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Research Article

Influence of Blasting Activities on Slope Stability: A Case Study

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Abstract

In the phosphate mine, the Kef-Essnoun deposit extended to (N75° E), soft and brittle tectonics resulted in an abrupt change in the dip of the phosphate layer flush or the dip angle is subvertical or steeply inclined towards the Southeast and sometimes the Northwest. The overall edge angle of the pit evaluated at 55° for a depth of 75 m. Several incidents of slope failure occurred in the mine, and a considerable disruption to production and monetary losses occurred. It is expected that slope failures may be triggered due to blasting in a steeply sloped laminate. In order to study the causes of slope failures, on the one hand, a back analysis was applied in order to assess the most probable physical and mechanical characteristics of the layer generating the movement, and on the other hand, the slope was analyzed by the limit equilibrium methods (LEM). The calculation of the safety factor (SF) value was carried out under static loads and dynamic loads were taken into account, which led to the conclusion that the dynamic load affects the safety factor.

Keywords: Slope stability; Blasting; Safety factor; LEM; Open-pit Mine

Introduction

The stability analysis of the rock slope, which is one of the most important research subjects in geotechnical and geological engineering, involves many infrastructure fields including, traffic construction, mining and civil engineering. Landslides are a great and important geological hazard that causes great concern around the world [1-2]. Landslides are one of the most important geomorphological processes that reduce the ground level. These landslides occur due to a decrease in the shear force of the slope material, or an increase in the shear stress on the material, or both together, which leads to its slow or rapid movement towards the bottom and outward of slopes materials [3], which may spread over many kilometres. Some types of landslides, especially rapid ones, lead to loss of human life and the destruction of many human facilities, such as roads, dams, water sources, surface mines, and others, which have great economic and environmental consequences [4]. For these reasons, landslides are among the difficult problems in Earth sciences [5].

Landslides are one of the rapid ground processes, which occur due to the influence of the gravity force as a major factor. There are other auxiliary or secondary factors that affect the activity of landslide processes, including those related to the geological structure and natural phenomena such as rain [6], earthquake [7], groundwater pressure [8] and slope ratio [9], and others related to human activities such as vibrations caused by Blasting and mining works, engineering errors resulting from excavation works (for example changing the shape of the slope or adding new loads), and other various activities.

In recent times, the occurrence of landslides and giant pits has been widely observed, and the reason for this was not only the geological changes of the earth's crust, but scientists attributed some of them to the human activities [10]. Many researches were conducted [11-12] in order to find the appropriate relationship between these factors and the slope stability, and there are many authors [13-14] who have obtained some important achievements.

The Kef-Essnoun mine is one of the main sources of phosphates in Algeria. Currently, most of these resources are extracted by the open-pit method, just because it is a cost-effective mining method. Phosphates are extracted by drilling and blasting. Whereas, blasting activities provide multiple dynamic stresses to smashing the structural integrity of the slope frequently [15-16]. However, the most important safety factor for open-pit mines is slope stability, and controlling them is one of the very difficult factors [17-18].

The landslide that has already occurred in the Kef-Essnoun mine, resulting in days of interruption of production and monetary losses. Ground vibrations generated by blasting may be one of the causes of these failures.

In this paper, firstly, a back-analysis was applied on the edge of the pit (Kef-Essnoun) in order to approximate the most probable physical and mechanical characteristics of the layer generating the movement through SLIDE geotechnical software, and on the other hand, the value of the safety factor (SF) was calculated under static loads as well as dynamic loads. For this reason, the main objective of this work was to obtain a better understanding of the mechanisms of rupture by exploring different potential scenarios of instability.

Geological framework

The Jebel El Onk mining field is one of the largest mineral deposits in the world. It contains approximately the half of Algeria phosphate reserves. This mining basin contains several phosphate indices and five deposits 'figure 1': the Djemi-Djema deposit, Jebel El-Onk North, Bled Hadba, Oued Betita and Kef-Essnoun. The site in question (Kef-Essnoun mine) is located on the southern flank of Jebel El Onk cretaceous anticline. It is about 7 km in the southeast of Bir el Ater city in the south of Tebessa province (Northeast of Algeria) and about 21 km to the Algerian-Tunisian border 'figure 2'. The study site has an area of approximately 250 ha and belongs to the same mining basin than Metlaoui phosphate mine (SW Tunisia) [19-23]. The fluvial sedimentary series of the region includes a stratigraphic succession from the upper Cretaceous (Maestrichtian) to the middle Eocene (Lutetian).

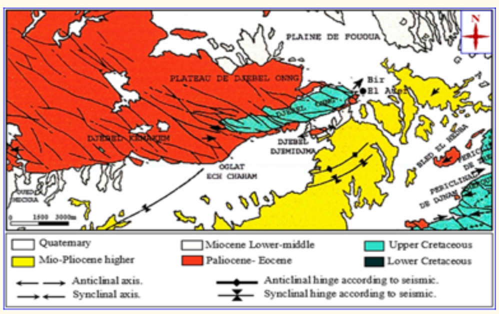

Figure 1: Geological map of the study area [20].

Figure 2: Location map of the study area [22].

A series of three major faults of NNW-SSE direction passes through the deposit without causing major deformations on the geometry of the layers. On the other hand, in the Kef-Essnoun zone 'figure 3', elongated to the Northeast (N75° E), soft, brittle tectonics resulted in an abrupt change in the dip of the strata with an almost sub-vertical dip to Strongly inclined towards the South-East and sometimes the North-West. From the point of view of the current tectonic situation and activity, the geological structure of the deposit has not undergone any recent tectonic activity.

The opening of the Kef-Essnoun deposit ‘figure 4’ takes place from the side of hole N°28 corresponding to the centre of the deposit and which has the following characteristics:

- Thickness of the covering layer (limestone-dolomitic) 40 m;
- Thickness of the phosphate layer 31.5 m, and indicated a discovery ratio less than 1.26.

The pit is excavated as benches with slope angles of 75° to 85°, 30 m in height, and 15 to 20 m in width. The depth of the base of mine is 75 m.

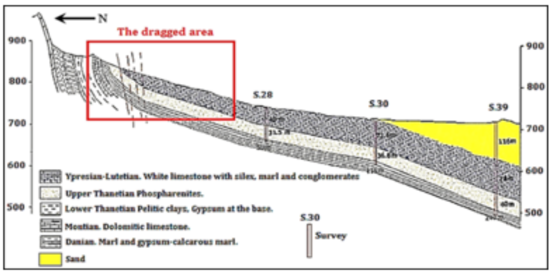

Figure 3: Geological section of the Kef-Essnoun phosphate deposit (before exploitation) [19].

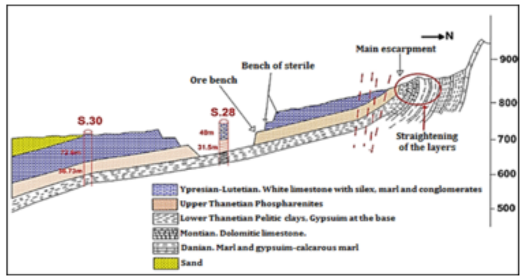

Figure 4: Geological section of the studied slope (Kef-Essnoun mine) after exploitation and before sliding [19].

Source of Damage Caused by Blasting Vibration and Influence Mechanism on Structural Plane

Blasting practice

In Kef-Essnoun mine, mainly the bench is blasted using ANFO-MARMANITE explosive. The length of blast hole varies between 31.5 and 32 m. The diameter of blast hole is 160 mm. Each hole is loaded with around 380–384 kg of explosives.

The burden and spacing of holes are 5 and 5 m, respectively. The typical density of the explosive varies between 0.9 and 1.33 g/cm^3 with a velocity of detonation of 4100–6500 m/s. Figure 5 shows the delay sequence of a typical blast round on phosphate bench.

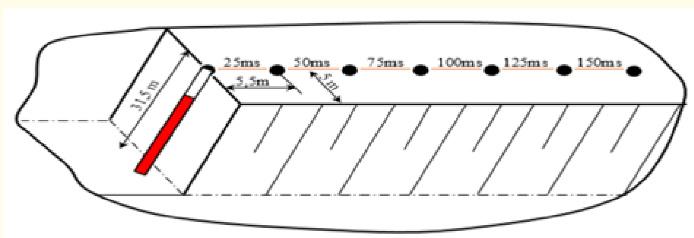

Figure 5: Delay pattern of a blast in Kef-Essnoun mine.

Blasting stress

The chemical energy produced by the explosive will spread in the form of a vibration wave and be transmitted to the rock mass structure to promote rapid rupture and extension of the structural planes, which will cause the adverse effect on its structure. Vibration wave caused by blasting is the mixture of horizontal and vertical waves. The additional stress F produced by the sliding body on the slope due to blasting vibration should be expressed as follows:

$$F = W.\,K_0 = W.\,A/g \qquad (1)$$

Where W (KN) is the gravity of slip mass, K0 is the seismic coefficient, A (m/s^2) is the acceleration due to blasting vibration; g (m/s^2) is the acceleration due to earth's gravity.

Converting F into static force F_0 as:

$$F_0 = \gamma . N = \gamma \frac{W.A}{g} \qquad (2)$$

Where γ is the coefficient of converting rapid transient vibration force into static force, being 0,25.

According to the experiment and the statistics, the experiential formula of the accelerated velocity produced by the surrounding rock mass unit due to blasting vibration is

$$A = 0{,}086. Q^{0,83}. R^{-3,5}. V_p^2 \qquad (3)$$

Where Q (kg) refers to the charge mass; R (m) refers to the distance to the blasting centre; Vp (m/s) refers to the transmission speed of vertical wave.

The charge mass of the hole is affected by the strength, structure and crack joint and weathering degree of the rock mass as well as other factors like type of the explosive, diameter of the explosive cartridge, charging way, blasting parameters and number of free surfaces.

The calculation formula is expressed as:

$$Q = q.a.b.H \qquad (4)$$

Where q (kg/m^3) is the unit explosive consumption; a (m) is the spacing of hole; b (m) is the burden; H (m) is the bench height.

According to the basic parameters of blasting operation, the additional static force N0 produced by the surrounding rock mass in different blasting ways can be calculated through the iterative computations of Eqs. (1-4).

Damage Mechanism of Multidirectional Blasting Stress on Structural Plane of Rock Mass

Within the scope of influence of blasting vibration, the chemical energy produced by the explosive will spread around in the form of vibration wave and be transmitted to the rock mass in the non-blasting area, which will cause the adverse effect on its structure. Vibration wave caused by blasting is the mixture of horizontal and vertical waves. In order to make clear the influence of vibration wave on the structural plane, the stress-strain law of horizontal and vertical waves on the structural plane of the rock mass is explored, respectively.

The loads produced by the action of horizontal and vertical waves caused by blasting on the sliding mass are

$$F_h = \gamma \frac{W.A_h}{g} \qquad (5)$$

$$F_v = \gamma \frac{W.A_v}{g} \qquad (6)$$

Where F_h (kN) and F_v (kN) are the loads in the horizontal and vertical directions, respectively; Ah (m/s^2) and Av (m/s^2) are the accelerated velocities in the horizontal and vertical directions, respectively.

Figure 6 shows the actions due to reference blasting by a force, most of the time horizontal or parallel to the average slope of the bench, proportional to the weight of the ground capable of moving (acceleration coefficient A) and applied generally to the center of gravity of the soil mass. In the case of Kef-Essnoun, acceleration of blasting vibration "A" was mentioned in the expert report of Kadri and Bougdal (2007) [24] for the horizontal and vertical components $A_h = 0.05$ (m/s^2) and Av = 0.0125 (m/s^2). This factor is undoubtedly the main trigger for this shift.

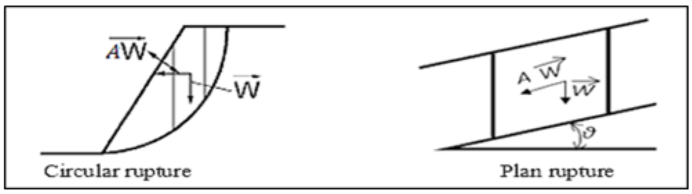

Figure 6: Action of the acceleration coefficient for circular and plane rupture [25].

Mass wasting of Kef-Essnoun mine

On September 8, 2007 at 5:00 a.m., the exploitation of Kef Essnoun open-pit phosphate mine stopped, because a large mass of rock got detached from the massif (sliding). Several researches [19-23] have been made, concluded that the failure mode is a planar sliding occurred in the phosphate marl interface. At present, it became clear that more stability problems could be expected. The slip mass covers an area of almost 11 ha with an average thickness of about 70 m (30 m of phosphate and 40 m of overlying land) so we can estimate the volume of the slipped mass at 7.7 Million m^3 filling almost the entire operating pit 'figure 7'.

Figure 7: Geological section of the studied slope (Kef-Essnoun) after sliding [19-23].

Based on the geological section of the slipped zone 'figure 7' and the observations made on the site, it has been found that the failure surface is due to straightened strata in the northern part of the quarry profile. Which implies that the sliding surface corresponds to the phosphate/marl interface, and its shape follows the topography of the latter, it would be a sliding guided by a stratigraphic plane inclined 14° towards the south.

Methodology

Blasting was required in open pit mines to provide multiple dynamic stresses to frequently damage the structural integrity of the slope. It is very difficult to take into account the dynamic factor of blasting, especially for the slope of the open pit.

In this paper, numerical modelling is performed by SLIDE geotechnical software to analyze the influence of dynamic load on the slope of an open-pit mine. The main objectives of this paper are as followings. Firstly, retro-analysis study, in order to determine the geotechnical characteristics most likely of the layer, layer generating the movement. Secondly, numerical modelling is performed to calculate the value of the safety factor (SF) through the geotechnical software SLIDE, the principle of this phase is based on the following models:

Static models

Only a static load in the form of gravity has been applied.

Dynamic models

dynamic and static loads are applied in the models.

Description of the model

Figure 8 shows the long profile of the northern flank, with the thicknesses of the various layers of phosphate, marl, and limestone of the Kef-Essnoun mine. It can be seen that the predominant rocks are limestone. The thickness of rock strata varies from a 35 to about 198 m. benches presented in the figure indicate 30 to 40 m height different. Thinner layers (thickness less than 7 m) are combined as one layer and included in the models. Rocks samples were obtained from the mine site and their engineering properties were determined. The material properties of rock strata used in this study are presented in table 1.

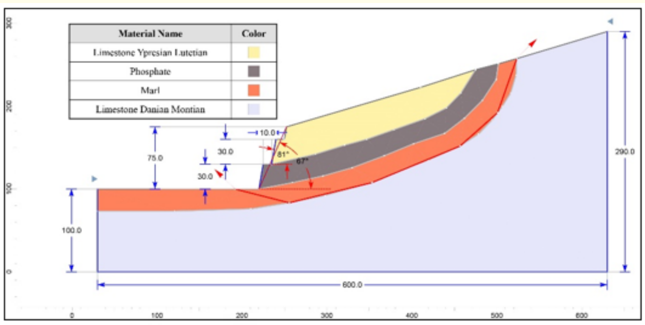

Figure 8: Geotechnical model of Kef Essnoun mine.

Properties	***Symbols units***	***Rock formations***			
		Limestone Ypresian-Lutetian	***Phosphate***	***Marl***	***Danio Limestone-Montian***
Unit compressive strength	UCS (MPa)	58.84	49	9.58	19.17
Dry unit weight	γ_d (KN/m^3)	25	24	22	27
Young's modulus	E (MPa)	27000	24000	10	27000
Cohesion	C (KN/m^2)	5400	2300	C*	3600
Internal friction angle	φ (°)	37	35	φ*	37
C* and φ*: Unknown values (to be determined).					

Table 1: Material properties of rock strata used in numerical modelling [26].

Back-analysis

According to studies and the observations made on the site, it was deduced that the possible slip affects the layer of marl, [19-23]. Given the lack of data concerning this layer, we opted for a slip back-analysis, in order to determine the most likely geotechnical characteristics. This involves returning to the value of the cohesion and the internal friction angle of the marl, compatible for the landslide, with a critical safety factor (SF = 1). For this model 'figure 9', the red line shown in the figure represent the location of sliding surface. The failure surface is planar and passes through a layer of weak material (brown material). The material above and below the weak layer (brown material) is significantly stronger than the weak layer, and the physical-mechanical properties of the Kef-Essnoun northern flank are shown in table 1.

The sensitivity analysis helps researchers evaluate the impact of an individual unknown variable, assuming all other parameters of the slope are known. In this analysis, one parameter varies and the other input parameters are kept constant. A sensitivity analysis indicates which input parameter may be essential to the assessment of slope stability and which of these parameters has a lesser effect on instability.

During the sensitivity analysis, the cohesion and the friction angle of the marl layer were analyzed. The results are presented as sensitivity graphs in figures 9 and 10.

According to the analysis of the graphs 'figures. 9 and 10' showing the variation of the SF as a function of the cohesion and the internal friction angle of the marl layer, it is noted that for a safety factor of 1, the values of cohesion (C*) and angle of friction (φ*) were 80.87 kPa and 16.38°, respectively.

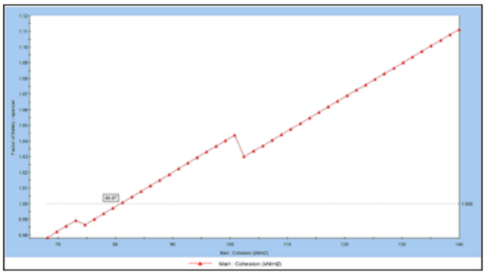

Figure 9: Variation of cohesion as a function of the safety factor.

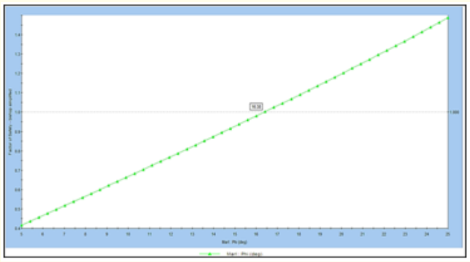

Figure 10: Variation of friction angle as a function of the safety factor.

Numerical modelling

The next step is to investigate the stability by the limiting equilibrium method (Slide), using the parameters of the slip plane which were calculated a posterior from the back-analysis.

Static model. The model is analyzed in plane strain conditions by applying gravity loading only. Three calculation methods such as; Spencer, Bishop and GLE/ Morgenstern-Price 'figure11' were chosen. Safety factor of the values calculated according to the three methods mentioned previously, shown in the following table 2.

Methods	***Bishop***	***Spencer***	***GLE/Morgenstern-Price***
SF	1.007	1.072	1.013

Table 2: Safety factor values in the static case.

Dynamic model. The models are analyzed in plane strain conditions by applying dynamic and static loads 'figure 12'. SF of the values calculated according to the three methods shown in the following table 3.

Methods	***Bishop***	***Spencer***	***GLE/Morgenstern-Price***
SF	0.882	0.900	0.832

Table 3: Safety factor values in the dynamic case.

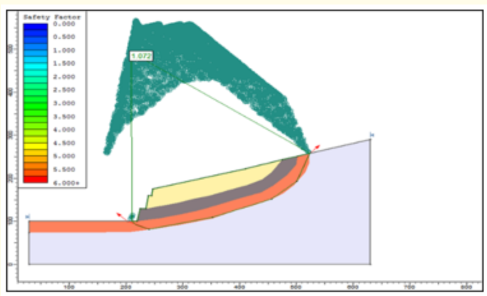

Figure 11: The sliding surface and the safety factor value (static load).

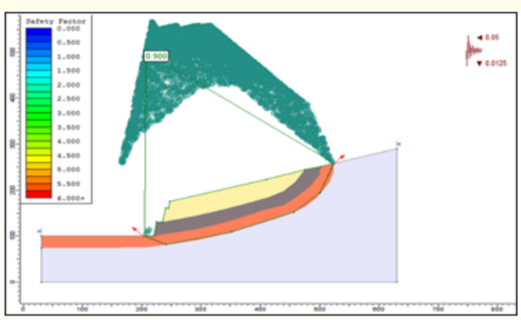

Figure 12: The sliding surface and the safety factor value (dynamic load).

Results and discussions

This software calculates the safety factor taking into account the integration of the geometrical aspect (height and slope of the embankment) and the mechanical aspect (cohesion and internal friction angle), as a function of the triggering factors represented in the case of the Kef-Essnoun mine by the anthropogenic seismicity coefficient resulting from the blasting. The results obtained are shown in Tables 2 and 3.

According to the results of the numerical modelling obtained using the SLIDE software, it can be seen that:

- In the first approach (static load) we did not consider the coefficient of anthropic seismicity, we noticed all the safety factors are greater than 1 (SF> 1). This implies that the slope is stable, with a minimum safety factor, given by the Bishop method (SF = 1.007) (Table 2).
- In the second approach (dynamic load) taking into account the anthropic seismicity coefficient (effects of blasting), all safety factors are less than 1 (SF <1). This implies that the slope is unstable with a minimum safety factor given by Bishop's method (SF = 0.822) (Table 3), which confirms the influence of blasting on the stability of the slope of the quarry.
- The removal of the abutment is the anthropic parameter of destabilization essential, with of course the influence of the seismicity due to the blasting works.

Conclusion

The analysis of the results allows us to say that in addition to the geological and geotechnical factors that can influence the stability of a slope, the dynamic loading due to the explosive must be taken into account. The control of this parameter can be achieved by reducing the height of the bench, the widening of the working platform and the modification of the operating method of exploitation.

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