated.

3. Modeling of studies slope

3.1 Geometry model

The finite element software of Plaxis is exactly applied for the stability analysis of the slope (Brinkgreve and Vermeer 2002). Its advantages are that the stress redistribution and coordinate deformation induced by excavation of slope of rock mass could be fully considered, as well as searching the location of sliding surface quickly and accurately. At the same time, the evolution of generalized shear strain increment and plastic zone can be dynamically displayed by applying the Staged Construction module of Plaxis. The slope section is used to discuss the relationship among stress field, displacement field and factor of safety slope. The geometry model of studies slope is shown in Fig. 3.

3.2 Material models

There are three soil layers and four building structures in the model. The soil properties are listed in Table 1.

The building structures are modeled by plate elements, when composed by reinforced concrete beams and foots. The mechanical parameters of structures elements are listed in Table 2.

3.3 Mesh generation

The first step of the studied slope concerned the use of 2D finite element modeling (Brinkgreve

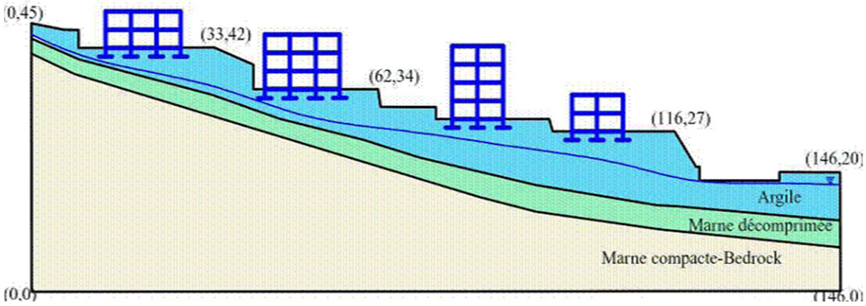


Fig. 3 Numerical model in Plaxis

Table 1 Properties of soil layers

Parameters	Clay	Marl	Marl bedrock
Model type	Mohr-C	Mohr-C	Linear elastic
Moist unit weight γh (kN/m^3)	18	19	21
Young's modulus E (kPa)	3593	4627	1E6
Poisson's ratio v	0.3	0.3	0.3
Cohesion c (kPa)	29.50	36	-
Angle of friction φ (°)	21.5	20	-
Angle of dilation ψ (o)	0	0	-

Table 2 Structures elements parameters

Parameters	Beams	Foots
Type of behavior	Elastic	Elastic
Normal stiffness EA (kN/m)	2.700E6	2.160E7
Bending stiffness EI (kN/m^2/m)	2.025E4	2.880E5
Weight w (kN/m/m)	7.50	10
Poisson's ratio ν	0.2	0.2

et al. 2016) in order to analyze the landslide. To apply the finite element method, the appropriate meshes were generated for the various slope geometry models by dividing each model into a number of elements; each element consists of a number of nodes. When the geometry model is complete, the finite element mesh can be easily generated. The finite element model has been setup in plane strain condition with 15-node triangular elements. The studied slope with a maximum height of 45 m extends over a distance of 146 m. The finite element mesh used in this study is shown in Fig. 4. In the current study, coarse mesh is used for the analysis. The number of total elements is 312 elements that have an average size of 4.69 m. The mesh includes 2649 nodes and 3744 stress points.

The two vertical boundaries are free to move, whereas the horizontal boundary is considered to be fixed as presented in Fig. 4. The foundation soil was considered to be stiffed and its stability is not considered in this analysis, therefore the bottom boundary is fixed.

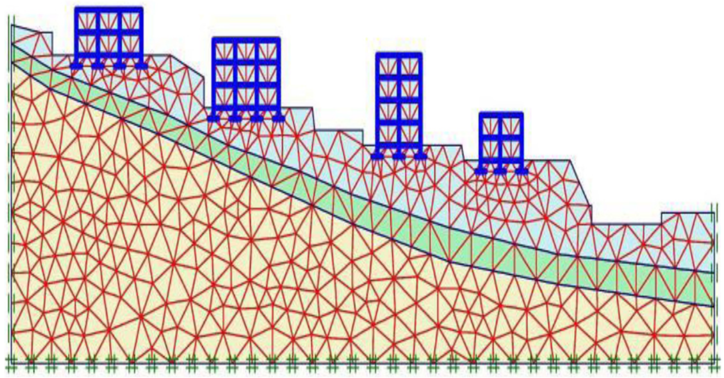
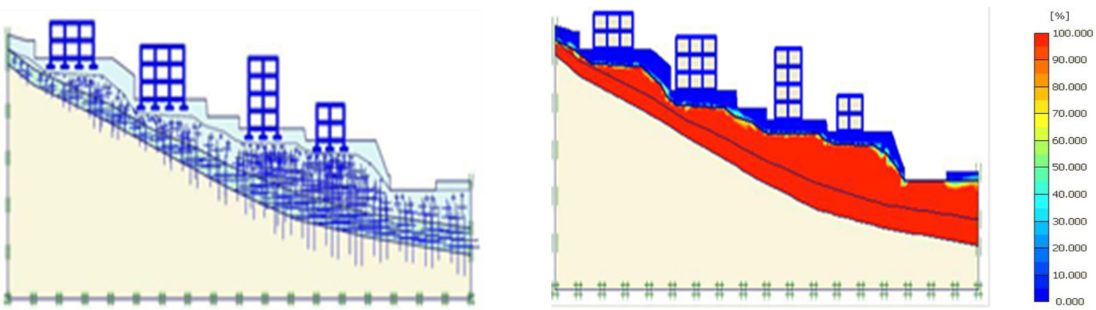


Fig. 4 Finite element mesh of the studies slope



(a) Pore pressures (max = – 131.96 kPa) (b) Degree of saturation (max = 100 %)

Fig. 5 Initial hydraulic conditions

3.4 Initial hydraulic conditions

The hydraulic conditions (pore pressures, and degree of saturation) are followed by generation of finite element mesh. The option ‘Generate water pressures’ has automatic mesh generator can greatly simplify the task. The voluminal weight of water is taken equal to 10 kN/m^3. The pore pressures and degree of saturation are shown in Figs. 5(a)-(b) respectively.

3.5 Calculation models

In order that Plaxis calculates the initial constraints, it is necessary to decontaminate the soil weight, by taking the values of K_0 by defect. The value of the coefficient of grounds at rest is calculated by the software by defect using the formula of Jacky ($K_0 = 1 - \sin \varphi$). Instead, the initial stresses must be calculated means of ‘Gravity loading’. The analysis considers undrained conditions and a linear elastic-perfectly plastic constitutive model with a Mohr-Coulomb failure criterion. Fig. 6 shows the principal effective stresses during gravity loading. The major calculated stress rate is about 322.41 kN/m^2. Maximum stress obtained at a bottom of slope.

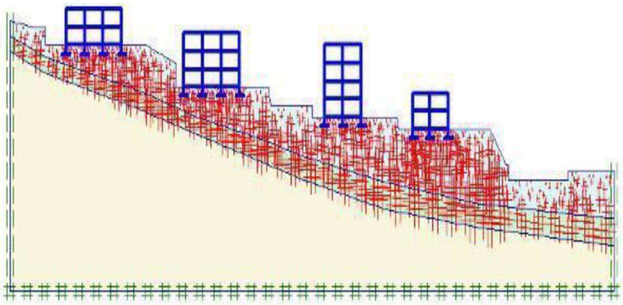


Fig. 6 Effective stresses during gravity loading (max = -322.41 kN/m²)

4. The calculations results

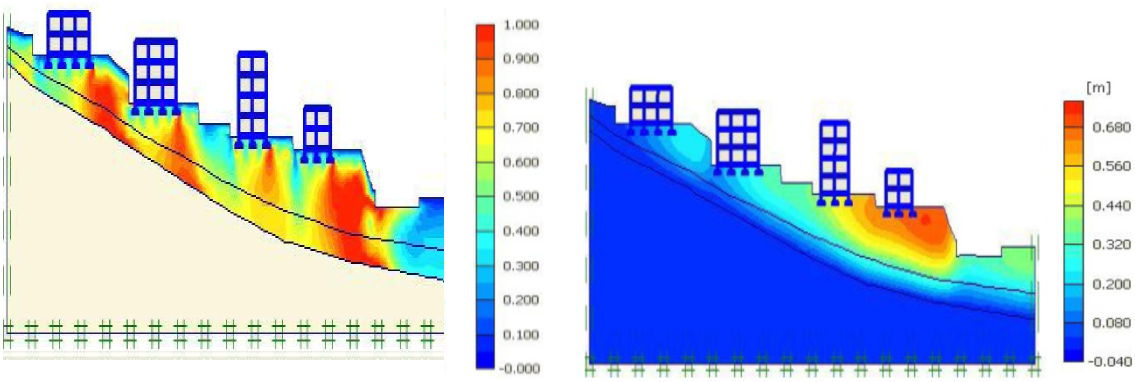
4.1 Stability analysis of slope of natural state

For natural slope, the calculation results show that the factor of safety is 1.01 without considering the lowering of the level of the water or the softening of slope of the embankment or the reinforcement of the slope. The distribution of stress level and displacement field of the slope is shown in Figs. 7(a)-(b) respectively. It can be seen from Fig. 7(a) that the sliding surface both appeared near critical stress level localized in the bottom slope, while the stress level in other areas is relatively low, with the value less than 0.7.

Fig. 7(b) shows the distribution of displacement field of slope. It is clear that the largest displacement in the bottom region, where the tress level and displacement field are greatest. Therefore, it is concluded that the deformation of area is larger in terms of higher stress level.

4.2 Analysis of slope with varying mesh geometry

In the finite element method, mesh geometry (coarse, medium and fine mesh) affect the numerical results if their optimum values are not quantified. Consequently, analysis of slope with



(a) Relative stress levels (b) Total displacement contours

Fig. 7 Distribution of displacement and stress levels

Table 3 Different mesh geometry

Mesh geometry	Very coarse	Coarse	Medium	Fine	Very fine
Number of elements	275	312	385	586	904
Number of nodes	2343	2649	3251	4905	7497
Number of stress points	3300	3744	4620	7032	10848
An average size of elements (m)	5.00	4.69	4.22	3.42	2.76

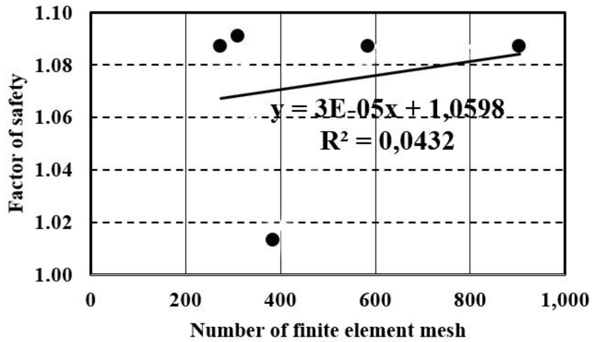


Fig. 8 Influence of the variability in number of elements

varying mesh geometry is very important. Different geometry of mesh such as very coarse, coarse, medium, fine and very fine 15-node triangle element are used and the factor of safety is calculated by using finite element method based software 2D Plaxis. The number elements, number of nodes, number of stress points and an average size of elements are presented in Table 3.

By varying the numbers of elements in the mesh, the sensitivity of slope factor of safety to the number of elements was determined, and the results are shown in Fig. 8. Results of corresponding finite element method analyses are also shown for comparison purposes.

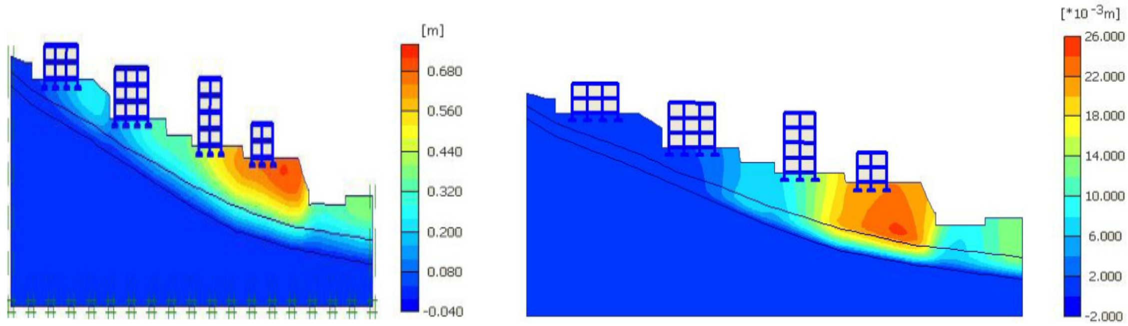
Irrespective of the type of failure criterion, there is a convergence of factor of safety values as the numbers of elements increase, but at the expense of running time. The factor of safety trend for coarse mesh (275 elements) and very coarse mesh (312 elements) is just slightly different from those for very fine mesh (904 elements) and fine mesh (586 elements). For case of medium mesh (385 elements), no significant influence of number elements on factor of safety was observed.

4.3 Influential factors on the stability of non reinforced slope

Based on the failure progress during hydraulic condition and constructing earthworks at the bottom slope, two procedure design schemes were proposed. The first one is to increase the water level above the surface slope for protection and drainage; the second one is to carry an embankment at the area bottom slope. The water level at one meter to the surface slope is considered as a reference. The result of these propositions can be compared by reference for similar project.

4.3.1 Effect of water level

In order to analyze the effectiveness of water level to landslide occurrence probability, the



(a) Water level at 1 meter (Reference profile) (Fs = 1.011)

(b) Water level at 9 meters (Fs = 1.10)

Fig. 9 Effect of water level on the sliding surface

Table 4 Influence of the water level on the safety factor

Water level	-1 m (Reference)	-2 m	-6 m	-7 m	-8 m	-9 m
Safety factor	1.011	1.058	1.058	1.10	1.10	1.10

range of water level is varied into six values from one meter to nine meters. For comparing with effect of two cases, displacement field is analyzed under one meter and nine meters water level. Figs. 9(a)-(b) respectively shows that displacement field when water level varied to one meter and nine meters. The increase of water level can effectively improve stability of area bottom slope but it is insufficient.

The control factors of bottom slope stability under each water level are shown in Table 4. Through the comparative analysis, such as the safety factor of bottom slope is increased from 1.011 to 1.10 for one meter and nine meters, respectively, and the bottom slope stays always instable.

4.3.2 Effects of constructing an embankment

To study that effect of constructing an embankment on the stability of bottom slope, the slope is modeled by the second phase of software Plaxis. In the models, the earthwork embankment was used in bottom slope. By running the second phase models, the critical displacement of bottom slopes was obtained (see Fig. 10). It can be seen that the displacement field of the bottom slope

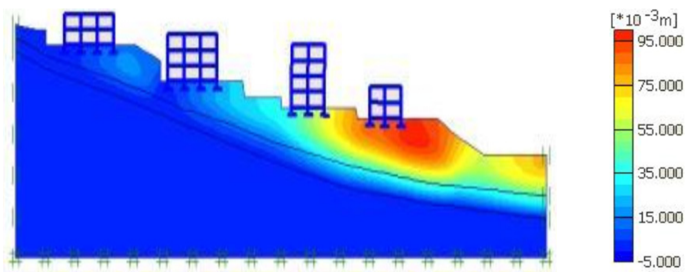


Fig. 10 Effect of constructing an embankment in the slope (Fs = 1.20)

is larger than that without embankment, and the factor of safety of this region is higher.

In this case, the displacement of this region is very large, thus it can effectively increase the factor of safety. The factor of safety of the bottom slope without embankment is 1.011, and it is 1.20 when using the earthwork, but the landslide was not stopped.

4.4 Stability calculation model of slope reinforced with retaining wall and prestressed anchor

The retaining wall with prestressed anchor is composed of reinforced concrete retaining wall embedded on the slope surface and prestressed anchor implanted into the slope deeply, which is widely used in railway, highway engineering, also used in good conditions. As a result, the prestressed anchor retaining wall in high slope protection engineering has a broad application prospect.

In this numerical case, the retaining wall is used to reinforce the slope, and is anchored into the bedrock of 18 m deep and 0.35 m thickness. The retaining wall is made of plate element and devised into four nodes. The material properties of the retaining wall are given in Table 5.

The geometry model of the support design of retaining wall is shown in Fig. 11.

The calculation consists of two phases. In the first phase, the retaining wall and the surface loads are activated. In the second phase, the safety factor of the slope reinforced is calculated. All calculation phases are defined as plastic calculations.

The total stress level and the total displacement field of sliding zone are presented in Figs. 12(a)-(b) respectively, showing that the stress level is very lower at the part of retaining wall,

Table 5 Material properties of the retaining wall

Parameters	Value
Type of behavior	Elastic
Normal stiffness EA (kN/m)	10.5E6
Flexural rigidity EI (kN/m^2/m)	8.75E5
Equivalent thickness d (m)	1
Weight w (kN/m/m)	8.75
Poisson's ratio ν	0.2

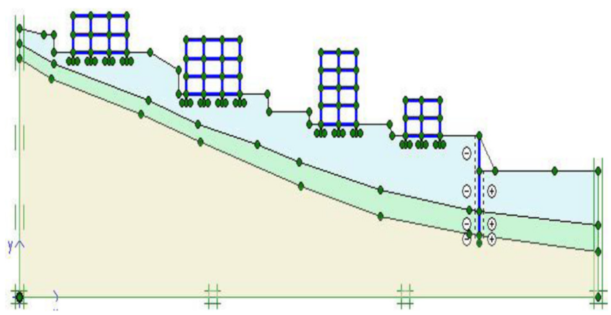
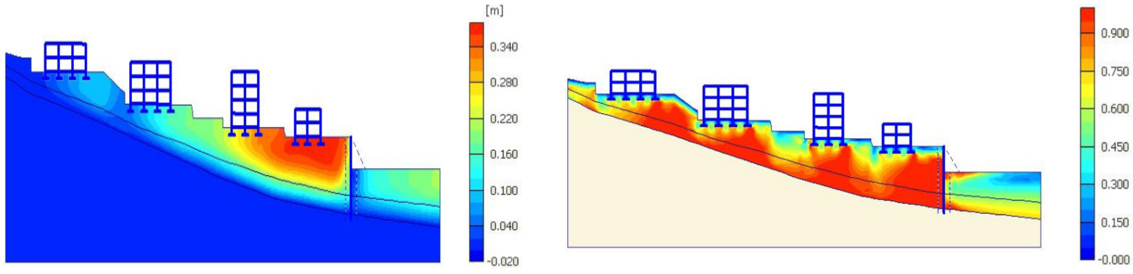


Fig. 11 Geometry model of a retaining wall



(a) Total displacement contours (maximum value = 381.20 10^{-3} m)

(b) Relative stress levels (max = 1)

Fig. 12 Distribution of displacement and stress levels of slope reinforced with retaining wall (Fs = 1.591)

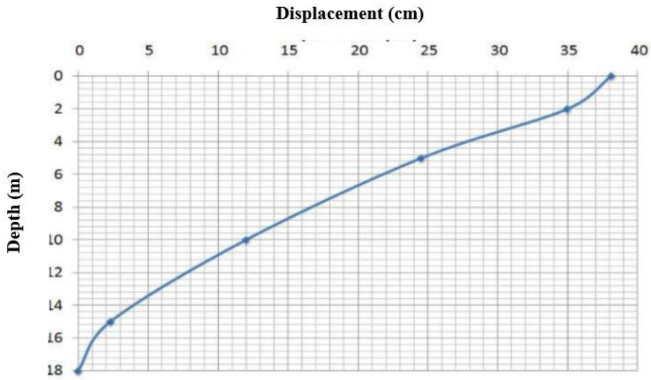


Fig. 13 Distribution displacements along the depth of the retaining wall

while relatively higher in the outside of this area. The strength of the slope is reduced by factor of 1.591, so as to observe the displacement field during its weakening. The retaining wall increase the stability of bottom slope, the factor of safety of the slope with wall retaining is increased to 1.591, which is 32.5% larger than that provided in the above solution.

The displacement field distribution along the depth of retaining wall is shown in Fig. 13. It can be seen that under the retaining wall application, the displacement field about the retaining wall is continuous and decreasing in shape, with a maximum value of 381.20E-3 m occurring in close proximity to the point of the crown wall.

Because of more efficient to improve the stability of bottom slope with retaining wall, the prestressed anchor is used in fixed to the wall at the point 116.24. The prestressed anchor is modeled by node-to-node anchor prestress and a geogrid. The anchor has a total length of 6.5 m and an inclination of 45°. The material used in this paper is based on work presented by P.J. Sabatini, D.G. Pass; R.C. Bachus in the document Geotechnical Engineering Circular N°4 intitule Ground Anchors and Anchored Systems. The proposed geometry model is given in Fig. 14.

The properties of the ground anchors are entered in a material set of the anchor rod. The properties are listed in Table 6.

Before the anchor reinforcement, the calculation and simulation are determined by this stress. The first step corresponding to generate of the initial hydraulic condition and the displacement field, then the displacement field is set to zero, the excavation construction of retaining wall and

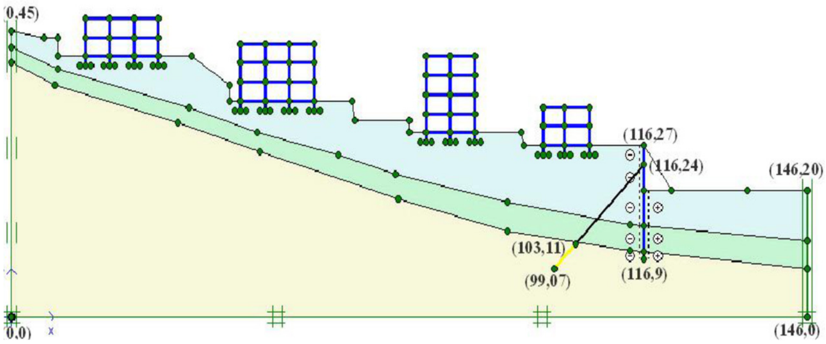
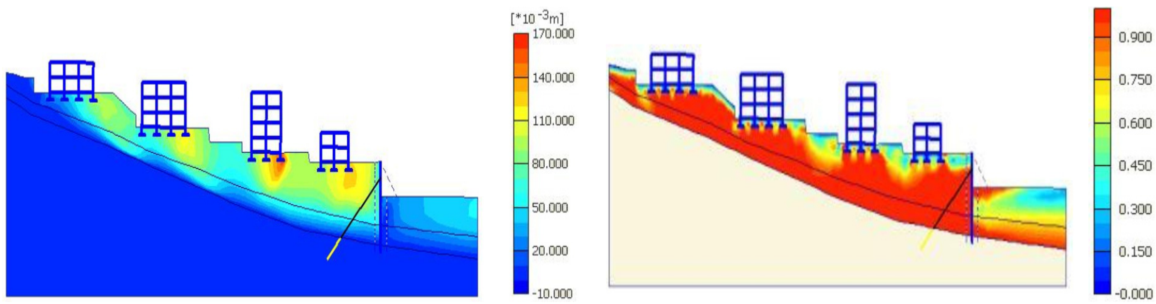


Fig. 14 Retaining wall with prestressed anchor model

Table 6 Properties of the anchor rod

Parameters	Value
Type of behavior	Elastic
Normal stiffness EA (kN/m)	10.5E6
Spacing out of plane Ls (m)	2.5
Maximum force F_{max} (kN))	777.81



(a)Total displacement contours (b) Relative stress levels (max = 1)

Fig. 15 Distribution of displacement and stress levels of slope reinforced with retaining wall and prestressed anchor (Fs = 1.965)

prestressed anchor presented the second step, and the last step is reserved to calculate the factor of safety.

The results of this analysis are presented in Figs. 15(a)-(b). The bottom of slope reinforced by retaining wall and prestressed anchor is very stable. The difference is embedded in the value of the factor of safety, which is the deformation of slope can be decreased if reinforcement adopted and while the stress level is increased. The factor of safety with the prestressed anchor is 1.965, which is 63% larger than the provided in the above solution.

5. Conclusions

In the present study, various processes for slope improvement and reinforcement using water level, constructing embankment, construct retaining wall and prestressed anchors show that a better improvement effect can be achieved when more improvement techniques are applied to the position characterized by high stress level of sliding zone (or large displacement). For slope reinforcement design, element finite per software Plaxis should be used to analyze stress level and displacement field, based on which the effective reinforcement procedure can be determined.

In these techniques to subsidence the water level and constructing embankment in the slope, the stability of the slope is improved and the factor of safety increase to 1.011 at 1.20. Therefore, the landslide is not stopped.

Concerning the slope reinforcement by retaining wall and prestressed anchor it has a better reinforcement effect, which the stability of slope was significantly improved after supported. Meanwhile, the procedure proposed here would serve as a useful tool for this study. For slope reinforced design, numerical methods results show that the factor of safety is 1.956 with considering the reinforcement of the slope. Compared with constructing an embankment and constructing a retaining wall, it can be found that the slope position of the most dangerous sliding surface changes with each improvement techniques. The phenomenon is very significant situation considering the effect of prestressed anchor.

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