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Study of the Causative Factors of El-Ghandouri Landslides and their Stabilization Methods

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***Abstract*— Tangier landslides are considered a common engineering problem throughout the construction of different roads or other engineering works in the north of Morocco. This research paper aims to identify the main causes of landslides in an area with an important tourist site to search for the most appropriate engineering solutions. Several geotechnical studies were carried out through boreholes up to 30 meters deep to determine the main causes of the landslides. These studies exhibit that the main reason for landslides is the presence of Layers of soil with weak mechanical properties, which are highly affected by rainfall. The limit equilibrium (LE) analysis method and finite element (FE) method was utilized to analyze the stabilities of the EL Ghandowri slopes before excavation, after excavation, and after stabilization treatment of the slopes for construction. The analysis results indicated that the EL Ghandowri slopes, before any excavation, were unstable in their natural state. The reinforced concrete piles' row with anchors and concrete piles cap were the stabilization methods, which give the best safety factor and horizontal deformation results. The soil-structure interaction method (SSIM) and finite element (FE) method were used to calculate the horizontal deformation of piles. The occurrence of EL Ghandouri landslides can be reduced if the main reason is addressed; thus, the problem of Tangier Province landslides, especially EL Ghandouri, should be given big attention throughout the survey and design of the engineering works, not only during the construction.**

***Keywords*— Landslides; limit equilibrium (LE) method; finite element (FE) method; unstable; weak mechanical properties; piles row with anchors; piles cap; soil-structure interaction method (SSIM).**

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I. INTRODUCTION

The Tangier Province lies in the north of Morocco and connects Morocco with European countries through many ports. Tangier city is characterized by chains of low-elevation mountains and hills with a strong sandstone block of the Numidian nappe that occupies a high structural status. It forms prominent edges reinforced by the sandstone layers on hills of a Cretaceous substratum. This para-autochthonous structure is divided into two internal and external units and is made up of marfyclay soils with intercalations of limestones in the form of yellow balls. This unit dates from the Cenomanian to the lower Miocene [1], [2]. This morphology results from the combination of highly contrasted lithology, the erosive dynamic, the climatic system, and the active tectonic regime, which lead to many landslides [3]. The landslides in Morocco are widely distributed in the north and cause big engineering problems. According to the studies and investigations conducted by the (Public laboratory of trials studies (LPEE), the Ministry of equipment and transport, the Consulting Engineering and Development (CID), and (NOVEC) the expertise engineering company); Tangier landslides can be characterized by four types, which are debris flow landslides, circular landslides, planar landslides, and pavement, cracks and irregularities in the longitudinal profile of roads. There are many factors causing mass movement. In this case, an EL Ghandouri landslide, which is induced by rainfall and weak soil layers was discovered during the geotechnical study for the construction of group of hostiles, is investigated.

The methods used for determining the causative factors of landslides and their treatments in the Al-Ghandouri area have confirmed to be successful because of the following reasons:

- Conducting an analytical study in the laboratory of the soil layers in the region up to a depth of 30 meters.

- Sensors (inclinometer measures) are used in order to track ground movements accurately for long periods of up to two years.
- Conduct a statistical study by analyzing all cases of landslides in the region and identifying the common factors between them.

In this paper, several experiments have been implemented to study the stabilization of landslides in the El Ghandouri area by using two different methods (Finite Element and Limit Equilibrium) to achieve the best solution that prevents the landslides in this area.

II. Materials and Methods

A. Location Of Study Site

The study area is located at the El Ghandouri tourist zone on the Mediterranean coast, 3 km north of downtown Tangier-Morocco (Fig. 1). This study is concerned with the landslides that affect the land allocated for the tourist hotels project on the northwestern hill of Tangier Bay.

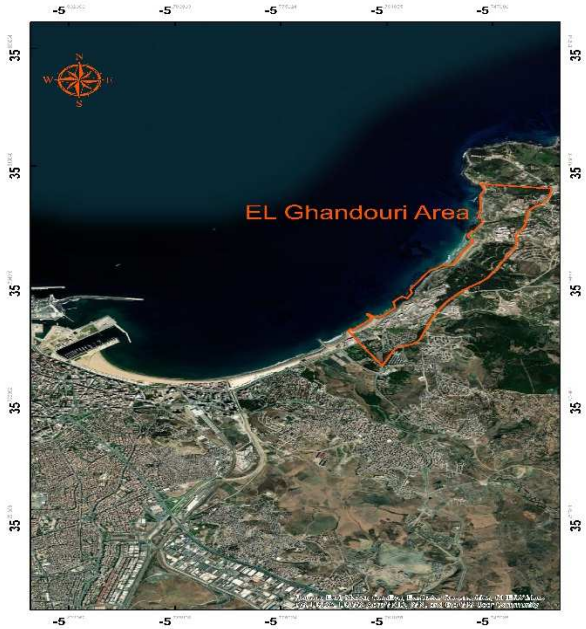


Fig. 1 Location of the study site

This area is subjected to large-scale instabilities. A large-scale landslide occurred in 2011, and more than half road in this region drifted (Fig. 2).

Fig. 2 Failed Road EL Ghandouri area

In addition, during 2014, land movements affected some buildings in the Al-Ghandouri area, causing various cracks to appear in these buildings (as reported by the studies and investigations conducted by the (LPEE), Public laboratory of trials studies, the ministry of equipment and transport, and the (CID) Consulting Engineering and Development). Al-Ghandouri area is subjected to landslides, whether the land is in its natural state without human intervention or when human intervention occurs in any form of interference that affects the stability of the slopes. In the case of the recent landslide (Fig. 3a), which occurred on an area of about 40413 m^2 that is designed to build a group of hotels. This landslide was discovered mainly by the results of inclinometer tests after conducting the necessary geotechnical studies.

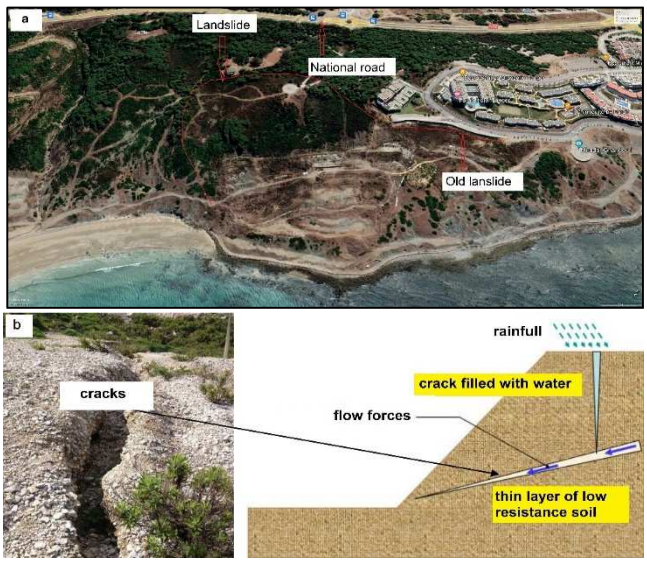


Fig. 3 a) Recent landslide, b) cause of the landslide

According to the results of inclinometric measurements, it is observed that the first ten to fourteen meters of the land are moving towards the coast. This part of the land consists of the weathered pelite, the compact pelite, and the indurated pelite, which is the part that had not been subjected to any movement. The landslides in this study are due to the conjunction of unfavorable conditions, which are listed as follows:

- One of the most important causes of the landslide is that the layers in which the landslide occurred are the weathered pelite and the compact pelite, where the soil in these layers is mostly composed of clay (Fig. 4).

Fig. 4 Nature of soil in EL Ghandouri area

- We also know that this type of soil is very vulnerable to water. In addition, sandstone passages between these layers have poor mechanical properties; when water enters them, it loses its consistency, and the slide occurs.
- Geology structure of the El Ghandouri slope allows for the presence of infiltration water: The presence of infiltration water after precipitation is one of the main factors that caused the landslides in Tangiers province.
- Presence of the sea at the foot of the slope: the resulting erosive force from the movement of the sea waves plays a role in undermining the foot of the slope.

The abundance of water and the clays of the region are the two main causes of landslides. Thus, the diagram (Fig. 3b) is shown the modification of the internal pressures of the hillslope and favors ruptures. To study a landslide case, it is necessary to involve several steps. (Fig. 5) shows the flowchart of the proposed methodology used in this research.

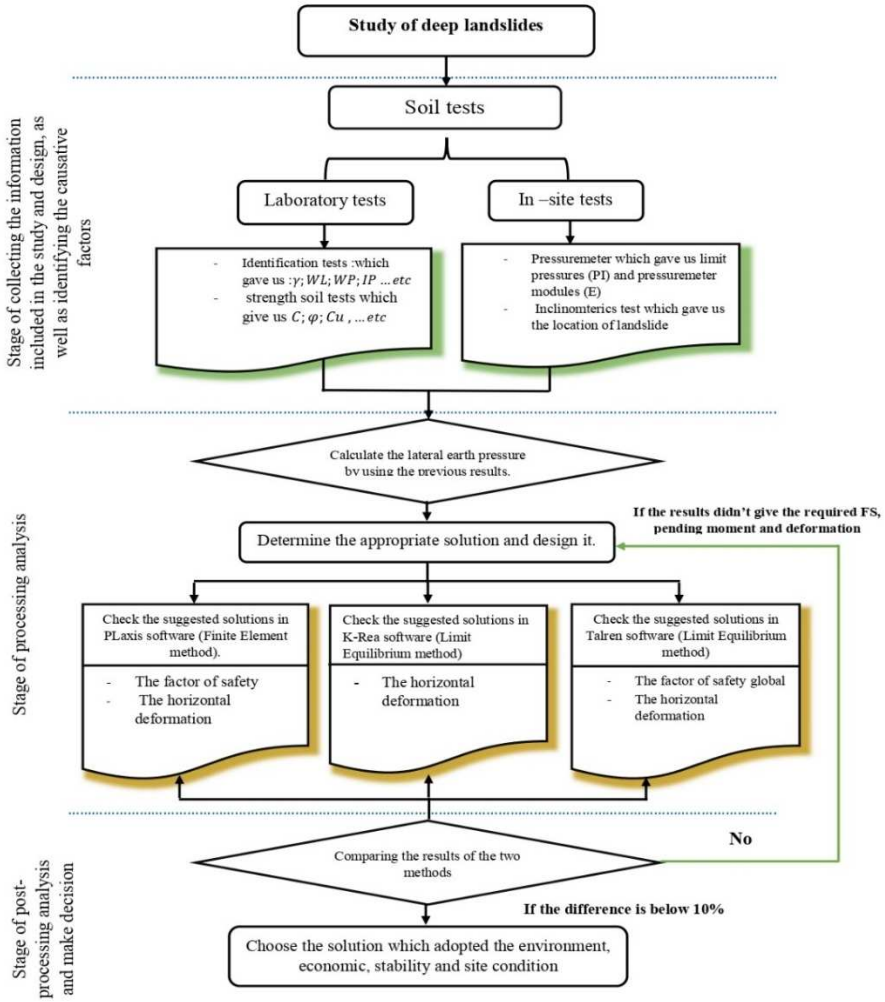


Fig. 5 The flowchart of the proposed methodology used in this research

The inclinometer tests showed us the presence of a landslide, and the location of the sliding surface was determined exactly. The inclinometer results show that the inclinometer (I1 bis) sheared at 5 m after recording two movements, one at the first 5 meters with a maximum movement of 20 mm in the direction A+ and 5 mm in the direction B-. However, the second movement was between 5 and 10 m with a maximum displacement of 4 mm in direction A+ and 2.5 mm in direction B-. The (I2 bis) inclinometer shows movements in the first 14 m with a maximum displacement of 40 mm in the direction A+ and 10 mm in the direction B- as shown in (Fig. 6). The (I3 bis) inclinometer shows movements in the first 9 meters with a displacement of 25 mm in direction A+ and 15 mm in direction B-.

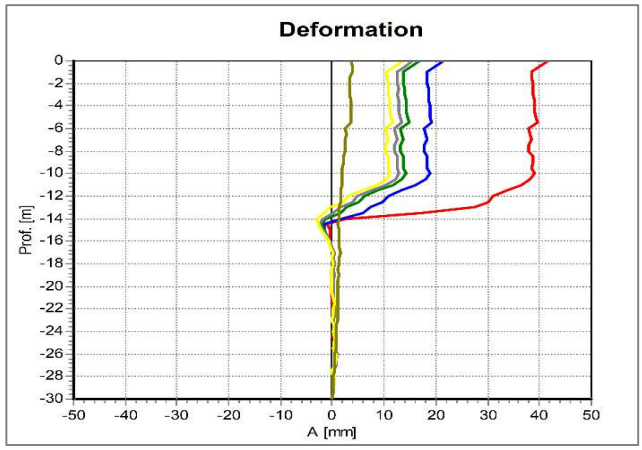


Fig. 5 Horizontal deformation of the soil at the inclinometer (I2 bis)

B. The Geological Properties of the El Ghandouri Area

The engineering lithology plan of EL Ghandouri landslide and five engineering lithology profiles are shown in (Fig. 7). From the figure, El Ghandouri area is located on the Melloussa Nappe, mainly made up of Middle and Upper Cretaceous. It is mainly composed at the base of a schisto-quartzite flysch and by blue-green argillites, with a few banks of fine sandstone and at the top by a marl-limestone series with locally phtanites [2], [3].

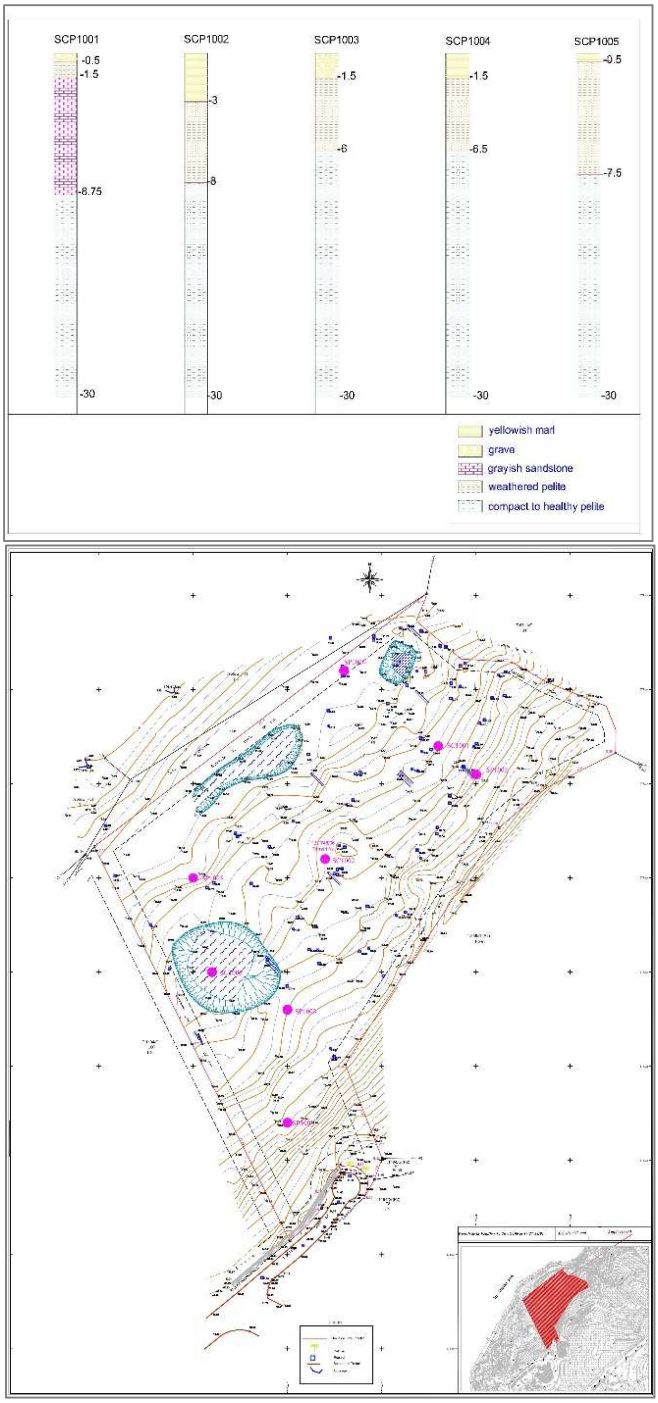


Fig. 7 Engineering plan and lithologic engineering profiles

The physical and mechanical parameters of the weathered pelite (yellowish marl, grave), sandstone, compact pelite, and healthy pelite were determined by laboratory tests, and the average values of the parameters are grouped into main groups and listed in Tables I and II.

TABLE I
MECHANICAL RESIDUAL PARAMETERS OF STRATA

Name of Stratum	Unit Weight (kN/m3) (saturated)	Cohesion (kPa)	Internal Friction Angle (°)
Weathered pelite (yellowish marl, grave),	18	7	13
Compact pelite	19	7	13
Healthy pelite	20	37	18

TABLE II
PHYSICAL AND MECHANICAL PARAMETERS OF STRATA

Name of Stratum	Young's Module (MPa)	Poisson 's Ratio	Pressure meter Module E (MPa)	Limit pressure Pl (MPa)
Weathered pelite (yellowish marl, grave),	3.465	0.35	6	0.5
Compact pelite	44.275	0.33	20	1.5
Healthy pelite	70.4	0.3	100	2.5

C. Study of the Stability of the El Ghandouri Slope

In order to achieve the best treatment for the EL Ghandouri landslide, the analysis of slope stabilities should be perfomed before and after excavation and treatment. The results obtained from field tests and engineering lithologic drilling manifested that the collapsing surface mainly occurred in the weathered pelite and compact pelite layers. The lithologic profile a–a′ (Fig. 8.a) was used to model and analyze the stability of the slope. Two methods were used in the analysis. The first method is the limit equilibrium (LE) analysis method, while the other is finite element (FE) method.

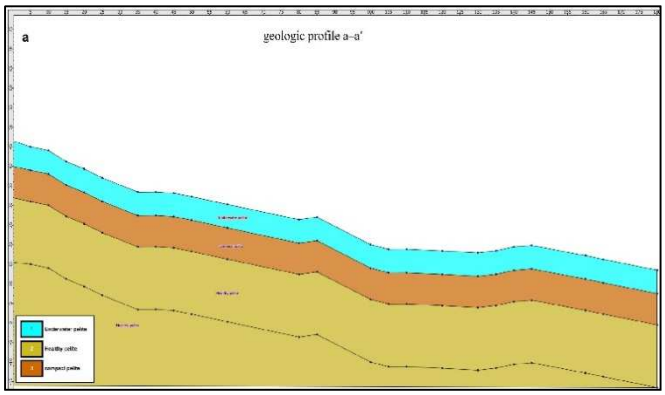
1) The stability before excavation and after excavation and treatment by using LE method: The limit equilibrium (LE) methods are most utilized to analyze the stability of the slopes [4], though, they have some theoretical defects [5]. To cope with these defects, some scholars [6], [7] have developed new or improved methods. These methods depend on dividing the slope into fine slices where their base can be identical to a straight line. Then the equilibrium equations (equilibrium of the forces and/or moments) are written. Bishop method is considered the most famous method. In this paper, the Bishop method is implemented in Talren software to analyze the stability of the slope. The factor of safety (FS) for the slope is given by the following equation:

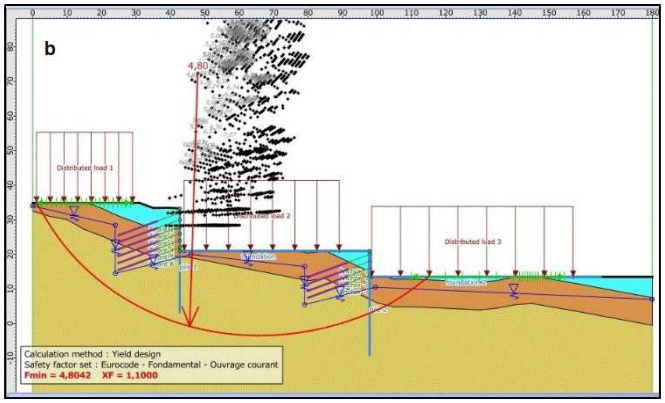
$$\Gamma_{Bish} = \frac{Resisting\ moment}{\Gamma_{s3}.Overturning\ moment}$$

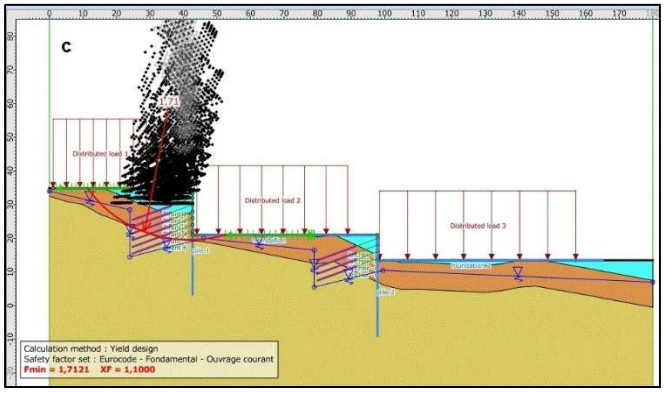
$$\Gamma_{Bish} = \frac{\sum_{i=1}^{n}\left(\frac{c_i}{\Gamma_{ci}}+[\Gamma_{s1}.\gamma_i.h_i-u_i]\frac{\tan\emptyset_i}{\Gamma_{\emptyset_i}}\right).\frac{b_i}{\cos a_i}}{\Gamma_{s3}.\left(\sum_{i=1}^{n}[\Gamma_{s1}.\gamma_i.h_i.b_i.\sin a_i]+\sum\frac{M_{ext}}{R}\right)} \quad (1)$$

Where:

Γs3: weighting factor for the uncertainty in the calculation method shear
Γs1: weighting factor for the soil unit weights
hi: Height of slice
ui: pore pressure
φi: soil internal friction angle
Γφ: partial safety factor for φ
bi: dx: width of slice
c: soil cohesion
αi: the inclination of the segment of the slip surface
Γc: partial safety factor for c
R: radius of the circular arc
ΣMext: the moment resulting from the forces located outside the soil mass
γi: weight per unit of the soil







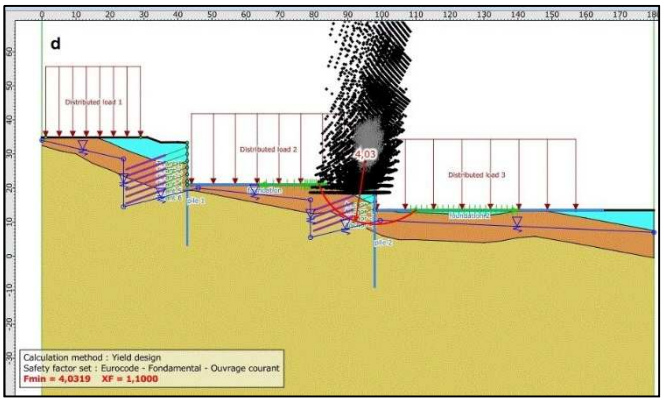


Fig. 8 Analysis of the stability by using LE method a) Engineering geologic profile a-a′ b) FS global c,d) FS in the critical places of piles anchor

In order to evaluate the stability of EL Ghandouri slope before excavation, the calculation of the FS based on the lithologic profile a–a′(Fig. 8a) was implemented. The calculated FS of the slope before the excavation was equal to 0.86 (Fig. 9a). Therefore, the slope is unstable in its natural state and requires treatment to stabilize it. The lithologic profile a–a′(Fig. 8a) shows that the indurated pelite located under the compact pelite is a relatively impermeable layer. The weather changes can affect the saturated conditions of the compact pelite (especially the interface between the indurated pelite and compact pelite). For example, under precipitation conditions, the interface between the compact pelite and indurated pelite or the sandstone passages existing between these layers may change into saturated states because of water leakage through the weathered pelite cracks. The EL Ghandouri slope is unstable before excavation. The average angle of the slope is about 24°. For the purpose of building the hotels (Fig. 7), the ground must be excavated and leveled 14m in maximum depth in the EL Ghandouri slope. In order to evaluate the stability of the slope after excavation and treatment, the FS was also calculated. The results of the FS of the slope after excavation and treatment under residual characteristics of layers and with stabilization treatment of double-row piles with caps were equal to 2.9 for the global stability and 2.5, 2.4 for the critical places (Fig. 9b,c,d), respectively. In addition, the FS under residual characteristics of layers and with stabilization treatment of piles with anchors were equal to 4.8 for the global stability and 1.71, 4.03 for the critical places (Fig. 8b, c, d) respectively. The slope after excavation and treatment under residual characteristics of layers and with stabilization treatments is stable.

1) The Stability Before Excavation and After Excavation and Treatment by using FE method: In this paper, another method is used to study and analyze the stability of the El Ghandouri slope, which is the finite element (FE) method proposed by [8] and developed by [9]–[13]. This method can measure the stresses and deformations in soil [14]. The elastoplastic Model (a model with internal friction without work hardening) is utilized in this work. This model corresponds to the basic assumptions of the analytical methods. The reduction of soil resistance properties method, also known as the c-φ reduction method, is used to calculate the FS of the El Ghandouri slope. Where c is the shear strength of the soil and φ is the friction angle of the soil. These parameters are decreased in steps until the soil mass fails. The

following equation is utilized by Plaxis software to determine the reduction factor of the parameters at any stage during the calculations [9].

$$\sum M_{sf} = \frac{\tan\tan \varphi_{input}}{\tan\tan \varphi_{reduced}} = \frac{C_{input}}{C_{reduced}} \qquad (2)$$

Where:

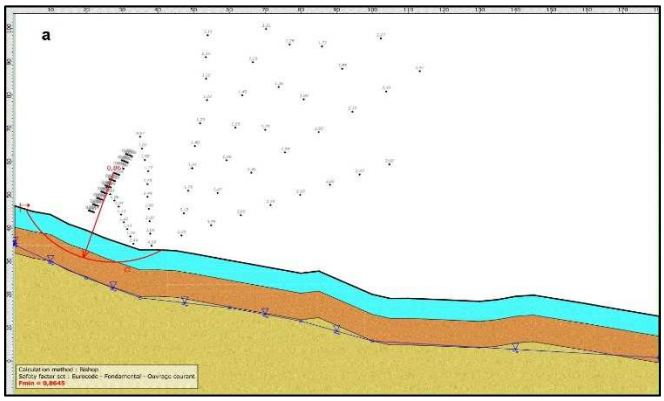
Msf : represents the reduction factor,

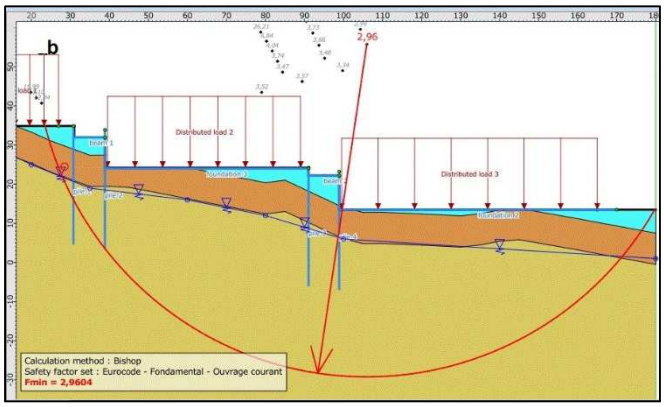
$\tan_{\varphi input}$, c_{input} : are the input parameters of the soil,

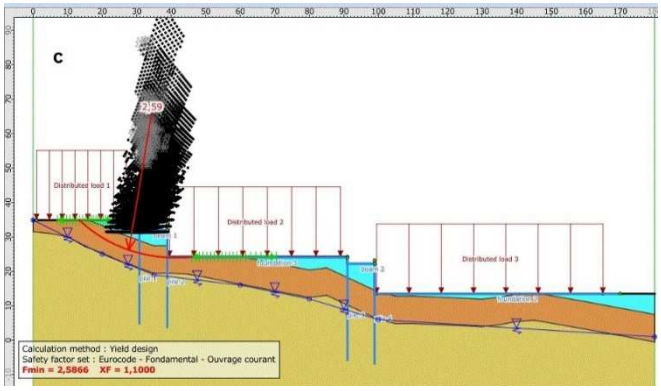
$\tan_{\varphi reduced}$, $c_{reduced}$: represent the reduced parameter.

To determine the value of the soil strength parameters at a given stage in the analysis, the total multiplier M_{sf} is utilized. At the failure stage of the soil, the total safety factor is shown as follows:

$$FS = \frac{available\ strength}{strenght\ at\ failure} = \left(\sum M_{sf}\right) at\ failure \qquad (3)$$







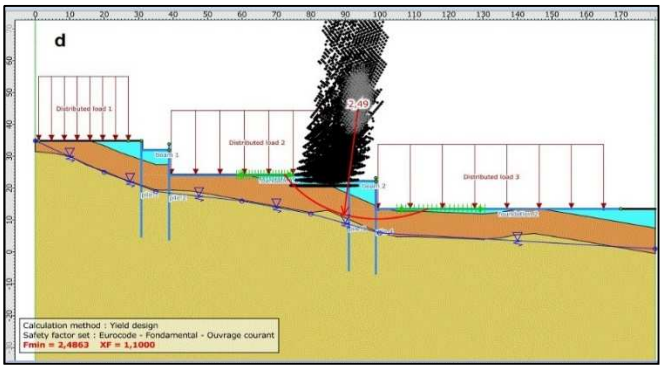


Fig. 9 Analysis of the stability by using LE method a) FS before excavation b) FS global c,d) FS in the critical places of piles cap

To evaluate the stable state of the EL Ghandouri slope before excavation and after excavation with treatment by the strength reduction FEM, the lithological profile a–a′ (Fig. 8a) was checked. The mesh for the FE method before excavation and those after excavation and treatment by piles anchors and piles cap are shown in (Fig. 10a, b, c), respectively.

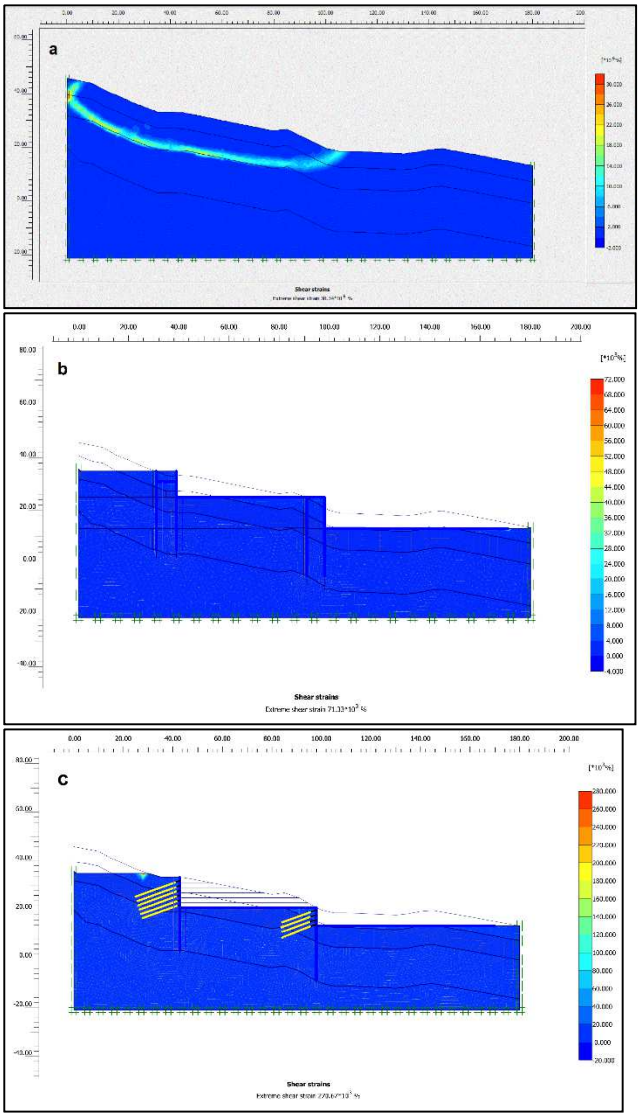


Fig. 6 Analysis of the stability by using FE method (a) FS before excavation (b) FS global of piles cap (c) FS global of piles anchor

The calculated FS of the slope before excavation under residual characteristics of layers using the strength reduction FEM was equal to 0.95. Compared with the FS computed by the previous LE analysis method, the FS computed by FEM is larger and more consistent with the field survey. Figure 11a shows the slide of the slope at the calculated failure layers. This figure shows that the calculated critical clip surface corresponds to the weathered and compact pelite. This result is consistent with the result of the test and field survey.

The stability of the EL Ghandouri slope after excavation and treatment by double-row piles with cap and piles with anchors using the strength reduction FEM is shown in (Fig. 10 b, c). The calculated FS of the slope after excavation and treatment under residual characteristics of layers and with stabilization treatment of double-row piles with a cap was more than 1.2. In addition, the FS under residual characteristics of layers and with stabilization treatment of piles with anchors was more than 1.3. Compared with the FS computed by the previous LE method, the FS computed by FEM is smaller. However, it is more accurate than the FS computed by LE, because Plaxis software, which adopts the FE method, is more accurate in calculating the factor of safety and the horizontal deformation than the Talren software, which adopts LE method. (Fig. 10 b, c) shows that the slope is stable at the calculated failure layers. It was also observed from the figure that the treatment against the current landslide is very successful.

III. Results and Discussion

Researchers in geotechnical engineering have paid great attention to the stabilization treatment of slopes and landslides [15]–[22]. The increase in the available resisting forces or/and reduction in the driving forces is necessary to achieve the stability of an effective mass movement. The most frequent treatment of landslides is slope stabilization. There are several methods to achieve the stabilization of the slopes. These methods can be grouped into four main categories:

1) Modification of slope geometry: The techniques of this category are based on adding materials to the area maintaining stability, removing material from the area causing the landslide, and reducing slope angle [23].

2) Drainage: The techniques associated with category 2 include surface drains, shallow or deep trench drains, and Vacuum dewatering...etc.

3) Retaining structures: The methods of category 3 involve the use of gabion walls, retaining walls, protective rock passive piles and reinforced earth retaining structures with strip/ sheet- polymer/metallic.

4) Internal slope reinforcement [24]–[27]: Category 4 systems involve the use of piles, anchors, soil nailing, stone or lime/cement columns and vegetation planting ...etc. To treat the EL Ghandouri landslide, two stabilization techniques was selected. The first stabilization technique consists of three parts:

- Two reinforced concrete piles rows located at each 60m from the beginning of the outer limits of the building land.
- A cap which fixe the head of the two rows piles.
- Drainage system of water.

The second stabilization technique also contains three parts:

- A reinforced concrete piles row located at each 60 m from the beginning of the outer limits of the building land.
- Anchors which vary according to position of piles.
- Drainage system of water.

The role of the piles' row is to increase the system forces to resist instability, while the role of the anchors and the cap is to improve the piles systems to resist horizontal deformation [28], [29], and the role of drainage of water system is to improve the soil strength.

The stability of the slope should respect the safety requirement. The safety requirement is different according to the important degree of the project. In Morocco specifications, the stabilized slope's safety requirement must be more than 1.3. It is also different for different coefficient used in the calculation of FS. The required FS of the slope must be more than 1.5 in the traditionnel/sit provisoire and more than1.3 in Eurocode-fondamental-ouvrage courant standerds.

To obtain the design calculation on the stabilization slope, the calculation on the pile, excavation soil, and drainage should be performed. The piles row position and the slope geometry calculations were specified based on the plan of the building area and its external boundaries.

In this paper, only the design calculation on the pile with cap and with anchors was implemented. To perform this calculation, the horizontal forces (the driving and resisting forces) acting on the pile [30], [31], the geometry size, and the material of the pile and anchors should be determined.

In the European and French standard NF EN 1997-1, Coulomb's method is used to determine the active earth pressure (Pa) and Caquat-Kerisel's method is used to determine the passive earth pressure (Pp). While, in the USA stander (ACI 318-11), they use Coulomb's method to determine the (Pa) and Rankine's method to determine the (Pp) [32], [33] .The lateral earth pressure results are summarized in table III.

TABLE III
THE RESULT OF THE LATERAL EARTH PRESSURE

Lateral Earth Pressure Results	**Methods of Calculate**		
	Coulomb (KN/m)	**Rankine (KN/m)**	**Caquot and Kerisel (KN/m)**
The passive force per unit length of pile (Pp)	Not use in FN-P 1997	1597.97	2160
The active force per unit length of pile (Pa)	1755.27	1597.97	Not use in USA stander (ACI 318-11)

After implementing several experiments on analyzing the horizontal deformations of the pile with different lengths and section sizes to achieve the best result of the stability of the El Ghandouri slope and concerning the safety requirements, we found that the pile should be with 30m in length (14m above the sliding surface and 16m below the sliding surface) and with 1.2m in diameter. We also found that the center distance between two neighboring piles should be 1.2m. The reinforced concrete pile is designed with characteristic geometric, and materials are listed in table IV and table V.

TABLE IV
CHARACTERISTIC GEOMETRIC AND MATERIAL OF PILES

Properties	Values
Length (m)	30
Spacing (m)	1.2
Pure tensile strength per pile (kN)	8844
Plastification moment of the inclusion (kN.m)	700
Rigidity of the inclusion (kN.m2)	2.54*106
Normal stiffness (kN/m)	2*107
Unit weight of concrete	24
Poisson's ratio	0.15

TABLE V
CHARACTERISTIC GEOMETRIC AND MATERIAL OF ANCHORS

Properties	Values
Length (m)	17
Spacing (m)	2
Engle (°)	20
Width of diffusion base (m)	2
Pull-out resistance of the anchor (kN)	1578.7
Pure tensile strength per anchor (kN)	402

The horizontal deformations acting on the pile can be obtained by the finite element method (FEM) and by the soil-structure interaction method (SSIM) [34], [35]. The horizontal deformations are equal to 11.3mm using FEM and 16.26mm using SSIM for the piles' cap. While they are equal to 11.7mm by using FEM and 19.02mm by using SSIM for the piles' row with anchors. From the calculation of the horizontal deformations, we notice that the use of the piles with caps is better than the use of the piles with anchors. However, the method of stabilization by using piles with anchors. It was applied in some cases of landslides in Al-Ghandouri area, which are determined by some factors such as the position of the landslide and the cost of the materials (Fig. 11). As the cost of the use of the piles with anchors is cheaper than the use of the piles with caps.

Fig. 7 Treatment by the use of piles anchor for some cases of Al-Ghandouri landslides

IV. CONCLUSION

Al-Ghandouri landslides were discovered during preliminary geotechnical studies in Tangiers Province of Morocco. Several geotechnical studies were carried out through boreholes up to 30m deep to determine the causes of the landslides. These studies exhibited that the two main causes of landslides are the abundance of water and the clays of the region. Therefore, several researchers and scholars paid great attention to solving the landslide problems. There are many methods to address landslide problems. The two methods which gave the best results were the use of the piles' row with anchors and the use of the pile's row with cap.

The experimental results manifested that the use of the piles with caps is better than the use of the piles with anchors. However, the method of stabilization by using piles with anchors was applied in some cases of landslides in the Al-Ghandouri area, which are determined by some factors such as the position of the landslide and the cost of the materials. The use of piles with anchors is cheaper than the use of piles with caps.

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