Static and Seismic Stability of a Slope Reinforced with Two Rows of Piles

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ABSTRACT

The use of piles for slide stabilization is considered among the most important innovative reinforcement techniques. Piles have been successfully used in many situations to stabilize slopes or as parts of a stability improvement. Our case study is in the Tlemcen section. The left side of the roadway collapsed following the slide of the downstream side. Inclinometer readings showed signs of instability with a slip depth of about 9m near the motorway platform. The likely causes of the instability were the removal of the lower abutment of the embankment upstream of the road and the establishment of an earth deposit which overloaded the embankment and disrupted the flow of water downstream. The stabilization study is based on the installation of two rows of anti-slip piles. Stability analysis study was carried out under static and dynamic loads and highlights that this solution is advantageous and effective.

Keywords-pile behavior; dynamic study; finite elements; slope; highway

I. INTRODUCTION

Many methods have been developed for the analysis of piles [1-4]. The limit equilibrium method was used in [3] to deal with the problem of stability of embankments containing piles. The safety factor of a slope reinforced by piles was defined as the ratio of the moment of resistance to the moment of overturning (engine) acting on the mass of the potentially unstable ground. The time of resistance consists of two components: the moment due to the resistance of the ground to the shear along the sliding surface and the moment provided by the reaction force piles. The driving moment and the moment of soil shear resistance were obtained by the simple slice method. The study of a slope includes, in addition to the recognition of the site and the choice of the mechanical characteristics of the soils, stability calculation in order to determine not only the breaking curve along which the risk of landslide is the highest, but also the corresponding value of the safety coefficient [5]. It should be noted that ground movements are very varied in nature and size. The problems of slope stability are recorded in a general way in the realization of roads, dams, and natural slopes. The landslide passes through several chronological stages of activity. There are major factors that control the type and rate of mass movement that could occur.

The methods of slope stabilization by the so-called anti-slide piles have attracted the interest of several researchers and many studies have been conducted on slopes introducing stabilization piles. We distinguish 2 methods of calculation: limit equilibrium methods and numerical methods. The kinematic approach of treating the slope with one or more rows of piles called "passive piles" has the advantage of improving its stability [1]. We note that the major problem in the design of the slope-pile system is the determination of the appropriate and effective location of the piles. The influence of pile reinforcement on the stability of the slope was studied in [6]. A 2D numerical modeling was used to validate the proposed approach by comparing the numerical results with the field measurements. The effect of pile position as a function of soil shear parameters was also studied. The results indicate that the ideal position for this type of stabilization piles is in the average height of the slope. The slope should be between 30° and 60°.

It should be noted that this study is focused on a problem that occurred at the section of PK 210+480 to 210+800 of the East-West Algerian highway near the Didouche Mourad, Constantine. The results of this study confirm that soil suction has a significant effect on slope stability. Negative pressures from pore water in the slope must be taken into account. It is imperative that an appropriate drainage system is in place and that it is properly maintained.

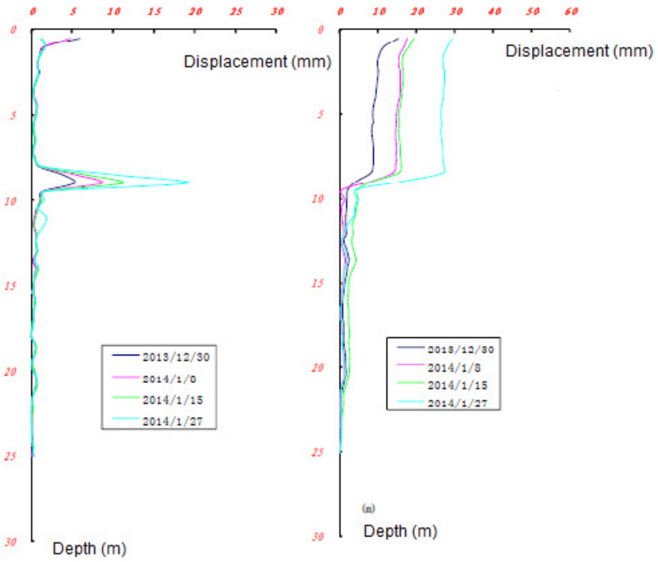
Authors in [7] conducted an experimental and numerical study of the stability of a slope reinforced with a concrete pile. This study showed that when the pile is located in the middle of the slope, the soil structure collapses under a pressure of about 10.9kPa, which is the highest pressure that caused the instability of the slope consisting of reinforced sand. However, when the pile is located upstream or downstream, slope failure occurs under a pressure of 7.8 or 3.12kPa, respectively. Therefore, his work showed that a pile located in the middle of the slope can improve the reinforcement of the soil, providing it with optimal stability. Authors in [8] investigated the stability of a slope under 3 configurations, i.e. without protection, with one row of piles, and with two rows of piles. This study focused on the analysis of the sliding mode, the distribution of bending moments, and the factor of safety of the slope. For the single-row stabilization pile reinforced slope, the optimal location of the piles is in the lower and middle part of the slope where the factor of safety takes a maximum value of 1.26. For the two-row stabilization pile reinforced slope, the appropriate location of the piles is in the lower and lower middle part of the slope. The factor of safety in this case has a maximum value of 1.38. The bending moment and thrust on the double-row piles are more reasonable than the other configurations.

II. PRESENTATION OF THE LANDSLIDE OF HIGHWAY AT KILOMETER POINT 52

In this article, we study the landslide that occurred on March 2, 2014 on a section of the East-West highway near the city of Tlemcen (north western of Algeria). The platform at PK 52+040 to PkK52+220 underwent major deformations, with the rear wing moving vertically, i.e. by 3 to 4m horizontally. As a result, the left side of the roadway was completely closed to traffic and the outer part was completely deformed, being subject to sliding, as shown in Figure 1.

Fig. 1. Deformation of the pavement of highway at Pk52.

According to the on-site observation, the landslide was rapidly developed while dense cracks were found in the body of the landslide not far from the river and there were clear deformations in the form of shearing. The vertical displacement of the slide platform was approximately 2m on an embankment section. Observation of the core samples showed a highly variable lithology, with high pebble content in the boreholes taken. According to the order of destruction of the inclinometer boreholes, the borehole next to the bank of the river was damaged first and the destroyed borehole next to the platform was next, so the slip was caused by a bottom-up pull. Furthermore, there is no evidence of deformation in the hole on the right side of the route. It should also be noted that the scouring of the river water on the front edge of the landslide quickly caused the landslide to appear. One day before, i.e. March 1, 2014, torrential rains that fell on the region caused water infiltration and the rise in the level of the underground water table in the body of the slope. This lubricating action accelerated the mechanism of the landslide phenomenon. Figure 2 shows the evolution of displacements over time.



Borehole S01 BoreholeS03

Fig. 2. The evolution of movements over time for boreholes S01 and S03.

III. GEOLOGICAL AND GEOTECHNICAL PROFILE OF THE SITE

The geotechnical profile of the site was determined by reconnaissance, with 6 boreholes to a total depth of 127.4m. The determined geotechnical profile of the site shown in Figure 3 shows that the area has a sloping profile. The soil layers are made up of a bedding fill of medium density, followed by a layer of brownish to yellowish silty clay, distributed mainly in the left embankment of the route. The soil is homogeneous, interspersed with a few pebbles and sand, very plastic, but not locally. Overlying a layer of completely weathered sandstone distributed mainly on the bank of the river, at the foot of the left embankment and at the foot of the right embankment, a layer of completely altered marl of yellow-green color with a clay structure, interspersed with very plastic sand. The water level varies in depth from 13 to 24.5m in the various boreholes drilled, with a tendency to flow in the direction of the slope. Analysis of the inclinometer reading data showed that the slip surface was at 9m, 7m, and 3m as shown in Table I.

TABLE I. VALUES OF THE INCLINOMETER READING [9]

Borehole number	Start date of measurement	End date of measurement	Slip depth (m)	Final displacement (mm)
S01	13-12-2013	29-12-2014	9	26.99
S02	18-12-2013	30-12-2013	7	-
S03	25-12-2103	02-03-2014	9	58.81

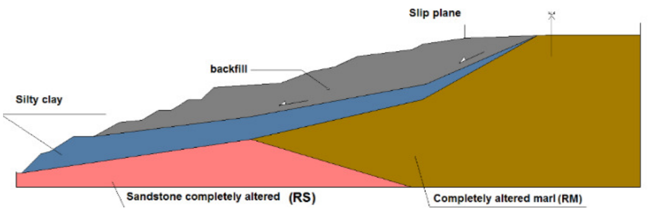


Fig. 3. Geotechnical profile of the site.

The results of the displacements recorded at the foot of the slope on the right side of the platform, showed no signs of significant deformation for 3 months after the event day.

IV. NUMERICAL MODEL OF THE LANDSLIDE

The static calculations led to the assumption that the main cause of the landslide, in addition to the local geomorphological and geotechnical conditions of the site and the presence of the water table, is the head loading due to the motorway traffic. This can be neglected or at least not properly taken into account in the pre-dimensioning. Figure 4 shows the distribution of horizontal displacements in the model. They are maximal at the bottom of the slope with values of 1.00m.

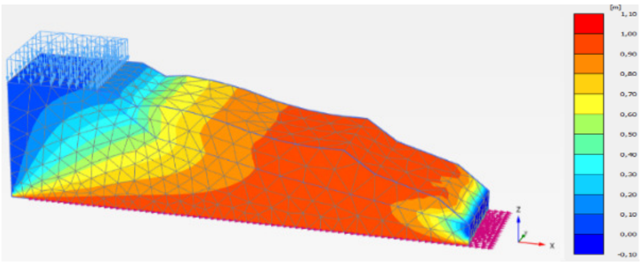


Fig. 4. Horizontal displacement fields (U_x=1.00m).

A. Static Analysis

The landslide section for the solution chosen for the treatment [10-12] consists of the installation of 11 piles in a single row at the edge of the landslide (in the middle of the alignment) in order to ensure the safety of the motorway users, during the emergency works, and then the realization of a row of 60 piles on the left side of the section PK52+040~PK52+220, with a beam connecting them at the head.

1) Static Analysis without the Effect of Rainfall

The model area of the massif extends laterally for 30m, and to a depth of 40m. For the boundary conditions, the vertical and horizontal displacements at the model boundaries are assumed to be zero. The soil-pile system is discretized using the 3-dimensional mesh options of the software into 23010 elements. Each finite element has 10 nodes with 3 degrees of freedom for a total of 35295 nodes. The average element size is 2.797m [3-5, 7-19]. It should be noted that the bored piles are modelled by a linear elastic behavior law. The soil is modelled by an elastoplastic behavior law of the Mohr-Coulomb type. Figure 5 shows this proposed treatment of slip which was statically modelled in plane deformation using Plaxis 3D software. The piles have a diameter of 1.20m while the depth is 15m for the first row of 11 piles and 19-23m for the second row of 60 piles spaced at 3m. The nominal strength of the concrete used for the piles is 35MPa while the modulus of elasticity is E=35982MPa. The density of the concrete is 25kN/m^3.

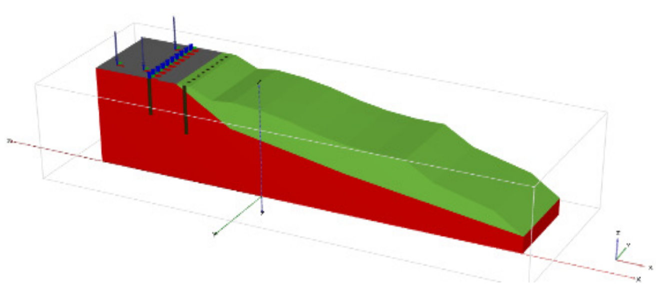


Fig. 5. Numerical model after the introduction of 2 rows of piles.

The analysis of the stability of the slide after the introduction of the 2 rows of anti-slip piles clearly shows that the slope is more stable than the initial configuration with an increase in the safety coefficient. Therefore, the pavement is now in a safe condition.

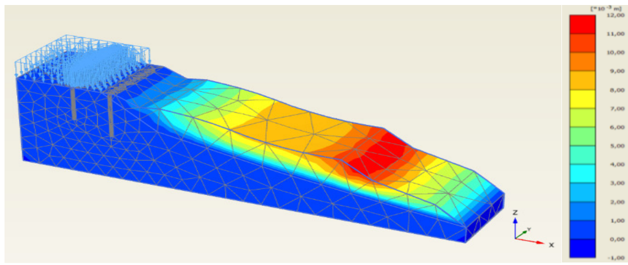


Fig. 6. Displacement fields U_x (U_x max =0.01186m, F_s=1.750).

Figure 6 shows that the model was really stabilized after the introduction of the two rows of piles and the displacements are almost zero. The largest displacements are of the order of only 1cm at the bottom of the slope.

2) Static Analysis with the Effect of Rainfall

Four precipitation values were taken as follows: Q = 0, 0.53, and 5.30m^3/day. This last value corresponds to the rainfall recorded during January in Tlemcen (i.e. 62mm). We note that the section of PK 52 that has undergone the slip makes a section of 2700m^2, or 27% of the area taken in the rainfall estimate. Indeed, a 1mm represents the rainfall of 10.000m^2 on an area of 100m×100m (1 hectare). Figure 7 shows an example showing the introduction of rainfall in the calculation code used: 3 simulations were carried out by changing the precipitation value in order to inspect the effect of this parameter in the evolution of the stresses. The Figure shows their changes according to the calculation steps, in a point B located at the bottom of the slope.

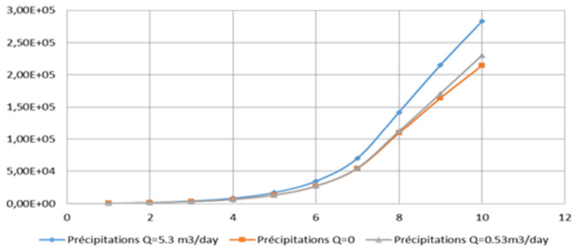


Fig. 7. Evolution of stress σ_{xx} according to the rainfall flow.

Figure 7 shows the rainfall which significantly influences the evolution of stresses under static loading. The recorded increase in stresses is 32%, passing from zero precipitation to 5.30m^3/day.

B. *Seismic Analysis*

The seismic loading, defined by an accelerogram that was taken into account for the dynamic analysis, is that of the Boumerdes earthquake of May, 21 2003, characterized by a magnitude Mw of 6.8 on the Richter scale. Strong seismic aftershocks were recorded, in particular at the Keddara site, located south-east of the capital Algiers and 20km from the epicenter. The proposed landslide treatment was also the subject of dynamic modeling in plane deformation using Plaxis [20]. The landslide was subjected to a combination of loads (permanent load, operational load, and seismic load from the Boumerdes 2003 earthquake illustrated in Figure 8).

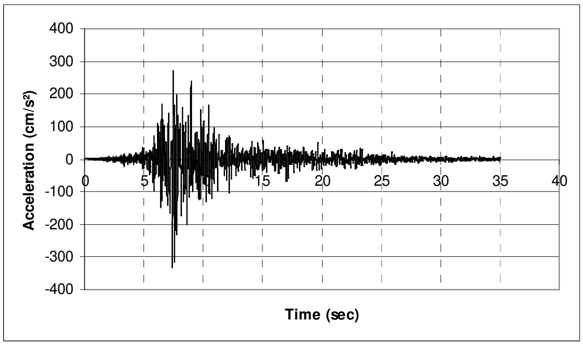


Fig. 8. The applied accelerogram of the Boumerdes 2003 earthquake.

The Peak Ground Acceleration (PGA) reached 0.58g in the East-West component (Keddara2 station) and 0.35g (Keddara1 station) in the North-South component of the horizontal direction, while it was 0.22g in the vertical component [15, 21, 22]. The data for these events were obtained from the network records of the National Center of Seismic Engineering (CGS) in Algiers. Although various simulations were performed, we only present the deformation of the configuration at the end of the seismic loading (t= 35s). We also note that several runs were carried out, changing the model configuration each time.

1) *Model with a Single Row of Piles with Length of 15m*

In order to analyze the influence and impact of the pile string located at the edge of the landslide (in the middle of the alignment), only one pile string was introduced [14]. It should be noted that this row was planned as an emergency solution. Figure 9 shows the location of this pile string at the level of the highway platform.

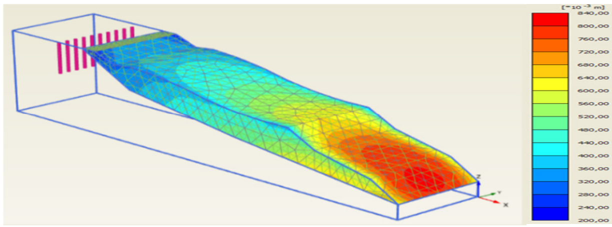


Fig. 9. The introduced pile row (emergency treatment) (Max U_x= 0.8216m).

2) *Model with Two Rows of Piles*

The analysis of the slip stability was conducted after the introduction of 2 rows of anti-slip piles subjected to dynamic loading. Figure 10 shows the deformation of the model of the pile system.

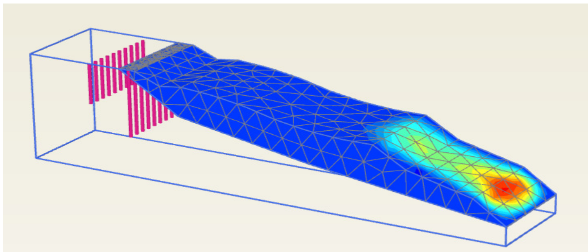


Fig. 10. Representation of the system model with two piles.

The dynamic study of this model shows that it is the second row of piles, with a length of l =20.00m, that provides significant stabilization of the slide. This results in a noticeable decrease in displacement, mainly at the motorway section. Note that the maximum value, which is 16.21cm, was recorded at the lower part of the model as shown in Figure 10.

3) *Numerical Model with Rock at the Foot of the Slope*

Although rock was not used, this modeling was initiated in order to see the rock impact on the overall behavior of the model. The new model configuration is shown in Figure 11.

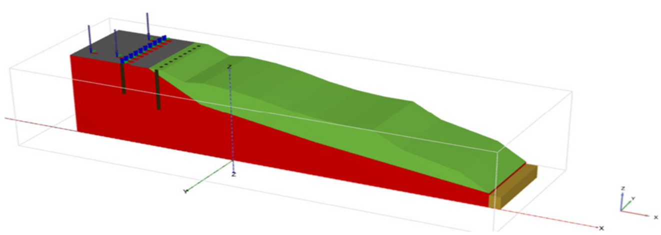


Fig. 11. Numerical model after the introduction of rock at the foot of the slope.

4) *Effect of Rainfall*

A parametric study was carried out, by varying the rainfall rate, the considered values were 0, 0.53, 2.4, and 5.40m^3/day

[18]. The seismic loading accelerogram taken into account for the dynamic analysis is that of the Boumerdes earthquake 2003. The main objective of the study of this parameter lies in the estimation of the stresses exerted on the stabilizer piles.

V. RESULTS AND DISCUSSION

A. Under Static Loading

Figure 12 shows the evolution of the displacements under static loading from the exploitation load. His value is equal to 10kN/m². Figure 13 shows clearly the very significant decrease in the stresses under the effect of the 2 rows of piles, after having reached a maximum value of 2.10^5kN/m^2 during the landslide.

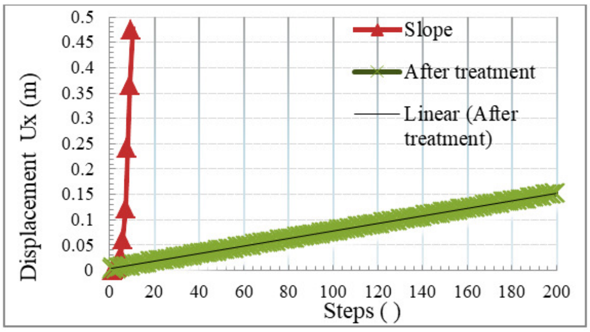


Fig. 12. Evolution of displacements U_x in a point A of the highway's platform.

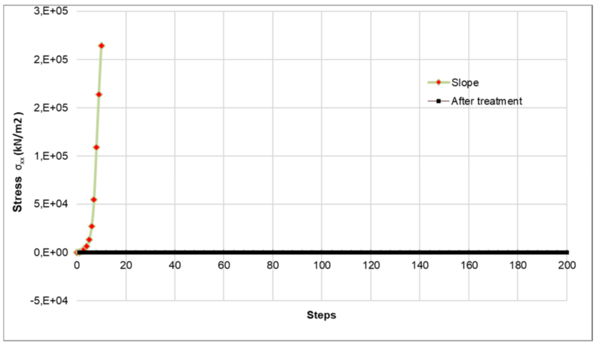


Fig. 13. Stresses σ_{xx} in a point A of the highway platform.

B. Under Seismic Loading with the Effect of Rainfall

The two graphic representations in Figure 14 and 15 show that under dynamic loading the stresses have a very short duration. The evolution of the stresses, under the effect of the rainfall is not significant and resulted in very close curves for the case of two distinct points.

TABLE II. SIMULATION RESULT SUMMARY

Model configurations	Displacement Ux (cm)	Stress σ_{xx} (kN/m^2)	Safety factor (Fs)
Before treatment	100.00	2.10 e+5	<1.00
1 row of piles (seismic case)	82.16	/	1.00
2 rows of piles (seismic case)	16.21	0	1.20
2 rows of piles (static case)	1.186	/	1.75

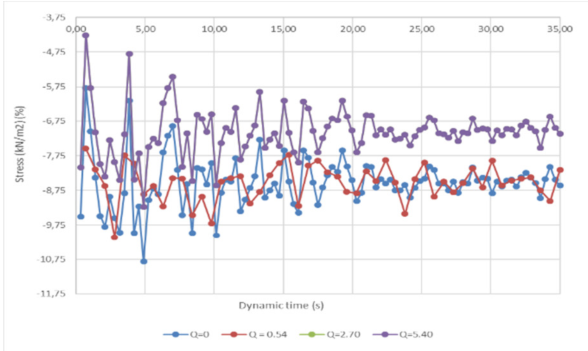


Fig. 14. Evolution of stresses σ_{xx} in point Q at the first row of piles.

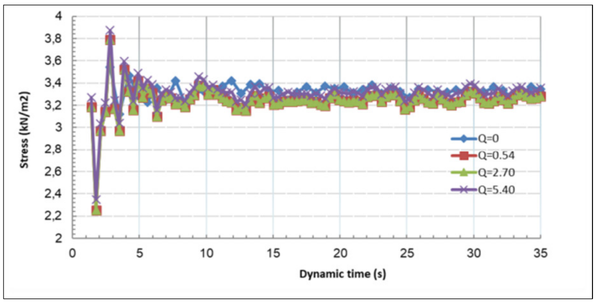


Fig. 15. Evolution of stresses σ_{xx} at the head of the second row of piles.

Table IV summarizes the results found in terms of displacements, stresses, and safety coefficients for the different configurations of the numerical model.

VI. CONCLUSION

In this article, the stability study of the landslide that occurred on March, 2, 2014 on a section of the East-West highway near the city of Tlemcen (North-West Algeria) was carried out. Vertical piles were used to stabilize the highway on the right-hand side of the PK 52 section in the boundary between the cities of Tlemcen and Sidi Bel-Abbes.

It should be noted that the company carrying out the treatment work did not rely on the analysis when establishing the treatment of this slide. Nevertheless, the calculations carried out in this work show that the treatment solution presents more stability compared to the initial state of the section that suffered the slide. This is justified by the maximum value of the displacement recorded, which is 16.21cm under dynamic loading and almost zero under static loading.

We would like to report that it is the second row of 61 piles that brings more stability to the slip section. The first one, consisting of 11 piles, was planned as an emergency solution. On the other hand, the introduction of rock at the bottom of the slope provides optimum stability for the model, essentially by reducing both stresses and displacements. It should be noted that this solution was not foreseen in the field. We note that the dynamic analysis based on the accelerogram of a very strong seismic movement of Boumerdes 2003, of the PK 52 slope shows the effectiveness of the slope stabilization technique by piles. This method is able to solve in a permanent way the phenomenon of the slides.

Rainfall remains a crucial parameter in the treatment of sliding stability, essentially under static loading. Particular attention must be paid to this parameter in order to have a correct digital model that represents the real case. This technique is mainly applicable to soils resting on coherent, sometimes soft or sensitive soil.

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