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Excavation Stability Study with Inclination of Cut Slopes at 45° and 90° in the long-term (LT) and short-term (ST) States: A Case Study

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ABSTRACT
The building project requires every time the assessment of the sliding risk of slopes which may contain different dispositions under excavation work. In order to demolish a care clinic, we undertook the geotechnical study in the site, which consists in determining the geotechnical nature of the soil, the evaluation of the mechanical quality of the ground, and the estimation of the bearing capacity as well as the foreseeable earthworks of the layers. In this paper, two-dimension numerical analysis by the computer code FLAC2D based on the finite difference method (FDM) are investigated to assess the safety factor (FoS) of excavated slopes of 45° and 90° degrees in long term (LT) and Short term (ST) states. The results show a clear impact of the influence of the slope degrees of soil layers behavior in the landslide, what allowed us to draw several recommendations.

Keywords: Cutting Excavation, Sliding Risk, In Situ Tests, Laboratory Tests, Numerical Simulation, Factor of Safety (FoS).

1. INTRODUCTION

Soil excavation and reclamation are fundamental steps of infrastructure development. The management of such excavated soils discharged through construction works is therefore an important consideration in geotechnical and geo-environmental engineering [1]. A ground movement presents different phases, different rupture mechanisms, and different materials. The study of a slip therefore requires knowing whether the problem is that of a given instant or if evolution is the key to the study [2]. Thus, the rigorous selection of soil parameters requires a deep understanding of soil behavior and proper knowledge of in situ and laboratory testing techniques [3,4].

The stability of natural slopes is a problem which interest geotechnical community in the literature until now, where; there is an increasing recognition of the need for assessment of landslide susceptibility and hazard and for landslide risk management. Stochastic versus deterministic slope stability analyses have been addressed to deal with soil properties variability via different analytical and approximate methods [5- 20]. Slopes need to be engineered considering the factors that influence slope design like depth of the pit, geology, rock strength, ground water pressures and blasting. An understanding of geology, hydrology, and soil properties is essential to apply slope stability principles properly [21, 22]. Determining the sliding surface is one of the important and complex problems in geotechnics. The shear failure mechanisms of embankment slopes and natural excavations or slopes depend on the shape of the rupture surface observed or assumed. In all cases, the stability calculations are carried out in short-term total stresses and / or in long-term effective stresses [23].

Over the years, numerous methods have been developed for assessing the factor of safety (FoS) of any slope against failure. Bishop [24], Fellenius [25], Janbu [26], Lowe and Karafaith [27], Morgenstern and Price [28] and Spencer [29] have contributed significantly towards the development of the slope analysis method. To determine the minimum FoS of any slope, the shape of potential failure surface should be assumed first. Application of different optimization techniques to search critical failure surface (CFS) still poses challenges to the geotechnical engineers. Many researchers have introduced different minimization/ optimization techniques for slope problems to estimate the CFS [30-41]. No prior assumption is required regarding the shape of failure surface, and it directly converges towards the CFS with the associated minimum FoS value.

In civil engineering projects, practical limitations significantly affect the ability to assess the stability of slope cuttings and benches in real-time, using analytical approaches such as kinematics, limit equilibrium (LE) and finite element (FE) methods or distinct element modeling. These key components enable geotechnical engineers to undertake site investigations, develop geotechnical models and assess slope stability faster and in more detail with less exposure to fall of ground hazards in the field [42-48]. Numerical techniques are used to obtain the distribution of slope stresses and deformations, and making it possible to determine the influence of different parameters and conditions of the natural slopes during the sliding process [49- 58]. They are particularly useful for the analysis of the conditions of stability when the slope is subjected to a variation of loading or geometry [59]. The degree of precision of the calculations will depend however on the quality of determination of the shear parameters, but also on the means of calculations used.

The safety factor is based on the type of soil, reliability of the soil parameters, importance of the structure, and consultant caution especially when dealing with problematic soils [60]. The factor of safety FoS of a slope can be computed with a finite element or finite difference code by reducing the rock/soil shear strength in stages until the slope fails (strength reduction method (SRM)). The resulting factor of safety is the ratio of the actual shear strength to the reduced shear strength at failure [61-63]. This technique is also adopted in several well-known commercial geotechnical finite element or finite difference programs like PLAXIS 2D, SNAIL, ANSYS, FLAC 2D [64, 65]. Theoretically, the slope is said to be stable if Fs> 1. The limit equilibrium state (rupture) is obtained when Fs = 1. But in practice, the coefficient Fs is between 1.15 and 1.30, taking into account different factors [66-71].

In this paper; in order to understand the evolution of excavated cutting slope behavior of a care clinic in Jijel province in Algeria and their deformation and the consequences of failure to implement effective engineering decision, the finite difference procedure (FDM) is used to analyze the regularity of the excavation process of cutting soil slopes and obtain the safety factor FoS in long-term (LT) and short-term (ST) states for slope cutting calculated with 45° and 90°, by using numerical software FLAC2D used by applying the so-called shear strength reduction (SSR) technique under Mohr-Coulomb constitutive models.

2. DESCRIPTION OF THE CASE STUDY PROJECT

In order to demolish a care clinic to rebuild another new in the Jijel province, in Algeria (figure 1), We undertook the foreseeable earthworks of the layers as well as the geotechnical study in the site, which consists in determining the geological nature of the soil, the evaluation of the mechanical quality of the ground, and the estimation of the bearing capacity.

Figure 1: (a) Recent site photos, (b) new clinic's design.

The site is characterized by a terrain with a regular sloping topography oriented towards the West, the site is stable and does not pose any problem related to the topography (Figure 2). The TAHER region in Jijel Province consists essentially of quaternary and Pliocene formations, consisting of clays, and marls [72].

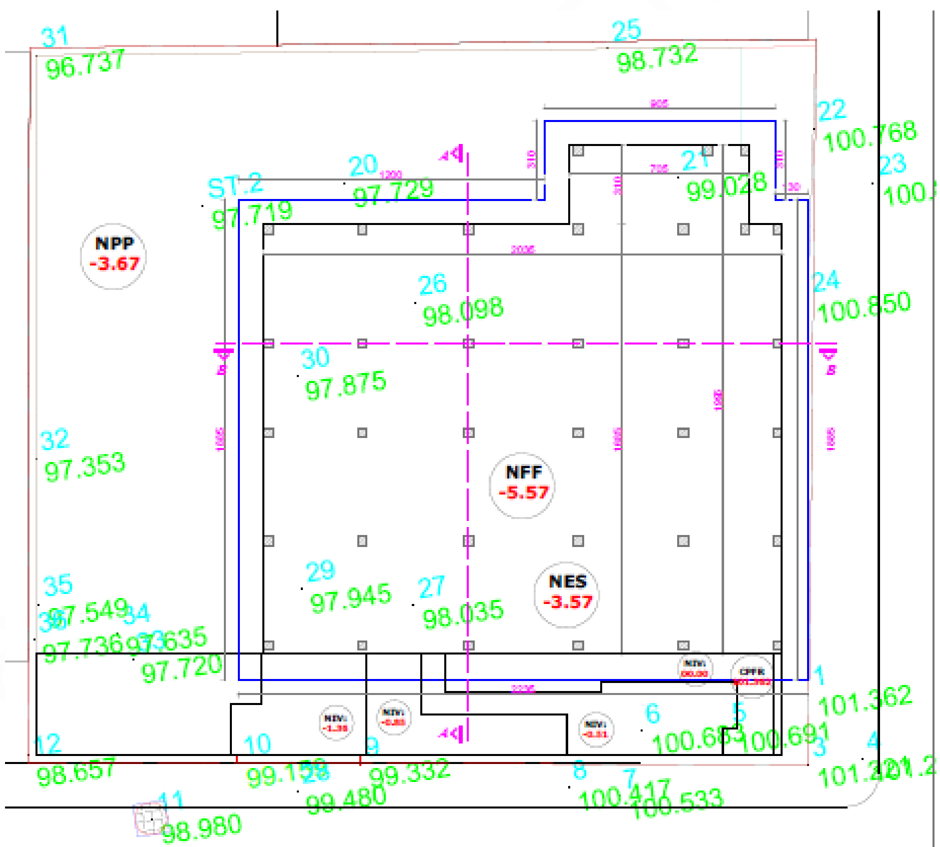


Figure 2: Earthwork Plan in Scale of: 1/200. NFF: Level of foundation excavation, NPP: Parking platform level, NES: Basement level, CPFR: Rating of the reference platform (00.00 level), Red line: boundary of the land, Blue line: limit of excavation, Black line: planned construction.

The deciphering and interpretation of (satellite) photo of the site studied (Figure 3) allows the existence of known lineaments because the geomorphologic features of large magnitude are visible. The geological interpretation is largely due to the fact that certain lineaments correspond to very known geological structures. The contrast in color of an object with its environment is a good deciphering criterion. For our site and with the visual interpretation of satellite photo which compared with field data, have found that the brown tint corresponds to sandy clays. The abrupt limits of vegetation sometimes have a geological significance, certain soils give rise to typical plant associations. In our site, vegetation cover at low density does not provide any index. The morphological criteria are the most important and the most encountered in landscapes. In our case, the study area has a regular pouring westward facing slope. No instability index were observed in the area. In our site the hydrographic network is of dense weak, or one recorded no presence of talweg in of ravines close to the site. The runoff water is abundant given the slope of the zone.

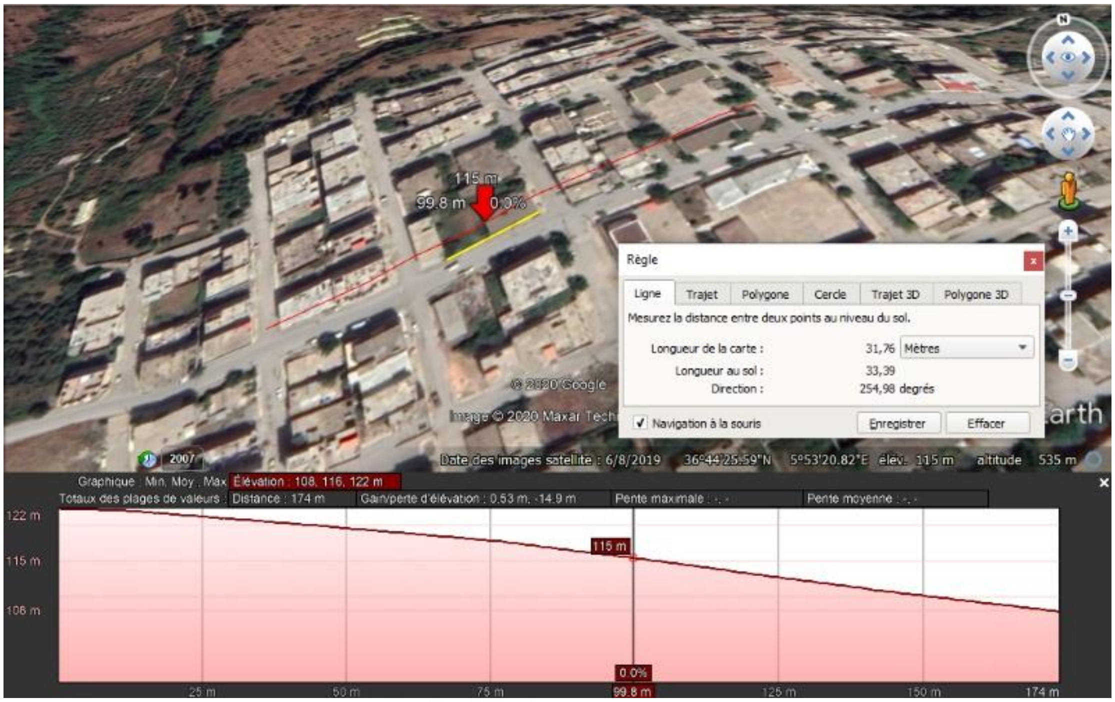


Figure 3: Google earth photo of the study site.

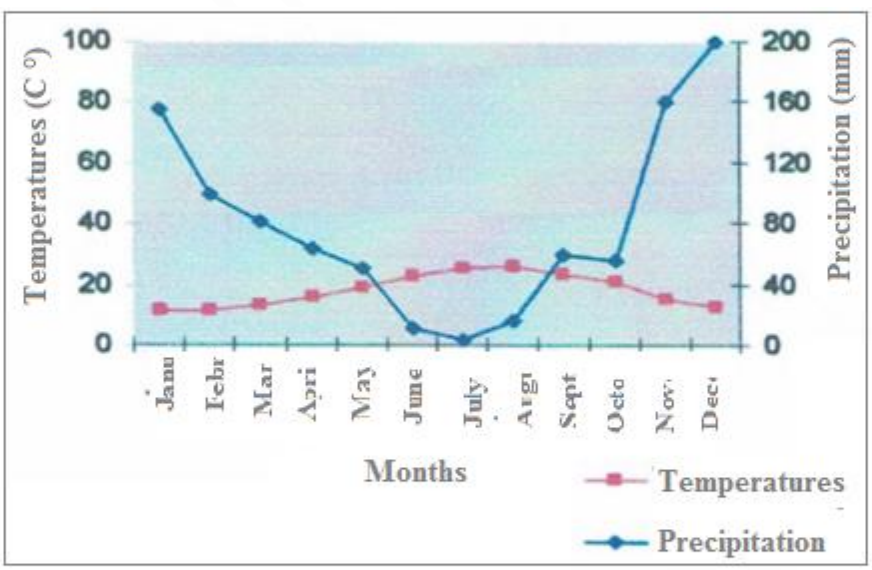


Figure 4: Ombrothermal diagram of the study area

From a climatological point of view, the region of Jijel province has a Mediterranean (temperate) climate marked by a rainy period which extends from October to May. Thunderstorms are sometimes very violent, of short duration and therefore of intense intensity (which increases their role in erosion). The dry periods that range from May to September will have some repercussions in the hydrogeology of the region. The temperature is a factor having a great influence on the evapotranspiration and therefore it plays an important role in the behavior of the soil vis-à-vis meteoric waters. The ombrothermal diagram makes it possible to determine the driest months corresponding according to the definition of Gaussen and Bagouler [73] to the month where the average precipitation is less than or equal to twice the average temperature. It results from the combination of the two main climatic parameters. This relationship makes it possible to establish an ombrothermal graph on which the temperatures are plotted on the double scale of precipitation (Figure 4). When the precipitation curve goes above that of temperatures, the corresponding period is in excess. On the other hand, if the temperature curve of that of precipitation, the corresponding period will be in deficit. In conclusion, we can say that the study region is located in a humid area.

3. PHYSICAL AND MECHANICAL PROPERTIES OF THE SOIL LAYERS

The geological and geotechnical reconnaissance of a sloping soil mass must first make it possible to locate the different layers which constitute it and to give its general configuration. Geotechnical reconnaissance must then make it possible to obtain information on the physico-chemical and mineralogical characteristics of the soils constituting the massif, but also and above all on their mechanical and hydraulic characteristics from the results of in-situ and laboratory tests.

To recognize the soil in depth, and take intact and altered samples to allow the execution of tests in the laboratory; we have completed our recognition by carrying out three tests with a dynamic penetrometer; they have been pushed to a depth of 10 meters. The test consists in seeing the heterogeneity of the soil, in making a correlation with the mechanical soundings, and also in qualitatively evaluating the bearing capacity of the carrying soil layers, as well as the execution of two tests of pressure meters. To carry out the in-situ investigation program, we used a boring machine, in order to know the geological nature of the soil and to take samples. In addition is to know the compactness of the site, we used a dynamic penetrometer.

The vertical sections which are made reveal the following lithology; deposits (0.0 / 0.8m), gravelly and pebbly sandy clay (0.8 / 3.2 to 4m) and marl (3.2 to 4m / 10m). The geological survey sections have shown that the ground is constituted by a gravelly and stony clay, resting in depth beyond 3.0 to 4 m on a marly substratum. Resistance to dynamic penetration varies in an orderly manner from the surface to the depth of 10m. The average resistance between 50 and 70 bars, then it increases remarkably in depth to reach values above 100 bars.

3. 1 Laboratory tests

For geotechnical engineering, the soil strength is usually expressed in terms of the two soil strength parameters, namely the cohesion c and angle of internal friction ϕ [74]. In soil mechanics, the soil strength is usually expressed in terms of the Shear Tests, and for the selection of representative soil parameters is to consider the particular stress path imposed by the loads [75], in terms of the Standard consolidation test or oedometer test (OED).

After receiving the samples in the laboratory, we carried out tests and analyzes in the laboratory, to determine the physico-mechanical characteristics as shown in the tables (1) and (2).

Table 1: Soil physical parameters

Depth. (m)	Identification							
	W (%)	γ (t/m^3)	γ_d (t/m^3)	Sr(%)	2 (mm)	0.08(mm)	WL(%)	IP(%)
2.0/2.5	17	1.79	1.51	61	90	64	42	21
3.0/3.5	18	1.82	1.53	65	89	68	40	20
4.0/4.5	18	1.86	1.57	69	96	85	45	23

The values of the water content of the sandy clays and the marls tested are between 17 to 18%, compared to the saturation water content, this humidity represents a degree of saturation between 61 and 69%, which indicates that the soil is moderately humid. Dry density values for sandy clays are between 1.51 and 1.53 t /m^3. For the apparent wet density, the values are from 1.79 to 1.82 t / m^3. For the marl revealed at depth, the dry and wet density values are respectively 1.57 t / m^3 and 1.86 t / m^3. The classification of soils based on the criterion of dry density makes it possible to qualify the sandy clay and marl as semi dense. The granulometric (Grain size) analysis shows that the soil in depth is fine, it reveals a fraction of passers-by at significant 80µ, that is to say a rate higher than 64%. The fraction of clay elements remains predominant in the soil. The plasticity of a soil is apprehended by the Atterberg's limit method. The test makes it possible to determine the liquidity limit (Wl), the plasticity limit (Wp) and the plasticity index (Ip). The samples of the sandy clay and marl tested, gave a liquidity limit of between 40 and 45% and a plasticity index of the order of 20 to 23%. According to the Casagrande's abacus it is a little plastic soil.

Table 2: Soil mechanical parameters

Depth. (m)	Shear test		Odometer test (OED)		
	C_{uu} (bars)	Φ_{uu} (°)	Pc (bars)	Cc (%)	Cg (%)
2.0/2.5	0.35	9	2.10	18.60	3.32
3.0/3.5	0.29	11	1.95	17.84	2.99
4.0/4.5	0.46	8	2.14	20.35	3.65

Mechanical parameters allow direct access to the bearing capacity of the soil, compatible with acceptable deformation (settlement). To determine these parameters, we used the Casagrande's box for the shear test and the Terzaghi's Odometric frame for the compressibility test. By mechanical shear characteristics, we intend the cohesion and the internal friction angle which is deduced from the shear test. This is how we carried out kind undrained tests (UU); they were carried out using the rectilinear shearing machine at a speed of 1mm / min in sandy clay and 1.2mm / min in marl. The values of cohesion for sandy clay varies between 0.29 to 0.35 bars, the values of the friction angle is between 9 to 11°. Concerning the marl revealed in depth, the intrinsic values are 0.46 bars of cohesion and 8° of angle of friction.

The compressibility is the object of the oedometric test (OED) which consists in studying the susceptibility of a soil to settlement, the tests were carried out on the different samples. The value of the consolidation pressure (Pc) for the sandy clay is between 1.95 to 2.10 bars, indicating an over-consolidated formation. The value of the compressibility coefficient (Cc) is 17 to 18%, which shows that this formation is moderately compressible. The swelling index (Cg) gave a value of 2.66 to 3.32%, showing a non-swelling formation. For the marl revealed in depth, the values are 2.14 bars of the consolidation pressure (Pc), 20% of the compressibility coefficient (Cc), and 3.65% of the swelling index (Cg).

3.2. Synthesis of physico-mechanical characteristics

The examination of all physical and mechanical characteristics makes it possible to provide the following elements of assessment; The soils analyzed are constituted by a loose formation, for the basic formation (sandy clay). The physical characteristics indicate that the soil tested is of fine texture, Their dry density characterizes semi dense soils, Their natural humidity level is qualified as moderately humid. For the marl revealed in depth, it has a fine texture, Their dry density characterizes a semi dense formation, their degree of natural humidity is qualified as moderately humid. From the mechanical point of view, the sandy clay and the marl are characterized by average values of cohesion and the angle of friction. As for their compressibility, the values have shown that these formations are over-consolidated, moderately compressible, and not swelling.

4. NUMERICAL MODELING AND ANALYSIS

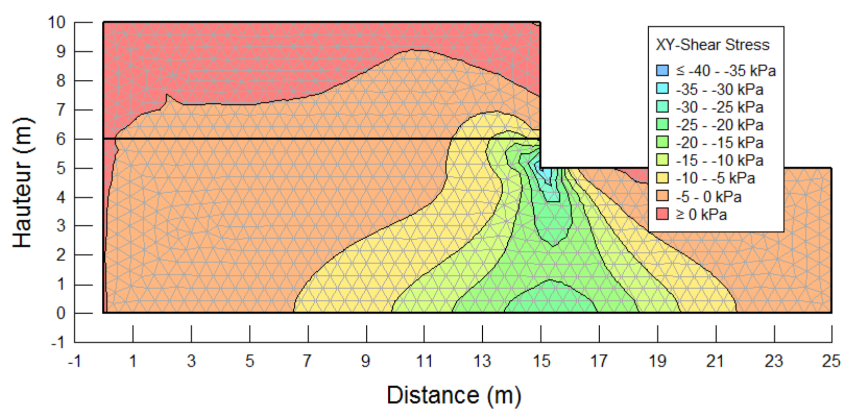
Slope stability finite difference (FDM) analysis has been implemented to compare the performance of different slopes degrees (45° and 90°) in long-term (LT) and short-term (ST) states by the computer program FLAC2D. It can be used to analyze displacement, stress and strain of slopes, especially suitable for nonlinear and large deformation [76, 77]. This program simulates the behavior of structures made up of soil, rock or other materials [78, 79]. The materials are represented by elements, or zones, which form a mesh adjusted by the user to correspond well to the shape of the object to be modeled [80]. Analyses were performed in undrained (ST), in drained (LT), plane strain, conditions. The shear strength reduction (SSR) technique was used as the analysis scheme [81-84]. Critical sliding surfaces, identified by shear strains localizations, were founded. The factor of safety (FoS) in FLAC was calculated via bracketing approach of c-ϕ reduction scheme [85, 86]. The current two-dimensional analyses were carried out on a soil with elastic perfectly plastic behavior bearing the Mohr-Coulomb failure criterion.

4.1 Geomechanical Model

In the present study, a finite difference slope model was considered for the stability analysis through determination the factor of safety (SoF). Accordingly, a drained/ and non drained slope of c-ϕ soil with 5 m height and the inclination of 1H:2V was considered in the excavation of 45° and the inclination of 1H:1V was considered in the excavation of 90° as shown in Figures (5) and (6). The fineness of the finite difference mesh has been examined to eliminate the boundary and size effects on the accuracy of the slope stability evaluations. The triangular mesh dimension was chosen to be (40cm×40 cm)/2 including 1896 zones. Appropriate boundary conditions were applied in the slope model; the left and right sides of the domain were constrained laterally in the horizontal direction and were set free to move in vertical direction; at the bottom surface of the grid, movements in all directions were restricted.

4.2 Simulation Analysis of the Cut Slope

Figure 5 (a): XY shear stresses distribution of 90° cut slope.



Short term (ST)

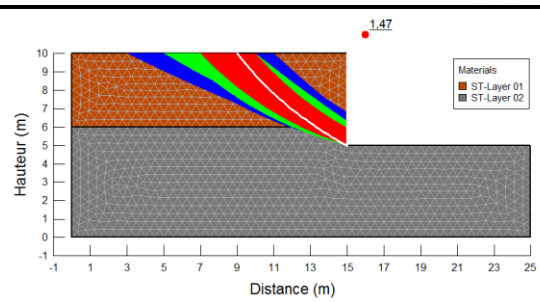


Figure 5 (b): free slope

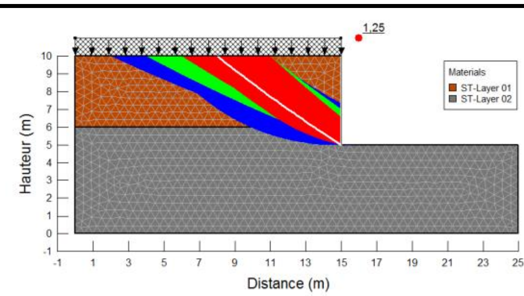


Figure 5 (c): loaded slope

long term (LT)

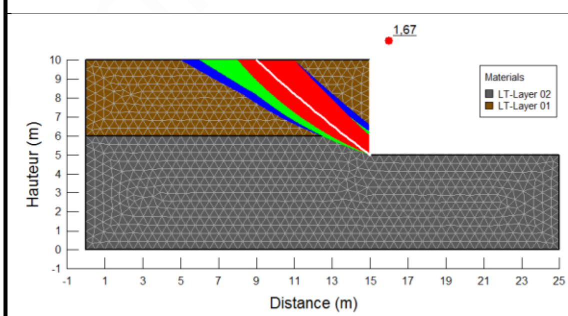


Figure 5 (d): free slope

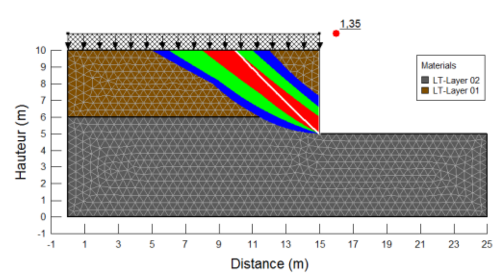
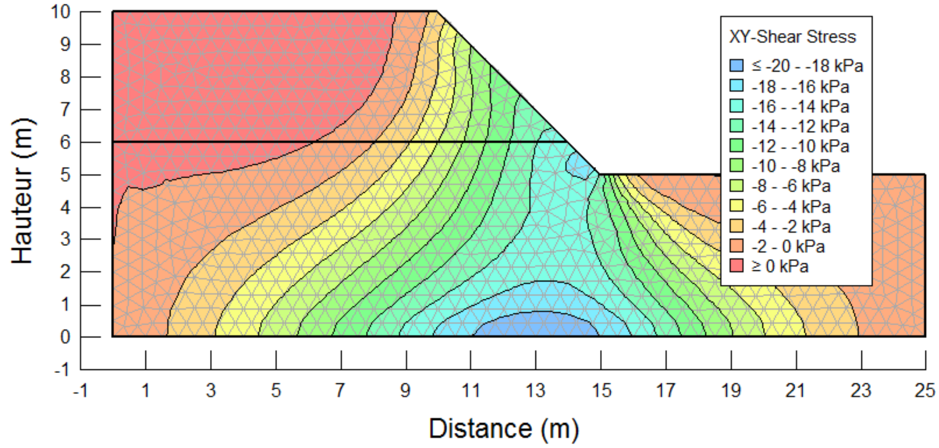


Figure 5 (e): loaded slope

The excavated process of slope were simulated by different excavating stages and each excavating stage was simulated to analyze the development of stress, strain, displacement and plastic zone in the slope. According to different properties of soil layers, the excavation process was divided into two stages; one surface gravelly and stony sandy clay and one layer of Marl. The model was developed on the basis of the results of topographic measurements (Figure 2). The results of cut slope of 45° and 90° tilts in ST & LT was presented in the figures (5) and (6).

Figure 6 (a): XY shear stresses distribution of 45° cut slope.



Short term (ST)

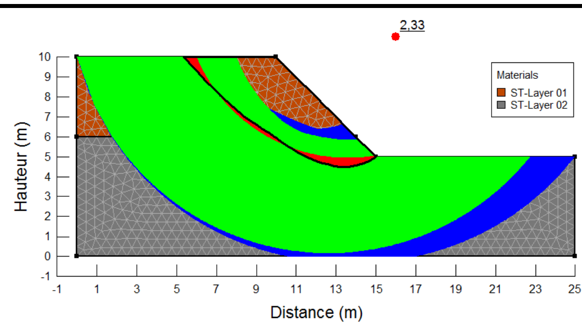


Figure 6 (b): free slope

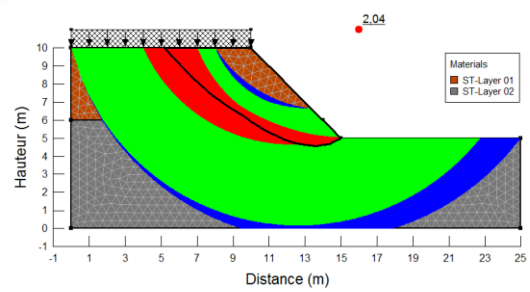


Figure 6 (c): loaded slope

long term (LT)

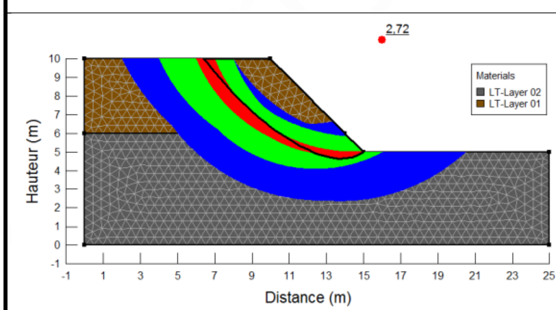


Figure 6 (d): free slope

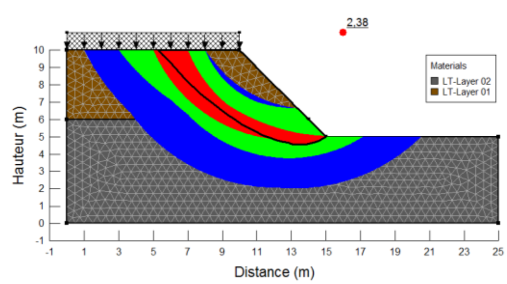


Figure 6 (e): loaded slope

Figure (5-a) shows the XY-stress distribution of 90° degrees cut slope. The overburden pressure decrease and free face increase because of unloading. These cause the shear stress concentration in the toe of slope, and the maximum shear stress value is 35 kPa. The maximum shear stresses distribution value of cut slope is appeared in the Lower slope. Meanwhile, the closer to the slope surface, the smaller of maximum shear stresses rate. As shown in figure (5-b and 5-c), the maximum safety factor (FoS) of excavated free slope and loaded slope are respectively 1.47 and 1.25. The failure band/ or circle occur and is still large in the range of first layer. It may be due to the unloading and resilience of soil excavation. Figure (5-d and 5-e) shows the failure band distribution of 90° tilt cut slope in LT state. The failure distribution are decreasing with increase in the depth of excavation. The maximum safety factor (FoS) of excavated free slope and loaded slope are respectively 1.67 and 1.35. Meanwhile, due to unloading and resilience of slope soil, the failure distribution at the first layer is maximum.

Figure (6-a) shows the XY-stress distribution of 45° degrees cut slope. The overburden pressure decrease and free face increase because of unloading. These cause the shear stress concentration in the toe of slope, and the maximum shear stress value is 18 kPa. The maximum shear stresses distribution value of cut slope is appeared in the Lower slope. Meanwhile, the closer to the slope surface, the smaller of maximum shear stresses rate. Sliding failure band with 45° Cut slope is shown in figure (6-b) and (6-c). The maximum safety factor (FoS) in short term (ST) state of free slope and loaded slope are 2.33 and 2.04, respectively. Where we notice that the slope slide failure band has occurred to the whole second layer of marl Unlike in the 90° cut slope. Sliding failure band with 45° Cut slope is shown in figure (6-d) and (6-e). The maximum safety factor (FoS) in long term (LT) state of free slope and loaded slope are 2.72 and 2.38,respectively. Where we notice that the slope slide failure band has occurred to the middle of second layer of marl Unlike in the 90° cut slope.

From the figures (5-b,c,d,e) it can be seen that a non-circular slip surface is generated for first layer slopes of 90°. It is also observed from the figures (6-b,c,d,e) that the circular slip surface is passing through the entire layers in cases with slope inclination of 45°. The red shaded portion of the slip surface indicates the band of trial slip surfaces with the different factors of safety.

5. DISCUSSION OF THE RESULTS

According to the mentioned above step-by-step excavation, every step of the safety factor (FoS) can be calculated by strength reduction method. Firstly, a safety factor is assumed and soil shear strength parameters *c* & *Phi* of the potential slip surface decrease by safety factor time. Then, using FLAC program interaction to calculate stress and deformation of the slope that was given the load and boundary conditions until the system balance stable state. Find out resistant shear force and sliding force of all units on the potential slip surface and judge its convergence. As the simulation analysis with 45° & 90° cut slope in ST & LT states, the safety factor of excavation of slope by steps are shown in the figure (7).

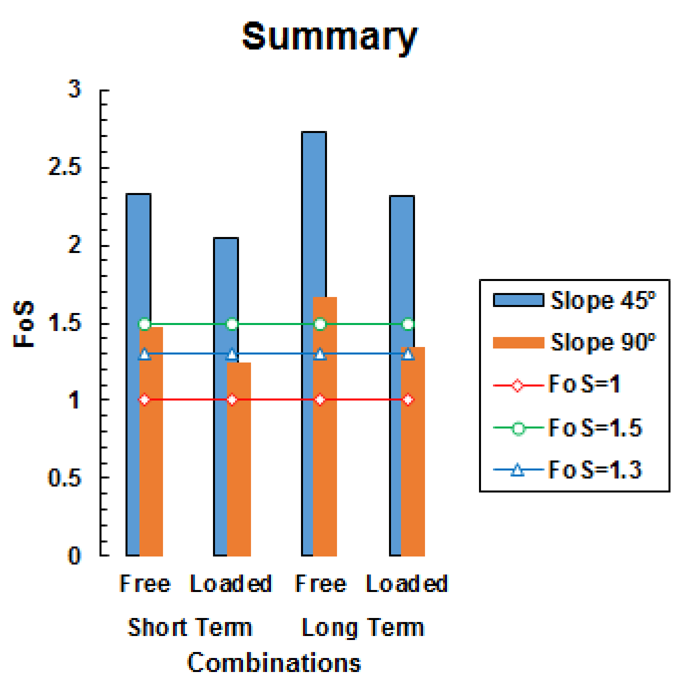


Figure 7: Summary of safety factors results

As seen in figure (7); the safety factor (FoS) is varying between 2.1 to 2.7 when excavating the slope to 45°; At short term (ST) it varying between 2.1 in loaded case to 2.4 in free case, At long term (LT) it varying between 2.4 in loaded case to 2.7 in free case. And the safety factor (FoS) is varying between 1.3 to 1.7 when excavating the slope to 90°; At short term (ST) it varying between 1.3 in loaded case to 1.5 in free case, At long term (LT) it varying between 1.4 in loaded case to 1.7 in free case. Consequently; the safety factor reduces with the increase in slope excavation degrees. It also reduces when loading slopes. Frequently; we can found that the safety factors are less in short term in comparison with long term states.

6. CONCLUSION

In this paper, 2D numerical simulation of care clinic's slope stability sliding susceptibility which contain a excavation steps was carried out. This study allowed us to confirm that the variability of the slope inclination has a decisive influence on the magnitude and rate of sliding taking into account the safety factors calculated using Mohr coulomb failure criterion. Overall, it can be said that FLAC2D program may address the examined problem satisfactorily.
From the study carried out in this paper, the following conclusions have been derived;
- finite difference method (FDM) predicts a higher factor of safety (FOS).
- The factor of safety (FOS) as obtained from FDM also signifies that the stability of slopes decreases by increase in slope inclination.
- The displacement field, stress field and strain field will be increasing during the process of soil slopes excavated.
- The distribution of stress in the upper slope and slope toe changed considerable according to the slope tilt (inclination) degrees.
- The failure band and sliding circle (stress lobe) expands to soil layers according to the slope tilt degrees.
- Constraint lobe can be a element in affecting safety factor.
-The slip surfaces obtained from FDM shows that as the slope angle gets steeper (90°) the failure band also shows a change from circular slip surface to non–circular slip surface.
-The most critical slip surface from FDM is found to be at a short term (ST) state whereas long term (LT) find the less critical slip surface state.
-The distribution of shear stress and failure band circle in the soil layers are dependent upon the cut slope inclination.
- In the case of excavations or applications of transient overloads, there may be changes in pore pressures with approximately constant void index, which affect the sliding behavior, which can be noticed in the difference of the short term (ST) and long term (LT) states.
- the shape of the critical sliding surface should be the result rather than the data of the analysis.
- The study of landslides always facing an optimization problem.

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The author declares that there are no conflicts of interests.

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All data associated with this study are present in the paper.

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