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STABILITY ANALYSIS OF JOINTED ROCK SLOPES USING GEOMECHANICAL, KINEMATICAL, AND LIMIT EQUILIBRIUM METHODS: THE CHOUF AMAR CAREER, M'SILA, NE ALGERIA

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Abstract: Many open-cast mines in Algeria are regularly affected by instabilities that disrupt the exploitation activity, such as Chouf Amar's career where recurrent failures are caused by the combined action of a number of predisposition and triggering factors. I this study we uses a commbined-Geomechanical, Kinematical, numerical and limit equilibrium analysis to evaluate the behaviour of the discontinuous rock masses in open pit mine, and we chooses the Chouf Amar career as a case study. We determines nine main sets of discontinuities in the three main facies of the stone-pit. We proved also that the quarry suffers from various types of failures and that blasting declines the values of safety factor. We find out the causes of the 2009 slip-incident. By this combined approaches we have made it possible to optimize operations and to improve career productivity while ensuring the safety of equipment and personnel.

Keywords: *discontinuity, rock slope stability, limestone quarry, RMR, FEM*

1. INTRODUCTION

North Africa countries are constantly exposed to geological and climatic hazards often manifested by floods, earthquakes or ground movements (Rouabhia et al. 2012; Hamed et al. 2014; Demdoum et al. 2015; El Mekki et al. 2017; Hamad et al. 2018a;

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Besser 2018; Anis et al. 2019). Terrain instabilities with multiple shapes of natural or anthropogenic origins often cause significant damages to facilities (Mouici et al. 2017; Manchar et al. 2018; Karim et al. 2019) and disrupt the socio-economic development of mountainous areas (Hamad et al. 2018; Tamani et al. 2019). In Northern Algeria, many regions are affected by instabilities (Hadji et al. 2017a; Mahdadi et al. 2018). Because of the disorder they cause in the road network (Achour et al. 2017; Dahoua et al. 2017a; 2017b), agglomerations (Hadji et al. 2014; Hadji et al. 2016; Hamed et al. 2017), and open-pit mining (Gadri et al. 2015) added to human losses (Mokadem et al. 2016; Hadji et al. 2017b), many researchers are working on this problem (Achour et al. 2018).

In this study, we are interested in instabilities related to "mining activity" in the edges of embankments in fractured rock masses. These instabilities hinder the normal cycle of operations of exploitation (Zahri et al. 2016) and cause considerable financial losses to businesses and even threat to the staff safety (Rais et al. 2017). The most illustrative example is the 2009 Chouf Amar quarry (NE Algeria) landslide that involved a mass slide of 5 Mm^3 and led to the cessation of mining for several months (Saadoun et al. 2019) (Fig. 1). After the incident, the work-operations bypassed the accident with bleachers 30 m wide and 15 to 20 m high.

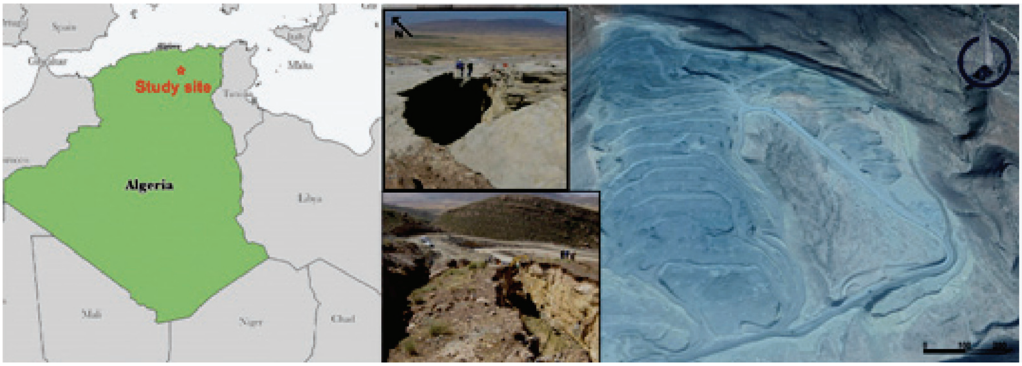

Fig. 1. a – Location map of Chouf Amar quarry, b – Landslide occured in 2009 in the quarry

Most of the stability studies of quarry edges tend to determine the geological, topometric and geotechnical factors that control the rock slopes balance and to consider their spatiotemporal occurrence intensity and frequency (Hadji et al. 2013; Havaej 2015; Hamad et al. 2018b). Several approaches exist to design open-pit mines slopes or underground excavations in rock masses. All require information on the network of discontinuities (Hoek and Bray 1981; Priest and Brown 1983).

The geo-scientific literature groups methods for calculating slope stability into classical methods with kinematic, geo-mechanical and limit equilibrium analyzes (Hadji et al. 2017; Dahoua et al. 2018), and numerical methods with continuum and discontinuum modeling, finite difference method, continuum and discontinuum modeling and Distinct Element Methods, (Tschuchnigg et al. 2015; Broojerdi et al., 2018).

Geomechanical approaches are based on Romana's Slope Mass Rating (SMR) index obtained from Bieniawski's (1976) Rock Mass Rating (RMR) classification. Since its publication in 1985, many researchers have adapted the SMR to the needs of their studies (Anbalagan, 1992; Romana 2003; Tomas et al., 2012).

Kinematic approaches allow failure modes determination on the basis of geometric considerations by neglecting some forces (Hudson and Harrison 2000). Stereographic projection makes it possible to highlight the geometrical configurations favorable to a break according to a given mechanism.

Limit equilibrium methods make it possible to calculate the rock block stability using a safety factor. A safety factor ($Fs = 1.3$) is commonly used as a critical stability limit in open pit mines (Hoek and Moy 1993). The theory of Norrish and Wylie (1996) and Hoek (2007) are used to calculate the safety factor for planar fractures and that of Kumsar et al. (2000) for wedge for failures.

Numerical methods that combine the Finite Element Method with the Shear Strength Reduction Method (FEM-SSR) for blocky rock masses allow calculating the rock slope safety factor for linear and/or nonlinear criteria (Wyllie and Mah, 2004. The SSR is used to determine the critical Strength Reduction Factor (SRF) (Rocscience, 2011). The main objective of our study is to assess rock slope stability and excavatability of the the Chouf Amar's career, NE Algeria. The parameters likely to develop modes of rupture inside the quarry are identified, and more generally one tends to establish a valid and transferable approach of analysis towards similar sites in the Mediterranean basin. To determine the discontinuities network effect on the mechanical behavior of the massif of the Chouf Amar quarry, we methodologically exploited geomechanical, kinematic, limit equilibrium and numerical approaches to control the tectono-geological and morpho-structural factors of the study site. Once completed, our research helps optimize operations, improve career productivity while ensuring the security of work tools and workmans.

2. GENERAL SETTING

The Chouf Amar limestone deposit (159 ha) is exploited for the manufacture of cement by the Algerian Cement Company (ACC). It is located in NW of M'Sila province, at 8 km of Hammam Dalaa municipality. The deposit is composed of two monoclinal compartments separated by a trough, oriented SNE–NSW (N 75°) with a dip of 15° (N 170°). The reserves of the deposit exceed 200 M tons, which gives a career 50 years-life depending on production capacity (4 M ton/year). The deposit is represented by upper Cretaceous formations subdivided into three layers. At the base, the layer (C3), (15 m), composed of micric Bioclastic, and massive limestones, outcrops in the southwestern part due to tectonic accidents. A thicker intermediate layer (C2) (30 m), consisting of a series of dark gray limestone beds, often fossiliferous outcrops in the western and southwestern parts. The upper layer (C1) of variable thickness (14–30 m) due to erosion outcrops throughout the deposit except in the southwestern part. It consists of crystalline limestone beds, locally fossiliferous (Fig. 2). The study site is dislocated by a fault with vertical displacament, dividing the deposit into two major compartments, in addition to many secondary sub-parallel lineaments. This faulting is the main responsible for the recurrent instabilities in the platforms (920–1000 m a.s.l.), imposing the change of the direction of exploitation (Saadoune et al. 2018).

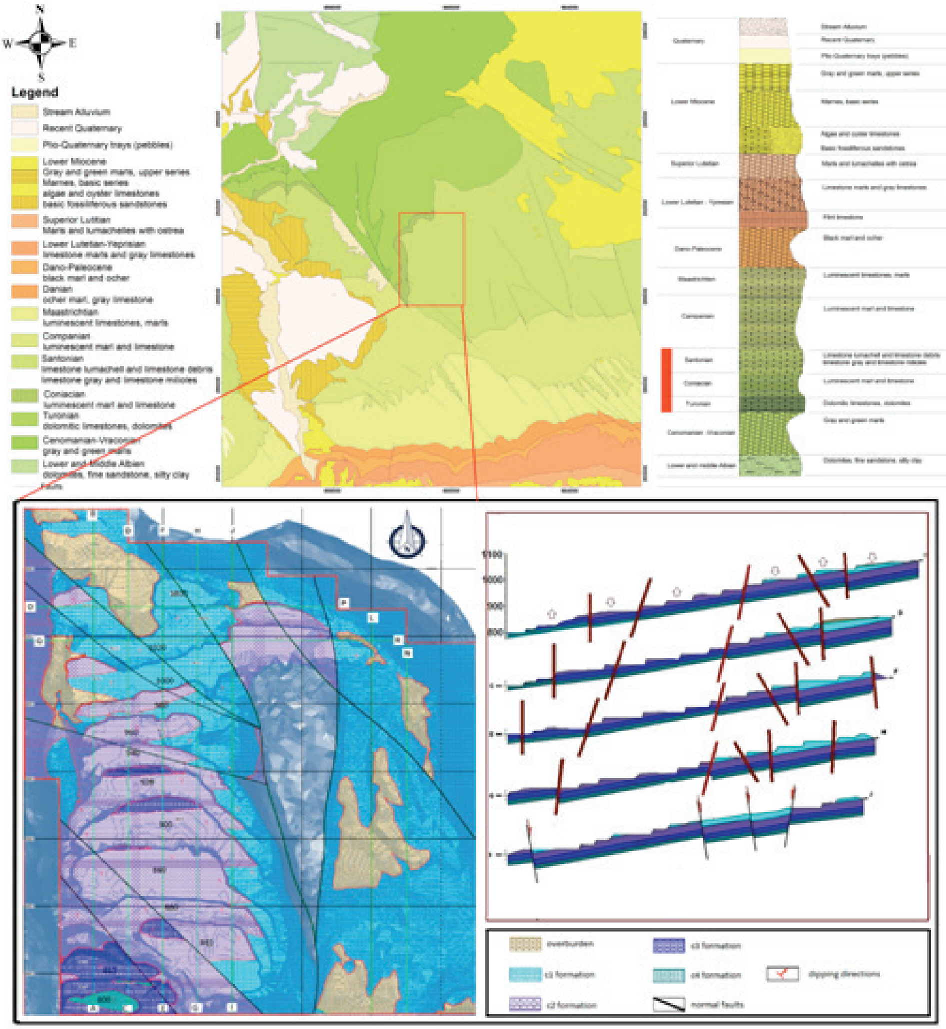

Fig. 2. a – Simplified and detailed geological map of the study area, b – cross sections of the career

3. MATERIAL AND METHODS

The data used for this study were collected in 2018 as part of the project "Risk Management in North East of Algeria" (IAST, UFAS). We started by collecting available geological morpho-tectonic and geotechnical data, and then we proceed to measure the different discontinuities geometric variables of the rock mass according to the method of the traverses (Zahri et al. 2017). Next, we measure the rock matrix physico-mechanical parameters and discontinuities from the laboratory tests on intact samples according to the norm (P18-418) (NF 1989). The rock joint roughness coefficient (JRC) is estimated from Barton's standard profiles (1973), and the joint compressive strength (JCS) is measured with the help of the International Society for Rock Mechanics method (ISRM 1978). The Rock Quality Designation (RQD) values were determined from three core holes conducted by the M'Sila Central Laboratory of Public Works (LTCP). Its results were supplemented from the Edelbro (2003) method. The Geological Strength Index (GSI) (Hoek et al. 1995) has been evaluated from the improved version of Sonmez and Ulusay (1999).

The main sets of discontinuities have been inventoried from the structural surveys measured on the front of the quarry. The families of discontinuities are then represented by stereographic projection and identified and associated with the corresponding lithological facies using Dips software (V6), (Francioni et al. 2017).

For the data analysis, discontinuity family data were used in a geo mechanical approach to assess career stability based on the SMR. This index is obtained by adding an adjustment or correction factor to the Bieniawski's RMR (Romana et al. 2003) using the SMRTool/MATLAB application allowing the insertion of multiple input parameters and the automatic detection of wedge failure.

A kinematic analysis based on the stereographic projection (Goodman 1989) was performed using the Rockpack-III software to identify the different families of discontinuities (planar, toppling, wedge) failure mode (Wyllie and Mah 2004). The data necessary for the analysis consist of the slope orientation and discontinuities sets added to the associated friction angle. Chouf Amar massif values of the mechanical parameters of the discontinuities are obtained using (RocData/Rocscience) software based on Barton and Bandis relations (1990). Once the potential breaks have been identified, an analytical approach is used with the limited equilibrium method in using the Rocplane and Swedge softwares (Zahri et al. 2016). The multi-approach technique adopted by our study is shown schematically in (Fig. 3).

Finally, we determined the SRF of the slope based on FEM-Phase2/Rocscience (V8) software following the shear strength reduction (SSR) method.

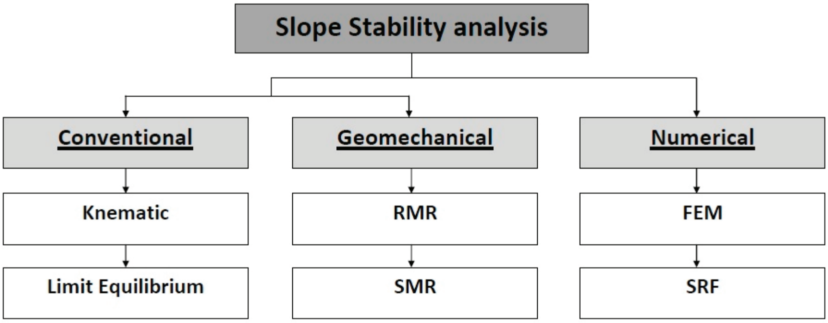

Fig. 3. Methodological flow chart of the study

4. RESULTS AND DISCUSSIONS

The results of the discontinuity measurements statistical analysis (raw data) allowed us to quantify the discontinuities orientation according to the Wittke convention (2014). The C1 rock formation of the Chouf Amar quarry has five pole concentrations corresponding to five families of discontinuities. The other two formations C2 and C3 present four families of discontinuities where the last family of each formation corresponds to the stratigraphic discontinuities (Fig. 4, Table 1). Chouf Amar career is marked by the presence of a faulting network with Dip/Dip direction presented in Table 2.

The SMR classification results prove that all facies are classified as stable to partially stable with the exception of two cases in the C1 facies, three cases in the C2 facies, and three other cases in the C3 facies with two faults (FA1, FA6) susceptible to planar rupture (Table 3).

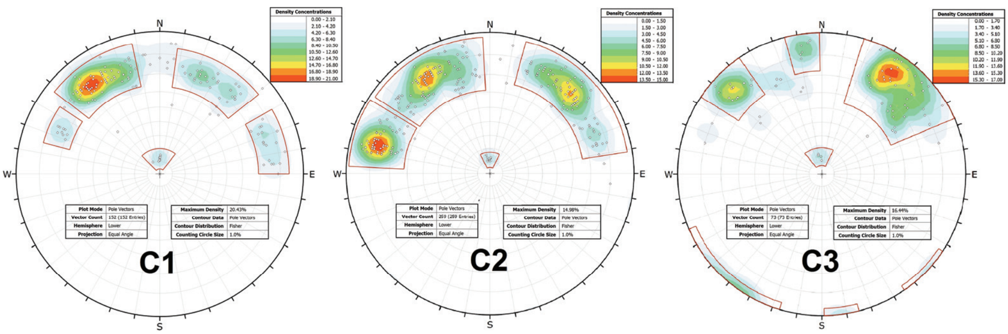

Fig. 4. Discontinuity Sets of C1, C2 and C3 formations

Table 1. Orientation of discontinuity sets

	C1		C2		C3	
	Dip (°)	Dip direction (°)	Dip (°)	Dip direction (°)	Dip (°)	Dip direction (°)
Set 01	75	147	76	106	77	223
Set 02	73	210	75	150	81	134
Set 03	76	255	76	225	83	172
Set 04	72	113	12	176	14	173
Set 05	12	177				

Table 2. Faults orientation in the study site

Faults	F1	F2	F3	F4	F5	F6
Dip Direction (°)	20	190	230	245	50	204
Dip (°)	70	75	66	60	60	68

Table 3. Classification and description of SMR classes of the study site

Facies	Dip Direction	Discontinuity sets	Class	Stability	Failure mode
C1	220, 100	F2, F4	IV	Instable	Planar
	180	F1&F2, F3&F4	V	Totally instable	Wedege
	180, 220	F2&F4, F1&F3	IV	Instable	Wedege
	220	F2&F3	V	Totally instable	Wedege
	100	F1&F4	IV	Instable	Wedege
C2	240, 100, 135	F3, F1, F2	IV	Instable	Planar
	180	F1&F3, F2&F3	V	Totally instable	Wedege
	135	F1&F2	V	Totally instable	Wedege
	195	F1&F3, F2&F3	IV	Instable	Wedege
C3	180, 220	F3, F1, F4	IV	Instable	Planar
	45	F1, F3	IV	Instable	Toppling
	180	F1&F3, F1&F4, F2&F3, F2&F4, F3&F4, F1&F2	IV	Instable	Wedege
	220	F1&F2, F2&F4, F3&F4	IV	Instable	Wedge
Level (815–860)	180, 220	FA1	V	Totally instable	Planar
Level (815–830)	180, 220	FA2	IV	Instable	Toppling
Level (890–1050)	180	FA6	IV	Instable	Planar

Toppling failure is possible in the F1 and F3 sets at the level of the individual dipping direction bench of 45° in the facies C3 and the fault F2 in the dipping directions (180, 220°). The wedge ruptures are more pronounced in the limestones (unstable to completely unstable) due to the intersection of several discontinuities in several dipping directions of the slope of the quarry. Figure 5 shows cases of planar and wedge fracture produced according to families of discontinuity sets and faults.

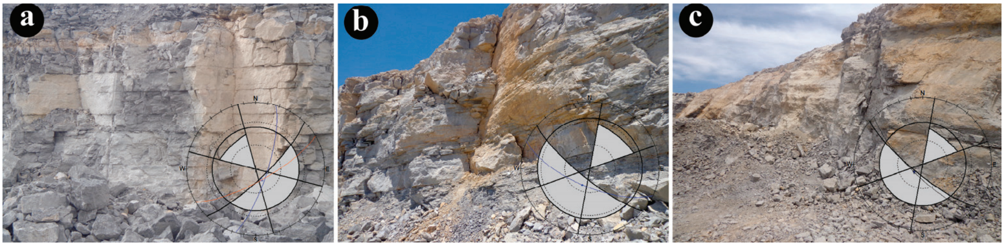

Fig. 5. Failures in benchs: a – wedge fracture according to 2 sub-vertical families, b, c – planar failures according to the faults

The analysis of the persistence of major faults or stratification joints at the interbank scale in various directions was taken into account. With an internal friction angle $\varphi = 10°$, the family of stratification joints can give rise to planar breaks in the benches and interbanks. Figure 6 illustrates the cases of kinematic analysis of families of discontinuities (faults) taking into account the exploitation directions. The examination of the results (Table 4) indicates that the C1 training is not subject to breaks. The analysis of formation C2 shows several directions of the front exploitation because of the structural instabilities (planar and wedge) encountered.

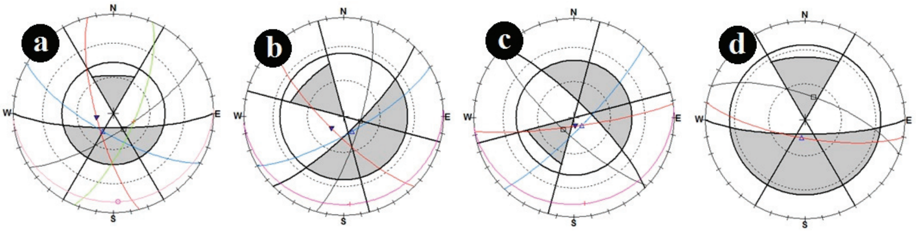

Fig. 6. Kinematic analysis of the different modes of failures: a) facies C1 (dip-direction of 180°, b) facies C2 (dip-direction of 135°), c) facies C3 (dip-direction of 45°), d – faults F1 and F2 (dip-direction of 180°, level 815, 830)

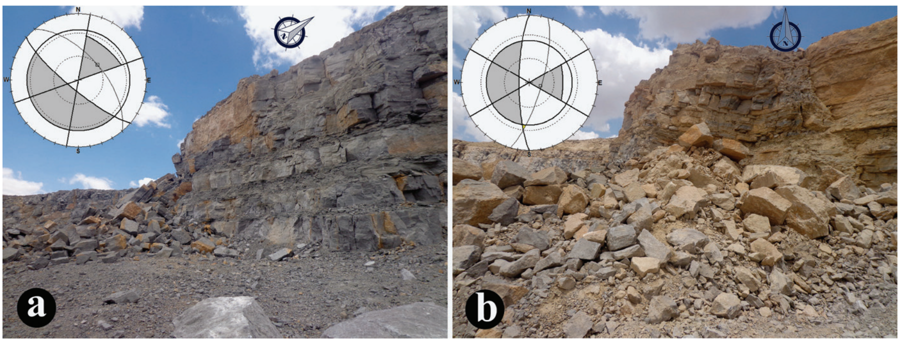

Fig. 7. Secondary toppling failures: a) according to fault F5, b) combination with marl joint

The proposed new directions cause toppling failures in some cases (Fig. 7). The possibilities of rupture in the facies C3 is less compared to the previous formation and this is due to the almost discontinuities vertical dip.

Table 4. Failures possibilities determined by the kinematic analysis

<table>
<tr><th colspan="2">Facies</th><th>Dip direction (°)</th><th>Planar failure</th><th>Wedge failure</th><th>Toppling failure</th></tr>
<tr><td colspan="2" rowspan="6">C1</td><td>180</td><td>F5</td><td>F1&F2, F1&F3, F2&F3, F2&F4, F3&f4</td><td>–</td></tr>
<tr><td>45</td><td>–</td><td>–</td><td>F2, F3</td></tr>
<tr><td>120</td><td>F4</td><td>F1&F4, F2&F4</td><td>–</td></tr>
<tr><td>280</td><td>–</td><td>–</td><td>F4</td></tr>
<tr><td>220</td><td>F2</td><td>F1&F2, F1&F3, F2&F3, F2&F4, F3&F4</td><td>–</td></tr>
<tr><td>100</td><td>F4</td><td>F1&F4, F2&F4</td><td>F3</td></tr>
<tr><td colspan="2" rowspan="7">C2</td><td>180</td><td>F4</td><td>F1&F3, F2&F3</td><td>–</td></tr>
<tr><td>240</td><td>F3</td><td>–</td><td>–</td></tr>
<tr><td>135</td><td>F2</td><td>F1&F2, F1&F3</td><td>–</td></tr>
<tr><td>100</td><td>F1</td><td>F1&F2</td><td>–</td></tr>
<tr><td>270</td><td>–</td><td>–</td><td>F1</td></tr>
<tr><td>220</td><td>F3</td><td>F1&F3. F2&F3</td><td>–</td></tr>
<tr><td>195</td><td>–</td><td>F1&F3, F2&F3</td><td>–</td></tr>
<tr><td colspan="2" rowspan="3">C3</td><td>180</td><td>F4</td><td>F1&F2</td><td>–</td></tr>
<tr><td>45</td><td>–</td><td>–</td><td>F1</td></tr>
<tr><td>220</td><td>F1</td><td>F1&F2</td><td>–</td></tr>
<tr><td rowspan="4">Fault and level (m)</td><td>815, 830, 860</td><td>180</td><td>FA2</td><td>–</td><td>FA1</td></tr>
<tr><td>845</td><td>220</td><td>FA2</td><td>–</td><td>FA1</td></tr>
<tr><td>940, 960</td><td>220</td><td>–</td><td>–</td><td>FA5</td></tr>
<tr><td>980, 1050</td><td>180</td><td>FA6</td><td>–</td><td>–</td></tr>
</table>

The potential breaks identified during the kinematic analysis are quantified using a limit equilibrium calculation. Thus, we calculated safety factors (*Fs*) for the different formations and we got an *Fs* without any influence of the external forces and a *Fs* under vibratory stress of the shot (an acceleration average of 0.1g obtained from 30 recordings). Figure 8 illustrates the case of a stratification joint with a stress crack in the 860 m level. The model consist of a planar break case along fault F2 in the 845° level (western part). Figure 8d shows the model obtained for the case of the wedge failure generated by the F1 and F2 sets. This scenario is in the bench scale with a slope orientation of (180/78). The results of this analysis are summarized in Table 5.

For FEM modeling, we have adopted an analysis in plane strain with a stop criterion of a square root energy (top = 0.001) and triangular elements of 6 nodes. The limitations of the model are chosen based on the recommendations specified by Wyllie and Mah (2004). Table 6 gives input and output parameters for the rock mass in

Phase2/Rocscience (V8) software based on Hoek–Brown parameters. GSI index values reached (70, 62, 52.5) for the formations (C1, C2, C3) and 35 for the marls (C4).

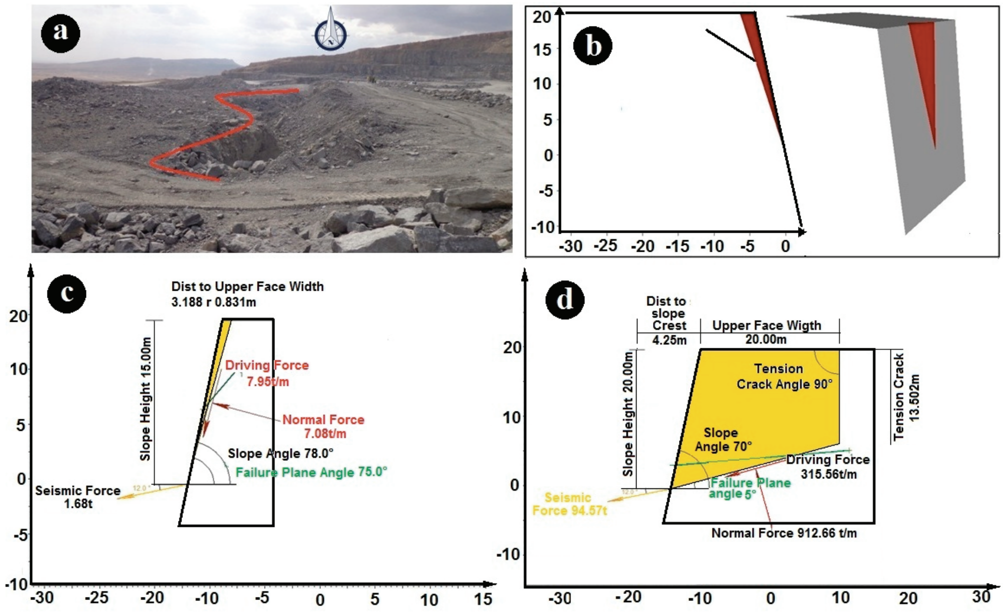

Fig. 8. Types of faillure in the career: a – planar failure model according to F4, b – tension crack, c – planar failure according to fault F2, d – wedge failure according to the intersection between F1 and F3

Table 5. Summary of the results of the limit equilibrium analysis

Facies	Dip direction (°)	Discontinuity sets	*Fs*	*Fs* seismic sollicitation	Number of bolts *Fs* > 1.3
Planar Failures					
C1	180 (inter benchs)	F5	1.64	1.13	84
C2	220, 240	F3	1.18	1.06	1
	100, 135	F1. F2	0.87	0.76	1
	180	F4+ tension crack	1.68	1.21	3
	180 (inter benchs)	F4	1.39	0.69	33
Faults	815–830–845	F2	1.08	0.99	1
	860	F2	0.86	0.78	2
	980	F6	0.42	0.35	7
	1050	F6	0.48	0.42	4
Wedge Failure					
C2	180	F1&F3	1.10	0.92	6
	135	F1&F3	1.15	0.96	5
	195	F1&F3	1.15	0.96	5
	195	F2&F3	0.95	0.82	4

Table 6. Parameters of the rock mass obtained by RocData

Formation	Mohr coulomb parameters		Deformation modulus (MPa)
	Cohesion (MPa)	Friction angle (°)	
C1	1.6	47.42	15811.39
C2	1.08	38.07	10464.99
C3	0.42	41	5345.16
C4	0.09	15.98	848.65

In the calculation, we start with an initial value *SRF* = 1, then we increase it with a systematic increment. We calculate the Mohr–Coulomb parameters and insert the new resistance properties into the model until it converges to a solution. Figure 9 shows *SRF* = 2 value in which the slope is considered stable for a maximum total displacement value of 5.445 m. The highest displacements appear in the 860 m level. The intensive cracks observed in this level are due to creep. In this analysis, the faults effect on the overall slope stability was examined and it was clear that the stability decreases slightly (*SRF* = 1.98) by the introduction of major geological structures.

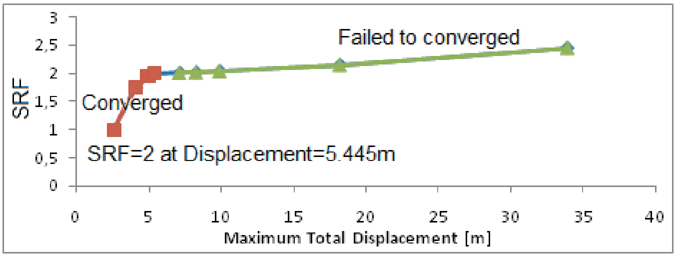

Fig. 9. *SRF* values versus to displacements

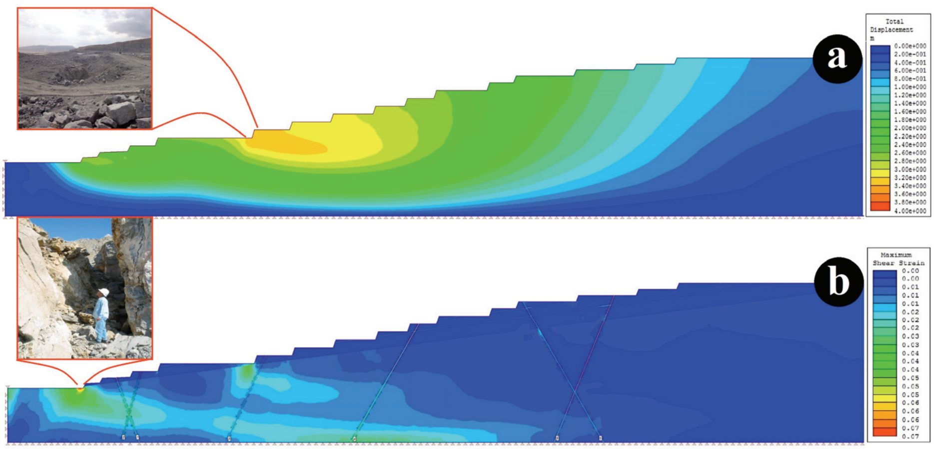

Fig. 10. The FEM model results (shading): a – displacements, b – shear stress

The FEM model (Fig. 10) shows a well-developed shear stress area especially in the fractured zone. In addition, maximum shear stresses are distinguished in the marly substratum which explains the 2009 slip causes.

5. CONCLUSIONS AND RECOMMENDATIONS

Several open-cast mines in Algeria are regularly affected by instabilities that severely disrupt the exploitation activity especially Chouf Amar's career where the instabilities are linked to the combined action of several complex factors. In fact, permanent factors (facies, fracturing, morphology...), create indispensable conditions to ground instabilities, and dynamic factors (geometry, design, exploitation, etc.) act under the control of the former and play the role of detonator. In addition, these disorders involve many socio-economic and technical-environmental issues.

In our study we uses a combined-approaches method (geo-mechanics, kinematics, numerical and limit equilibrium) to evaluate the effect of the discontinuities network on the mechanical behavior of the Chouf Amar massif, and to establish a diagnostic on the stability and on the movements amplitudes. Statistical analysis of orientation parameter allowed us to determine five large families of discontinuities present in the facies C1 and four families in C2, C3. The results of the RMR classification revealed that the quarry rock mass consists of low to good quality formations. The results of the geo-mechanical approach show that the quarry suffers from various types of fractures (planar, wedge , tilting) in several directions especially wedege failure. The different modes of potential instability have been characterized using a kinematic analysis. This analysis has confirmed the existence of several wedege failure opportunities at the quarry benches. The planar and toppling failures are generated by the discontinuities at the banks and by the faults and stratification joints at the inter-bank scale. The new directions of the proposed exploitation fronts led to the appearance of topplings in some cases. The limit equilibrium study proves that blasting declines in the values of *Fs*. This is reflected by the appearance of tension cracks influencing the long-term stability. The results of the numerical analysis allowed us to identify the causes of 2009 slip, related to the presence of two major faults upon a marly substratum. Our study has made it possible to optimize operations and to improve career productivity while ensuring the safety of equipment and personnel. It provides a reliable database that will help professionals and decision-makers to better reason their interventions in the field especially in sites lacking appropriate scientific and technical means. Based on these findings, we recommend the following:

Large-scale structural mapping with the aim to achieve structural zoning to implement specific firing plans for each area in order to improve operating performance (avoid oversized) while ensuring stability and safety of the site.

An analysis taking into account the tectonic constraints on the rocky slopes stability could be the subject of a new study.

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