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Numerical modeling of slope stability and Safety factor in open-pit mine and conceivable measures

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Abstract

The Open-pit mining operations and techniques can cause substantial modifications to the rock mass structure, which could result in the incidence of landslides in the slope regions of active mining operations.

Advances in the mining field have generated many stability analysis methodologies to address this issue. This study aims to assess the stability of the edges of the Kef Essnoun Phosphate Mine (Algeria) located in the northwest, where the current mining activities are taking place.

The numerical modeling of the rock mass, based on extensive field and laboratory testing for mass characterization, played a crucial role in determining the potential for danger along the slopes and steps of the mine. Calculations of safety factors indicated that the rock mass, with its complex geological conditions characterized by heterogeneity and weathering, was vulnerable and unstable on the northern edge, compared with the southern edge, which proved stable with a safety factor exceeding the required safety margin. In order to minimize the risk of landslides, we chose a reinforcement method adapted to our case study.

Keywords

Open pit, Stability, Kef-Essnoun, Numerical Modeling, Safety factor.

Introduction

The instability of open-pit mine slopes represents a significant challenge in the field of mining, influencing both technical and economic aspects. Technically, instability influences mine safety, the principles of operation, and the maximum mine depth and can cause significant damage to structures and buildings.

Slope stability in mining perimeters is important for the security of the production processes, mining equipment, and especially for workers. The purpose of the stability analyses is to evaluate the safety factor or to check the stability reserve of a slope and, based on it, to reduce the geotechnical risks that may occur by identifying and implementing the appropriate stabilization measures (Wyllie & Mah, 2004; Derek, 2005 ; Kumar & Kumar, 2022; Wang *et al.,* 2014; Khan & Wang, 2021). Quantifying the risks associated with open-pit mine edge instability is challenging due to the uncertainty of available data, its quality, and the knowledge of necessary parameters. Stability analysis methods are useful in identifying unstable areas, thereby reducing their impact or avoiding them altogether. The utilization of different stability analysis methods can lead to reliable results.

The Djebel Onk mining field is situated in the north-eastern region of Algeria. From the bottom to the top, the deposit is composed of a limestone dolomitic series with flint and marly limestones, followed by layers of sand and alluvium (Kechiched et al., 2016). The thickness of the overburden, consisting of non-mineral material, ranges from 40 meters in the north to 198 meters in the south, as Dass et al. (2013) reported. Fig. 1 shows the localization of the quarry object of our study.

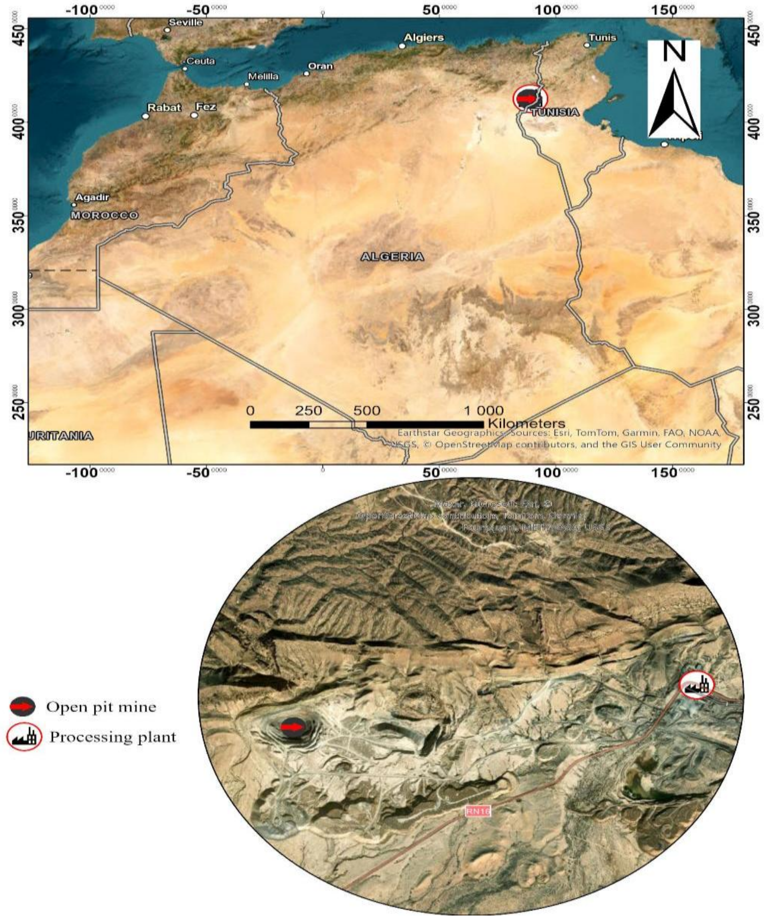

Fig. 1. Location map of Djebel–Onk quarry

Material and Methods

The analysis of slope stability requires a comprehensive understanding of the site's geological, hydrogeological, seismological, and geotechnical aspects, as well as proficiency in analytical and numerical methods (Rathod et al., 2012). It is crucial to identify the potential mode of failure in order to properly assess the stability of the excavation and choose an appropriate analytical method. The instability of the slope can result from a degradation of friction and cohesive properties or abrupt changes in boundary conditions (Eberhardt et al., 2004). It is imperative to validate the model through field observations or readings from installed measurement equipment (Coggan et al., 1998).

The stability of slopes can be analyzed using various methods that fall under three main categories: empirical, analytical, and numerical approaches. The appropriateness of a method is dependent on the level of site investigation and collected data (Stead et al., 2006).

Since rock masses are mostly discontinuous, anisotropic, and heterogeneous and have non-linear behaviors, using numerical models is often necessary to consider these more complex cases (Jing, 2003). According to Wyllie & Mah (2004), before starting a stability analysis, it is important to collect the information relevant to this analysis in sufficient quantity and accuracy to use the chosen technique properly. In the case of open pit excavations with low stresses and intact rock, the failure mode is primarily influenced by discontinuities and can take the form of one-plane sliding, two-plane sliding, overturning or tilting, or circular failures. Circular failures are more prevalent in materials of low strength or highly fractured masses (Aissi et al., 2019).

The utilization of probabilistic methods in rock engineering permits a rational treatment of various sources of uncertainties that significantly influence the safety of a rock slope (Duzgun et al., 2015). The stability calculations are typically performed using the limit equilibrium method, which determines a safety coefficient. The safety coefficient represents the stability state of the massif bounded by the topography and the assumed surface of failure, and a value less than or equal to one (1) indicates failure. Note that for Coggan et al. (1998), it is recommended to have safety coefficients of 1.30 for temporary structures and 1.50 for permanent structures in open rock structures. In more detail, Read & Stacey (2009) suggest various safety factors for several situations. Static and dynamic safety factors are provided for both large permanent structures and less critical excavations. For example, they propose dynamic safety factors ranging from 1.00 to 1.10 and static safety factors ranging from 1.25 to 1.50 based on the type of structure.

According to Read and Stacey (2009), and referring to the values of the safety factor, the stability state of the slopes can be evaluated as follows (Tab. 1).

Table 1. Equilibrium of the slopes depending on the safety coefficient

Scale	Consequence breakage	FS(min) static	FS(min) dynamic	PF(max) P [FS≤1]
Bench	-Low-High	1.1	/	25-50 %
Inter-ramp	-Low	1.15-1.2	1.0	25 %
	-average	1.2	1.0	20 %
	-High	1.2-1.3	1.1	10 %
Global	-Low	1.2-1.3	1.0	15-20 %
	-average	1.3	1.05	10 %
	-High	1.3-1.5	1.1	5 %

Over time, various methods have been developed for performing slice-based limit equilibrium analyses. Each method has unique assumptions, advantages, and disadvantages. The Morgenstern-Price method (Duncan and Wright, 1980), for example, is capable of handling complex cases with greater accuracy but requires more computational effort.

All methods are based on certain assumptions for the inter-slice normal (E) and shear forces (T), and the basic difference among the methods is how these forces are determined or assumed (Abramson et al., 2001). The specific characteristics and assumptions about the inter-slice forces of the main methods are summarized in Tab. 2.

Table 2. Characteristics of equilibrium methods of slope stability analysis (Duncan and Wright, 1980)

Method	Characteristics
Ordinary method of slices (Fellenius, 1927)	- Accurate enough for many purposes, more effective than detailed computer analyses. - Only for circular slip surfaces. Satisfies moment equilibrium. - Does not satisfy horizontal or vertical force equilibrium.
Bishop's modified method (Bishop, 1955)	- Only for circular, slip surfaces. - Satisfies moment equilibrium. - Satisfies vertical force equilibrium. - Does not satisfy horizontal force equilibrium.
Force equilibrium methods. (U.S. Army corps of engineers, 1970)	- Any shape of slip surfaces. - Do not satisfy moment equilibrium. - Satisfies both vertical and horizontal force equilibrium.
Janbu' s Generalized procedure of slices (Janbu, 1968)	- Any shape of slip surfaces. - Satisfies all conditions of equilibrium. - Permits side force locations to be varied. More frequent numerical problems than some other methods.
Morgenstern and Price's method (1965)	- Any shape of slip surfaces. - Satisfies all conditions of equilibrium. - Permits side force orientations to be varied.
Spencer's method (1967)	- Any shape of slip surfaces. - Satisfies all conditions of equilibrium. - Side forces are assumed to be parallel.

1. Characterization of the rock mass

Characterizing a rock mass is a crucial aspect of determining its impact on ground stability. Before starting a stability analysis, collecting the relevant information is important. This work started with important data collection, including geotechnical drilling documentation, geophysical surveys, and numerous laboratory and in-situ tests, to know the characteristics of the study area. (Fig. 2). The geotechnical data essential to apply the simplified Bishop and Fellenius methods are summarized in Tab. 3.

Fig. 2. Sampling and determination of the mechanical properties of the rock mass

Table 3. Mechanical and physical properties of the rock mass

The physic-mechanical properties of the rock mass	Limestone/ Conglomerate	Phosphate	Marl
Uniaxial compressive strength (MPa)	34.10	10.20	21.60
Triaxial compressive strength (MPa)	64.40	78.30	83.60
Tensile strength (MPa)	2.50	1.80	2.90
Shear strength (MPa)	64.4	78.30	83.60
Cohesion (KPa)	1.40	2.40	1.20
Internal friction angle (°)	23.00	30.00	19.00
Density (Kg/m^3)	21.5	21.70	20.20
Young's modulus (GPa)	5.20	4.60	3.60
Point load index (MPa)	2.20	1.00	1.60
Saturated density (Kg/m^3)	2.55	27.46	24.81
Poisson coefficient	0.21	0.24	0.14
Formation thickness (m)	10.00	30.00	30.00
Porosity (%)	0.50	6.50	5.00

These properties were determined either in situ or in the laboratory.

2. Numerical simulation analysis

The present study focuses on the Northwest block of Kef Essnoun, with a width of approximately 734m and a height of 193m. Our case study is not influenced by the water table.

Rocscience slide is the most complete slope stability analysis software; using Slide2's Finite Element Seepage Analysis tool, we can automatically generate our mesh and compute our steady state or transient analysis without needing separate programs. To carry out the modeling according to the chosen software, a section was made along the northern flank to have the profile with the thicknesses of the different facies. Figure 3 presents the current topographic plan of the Kef Essnoun region and the chosen profile.

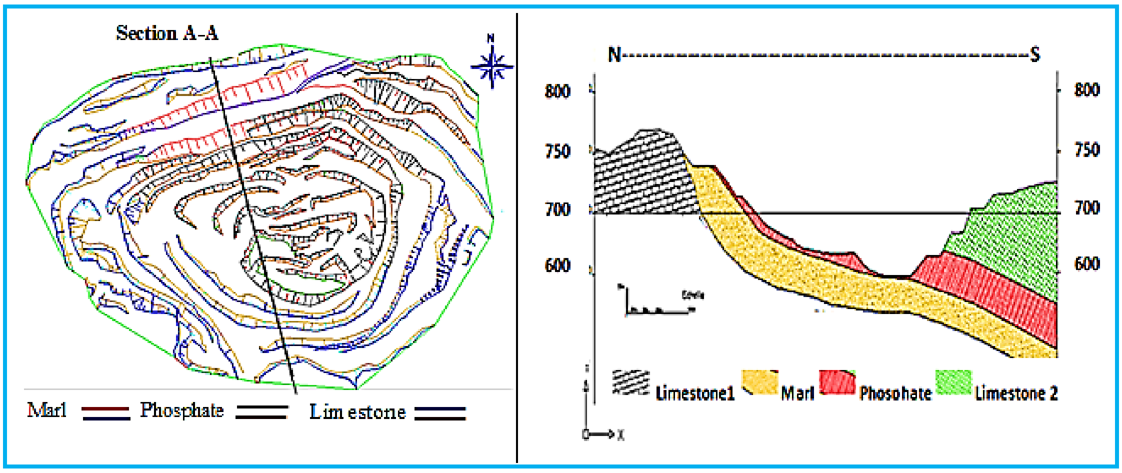

Fig. 3. Chosen profile and geological cross-section of the Northwest block

• Modelization and the calculation mode overview

All Stability analyses start with simple calculations; modeling using the slide's limit equilibrium approach offers good results if it succeeds in identifying the most critical surface (Tanguay, 2016).

Slide software is a computational tool designed to analyze slope stability. Giving solutions for civil, mining and geotechnical engineering, it can be utilized to model and/or analyze natural or artificial slopes, including embankments, earthen dams, and mine slopes. The software can also analyze user-defined non-circular failure surfaces and search for the minimum non-circular failure surface. The software features a graphical user interface that allows for flexible modeling and interpretation of feature data (Abramson et al., 2001).

Results

1. Stability calculation for the South edge

Fig. 4 below shows the southern edge of the Northwest block object of the first phase of the study.

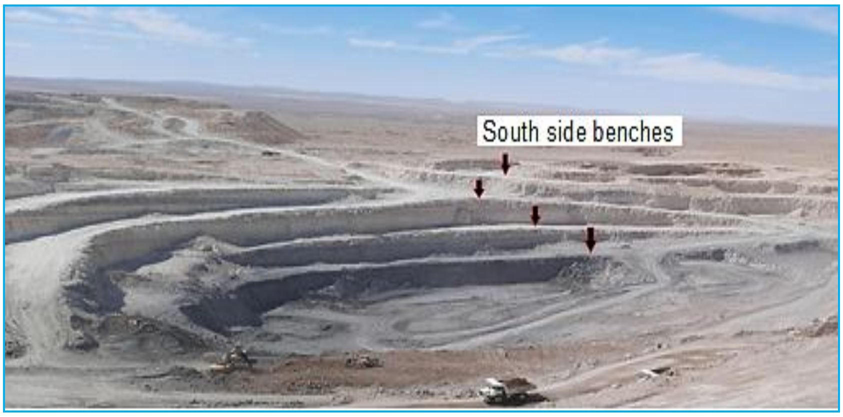

Fig. 4. Slopes on the south side of the Northwest block

Modeling results are shown in Fig. (5A) and (5B) for the Southern edge using the Bishop Simplified and Fellenius methods, respectively.

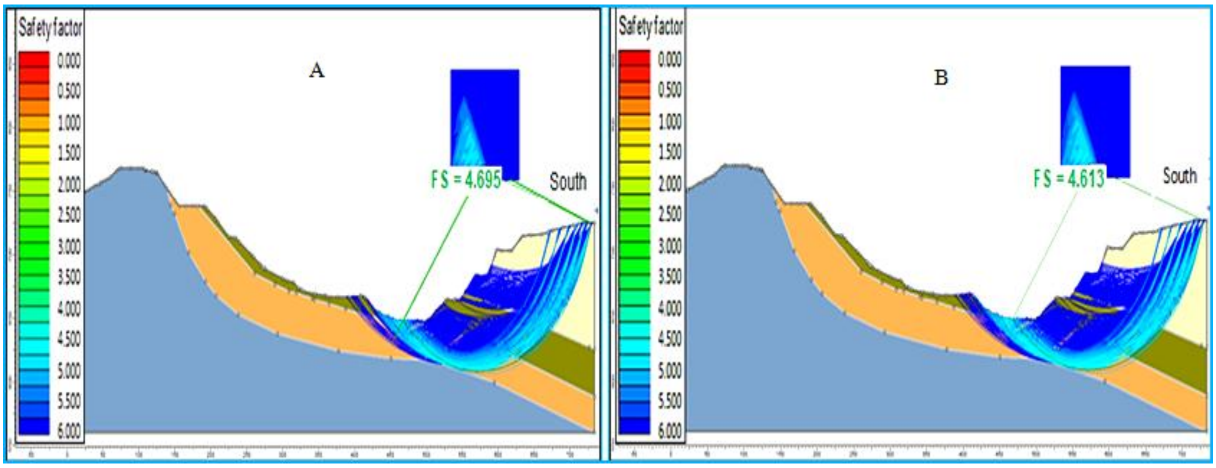

Fig. 5. (A)Safety factor value using simplified Bishop's method with minimum slip surface -Southern edge. (B)The value of the Safety factor using the Fellenius method with minimum slip surface -South Edge

2. Stability calculations for the north side edge

Fig. 6 below shows the north edge of the north west block object of the second phase of our study.

Fig. 6. North side slopes of the northwest block of the mine

Modeling results are shown in Fig. 7 (A) and (B) for the north edge using the Bishop Simplified and Fellenius methods, respectively.

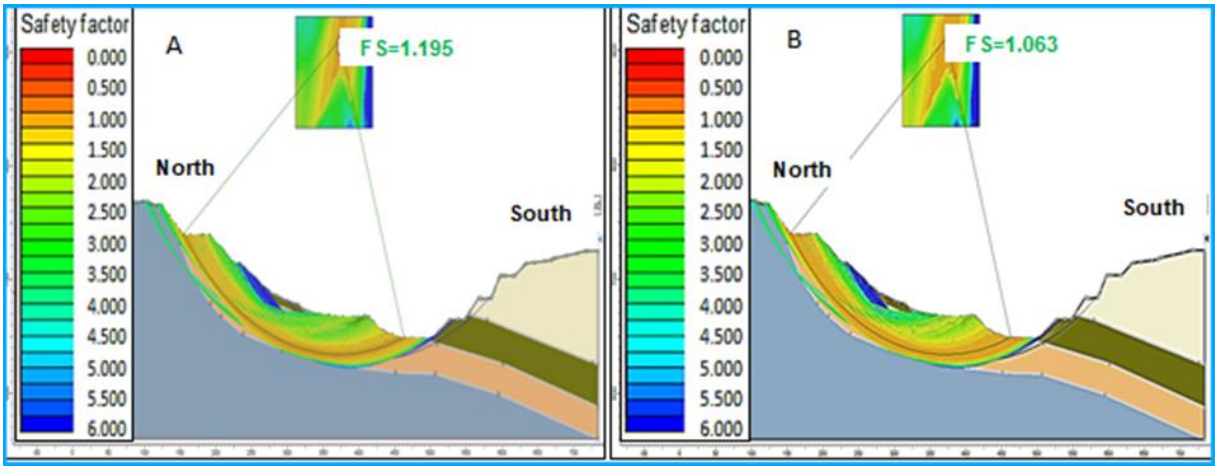

Fig. 7. (A) Safety factor value using the simplified Bishop method with a minimum slip surface -North edge. (B)The Safety factor value using the Fellenius method with a minimum slip surface --North edge-

The values of the safety factor calculated using the two previously mentioned methods are given in Tab. 4.

Table 4. The value of the safety factor for both methods

Methods	Bishop simplified	Fellenius
FS Value (North side)	1.195	1.063
FS Value (South side)	4.695	4.613

The safety factor (FS) obtained by the Fellenius method (Fig. 7.B) is lower than the one obtained by the simplified bishop method (Fig. 7.A). This is justified by the fact that with the simplified bishop method, only the horizontal components of the forces between the slabs are to be considered, and the safety coefficient is considered the same for each slab. This method allows to establish only the moment balance but not the force balance.

This is not the case for the Fellenius method, since it provides a more precise safety factor. With this method, the forces between slabs are neglected and imposes deferential safety coefficients between slabs. Finally, according to Mougin (1973), we can say that the Fellenius method could be closer to reality than the simplified Bishop method.

As has been proved by Gadri et al. (2015), the break line localizes much more at the Marne interface, as shown by the Slide software. The dip of the marl layer is estimated to be up to 60° and parallel to the stratification (Failure plane). Furthermore, the cohesion of the marl rock is 0 KPa.

Discussion

Since the marl layer presents the area with the lowest cohesion and angle of internal friction among all the other layers, then we will base on the influence of the cohesion and angle of internal friction on the stability of the edges only of the marl layer, since it represents the great risk of instability.

The studies conducted with the limit equilibrium method (Slide) show that the most sensitive area is actually the marl interface, which affects the value of the safety coefficient calculated by the simplified Bishop method estimated at 1.195, and the Fellenius method, estimated at 1.063.

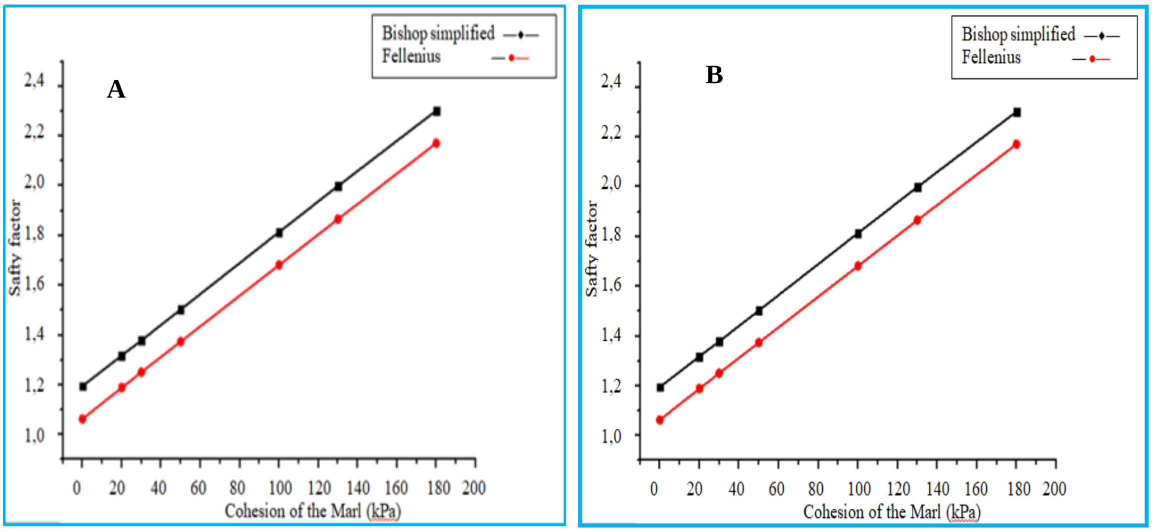

Fig. 8. (A) Curve represents the variation of safety factor as a cohesion function. (B) Curve representing the variation of safety factor as a function of the angle of internal friction

In this case, we change each time the cohesion and internal friction angle of the marl layer to obtain a safety factor, keeping all the properties of the other layers constant (C phosphate equal 2400 KPa), (C limestone equal 1400 KPa), (φ of phosphate equal 30°), (φ of limestone equal 23°).

The results found for different cases are shown in Tab. 5 and Tab. 6 above and presented graphically in (Fig. 8 A and B), respectively.

Table 5. Safety factor values for different cohesion values

Cohésion (KPa)	FS (Bishop simplified)	FS (Fellenius)
0	1.195	1.063
20	1.318	1.189
30	1.379	1.251
50	1.503	1.374
100	1.814	1.682
130	1.999	1.862
180	2.302	2.172

Table 6. The safety factor for different angles of internal friction

internal friction angle (°)	FS (Bishop simplified)	FS (Fellenius)
10	0.874	0.752
13	1.070	0.938
15	1.195	1.063
18	1.416	1.260
20	1.561	1.394
23	1.784	1.536
26	2.00	1.744

In light of the results obtained by the limit equilibrium method (Slide), we can say that:

First, the Southern Edge of the Kef Essnoun mine on the northwest side is very stable since FS >1.4 (Read and Stacey, 2009), which means satisfactory stability. In this case, we are more interested in the north side edge.

Concerning the northern edge of the north-western block of Kef Essnoun, the results of FS confirmed that it is an unstable edge (questionable security) and risks having a potential slip.

The failure line is located much more at the level of the Marne interface, as shown by the Slide software. Since the inclination of the marly layer is very high, estimated at 60° and parallel to the stratification (Failure plane). Therefore, the cohesion of the marl rock is (0) KPa. Given the results of the influence of geotechnical parameters on the safety factor, we can say the following:

According to the analysis of the graphs showing the variation of the FS as a function of the cohesion and the angle of internal friction of the marl facies, the value of the safety coefficient increases when the value of the Cohesion and the angle of friction increase. It is found that for a value of the safety factor (FS equal to 1.4), with the simplified Bishop method C equal to 36 KPa and φ equal to 18°, and for the Fellenius method C equal to 57 KPa and φ equal to 21°. There is a considerable increase in the stability of the northern edge when the value of the cohesion and the angle of internal friction of the marl layer increases.

These results, show that the northern edge of the Kef Essnoun Northwest open pit is exposed to potential instability, of which the necessary safety measures should be taken.

Proposal of a reinforcement method

According to the results of the previous analyses, and since the safety factor obtained is low on the northern edge, we opted for the use of a suitable reinforcement method to improve the stability of the study area and avoid a ground movement, which is the reprofiling method.

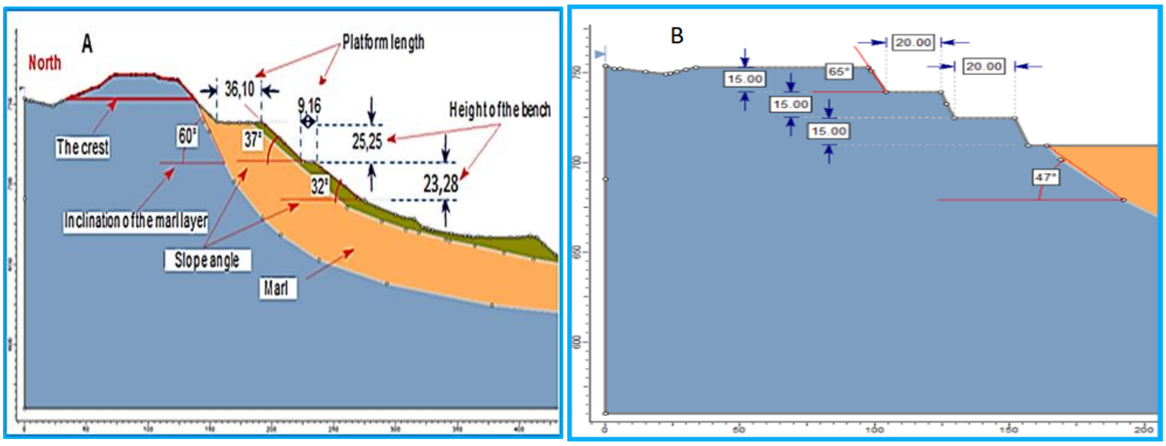

Fig. 9. Parameters to carry out the reprofiling. A/ Parameters to be modified B/ Recommended parameters

To carry out this method, the approach consists of improving certain factors (Figure 9.B). The following factors are taken into consideration:

- Bench height (Hg).
- Angle of the slopes of the bench.
- Inclination of the marl layer.
- Width of the work platform (Lp).
- Crest.

To achieve this method, the steps to be followed consist of improving some factors according to Fig. 9A. The steps consist of:

- Decrease of the ridge consists of digging out the upper part, which results in a decrease in the weight;
- Rectification of the height of the slopes up to 15m and adding others to increase stability, work platforms up to 20 m, and the angle of the slopes up to 65°-70°. At the same time, trying to remove the marl layer, thus eliminating the effect of the straightening of the layers.

The new safety factor calculations for the north edge are presented graphically in Fig. 10 (A) and (B) for both methods.

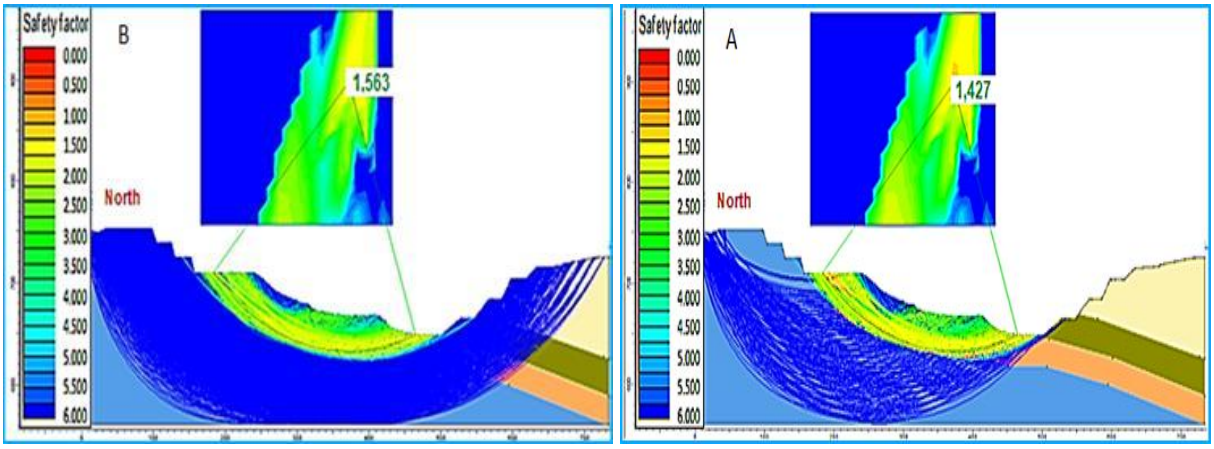

Fig. 10. (A) The value of the Safety factor (after reprofiling) by the Fellenius method with maximum slip surface -Northern edge. (B) The Safety factor value after (reprofiling) by the simplified Bishop method with maximum slip surface - North edge.

According to the result obtained following (Fig. 10), it can be seen that the reprofiling method allows an increase in stability with a safety factor largely sufficient to ensure the stability of the environment.

Tab. 7 summarizes the safety factor values obtained for the two methods used. In addition, the stability of the slope depends largely on the dip angle of the formation, the height and the angle of the slopes. The chosen reprofiling method can increase the safety factor, thus ensuring the stability of the north edge of the mine on the northwest side.

Table 7. Factor of safety values for the two methods

Simplified Bishop's method	Fellenius method
1.563	1.427

Conclusions

The initial examination of the site's geometrical, geological, and geotechnical data revealed that several factors might have a significant impact on the site's stability, including the presence of a weakly cohesive marl layer, the slope geometry, the soil type, and the parameters of the exploitation process.

Given the availability of physical-mechanical parameters and geotechnical and geometric characteristics, an instability analysis was carried out using Slide software to determine the safety factor and confirm the existence of a circular failure problem. The model proved that the northwest bloc is exposed to potential instability.

The results indicate that the northern block of Kef Essnoun Northwest is characterized by instability resulting from the existence of potential slip planes in the marl layer. The safety factor calculated lies in the range of 1 to 1.25, which is considered as questionable stability.

The stability was analyzed by evaluating the effect of cohesion and angle of internal friction of the marl layer on the safety factor. The analysis confirms that these factors significantly influence the stability of the North edge.

The proposed reinforcement method makes it possible to increase stability with a safety factor that is largely sufficient to ensure stability.

The reprofiling method significantly improves the safety factor for both Bishop simplified and Fellenius methods, respectively increasing to 1.563 and 1.427. Thus promoting the stability of the northern edge of the quarry located on the northwest side.

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