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# SLOPE STABILITY ANALYSIS IN OPEN PIT MINES OF JEBEL GUSTAR CAREER, NE ALGERIA – A MULTI-STEPS APPROACH

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**Abstract:** Several types of instabilities can menace the personnel and equipment in the open cast mines. Their kinematicis dependent commonly on the nature, the structure, the fracturing and the strength of the rock mass. A scientific assessment vis-a-vis their equilibrium is suggested. For this task a considerable amount of field work must already carrying out to supply the necessary data ie: geometric, mecanic and geologic parameters. The main purpose of this research is identifying different modes of slope failures that may develop on the career "ENOF" of Jebel Gustar, by a multi-step analysis. For this task, *i*) a structural analysis; *ii*) an estimation of the rock mass and discontinuity mechanical properties, *iii*) a rating of the rock mass quality, *iv*) and a numerical simulation of the stability are procedurally used. The results matched well with the field observations. They proved the poor stability of the career, showing a typical example of a bad slope-design. The application of such approaches can help stabilizing the mine and ensure the safety and a sustainable production.

***Keywords***: *geomechanics, planar, toppling, wedge, finite element method, kinematic.*

## INTRODUCTION

The extractive industry is considered as a fundamental sector in the economic growth of Algeria. The activity of exploitation can causes varied types of instabilities in open pit mines, especially when their schemes of development does not depends on scientific process (Gadri et al. 2015, Hadji et al. 2016). To evaluate the design perfor-

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mance of quarry; adaptive studies, from local bench design to overall stability of quarrie edges is required. This procedure involves the integration of various types of analytical and numerical analysis ranging from limit equilibrium analyses to finite elements simulation, which can considers intrinsic conditions of the field and manage mixed failure modes. An appropriate quarry edge design not only leads to enhancements in slope stability and safety but also minimizes charges, prolongates the longevity of mines and reduces the stripping ratio (Karaman et al., 2013). In the geo-mining literature, limit equilibrium calculation, kinematic analysis and rock mass classification systems are the main used methodes to evaluate the slope stability of rock mass in open cast mines. They depends on geological conditions, mechanical parameters, geometrical design and discontinuities characteristics (Brady and Brown, 1993). Each method has advantages and inconvenience. Limit equilibrium methods are used to assess the slopes stability regardless to slope conditions (Eberhardt et al. 2004). Kinematic analysis methods are mainly based on the bodies motion without taking into account forces action and geotechnical parameters (Kulatilake et al., 2012). Whereas, the rock mass classification system ignore analytical and observational design methods. The compilation of most efficient of these methods in a multi-approach process can overcome these difficulties. For this task our study combines four approachs to evaluate the overall slope stability of Jebel Gustar open-pit (NE Algeria). Empirical, geometric, statistic, geo-mechanical and numerical approachs were used. This approach can open up broad prospects the in open pit walls design and in mining safety improvement. The more important aspects of this research integrates: geology and faulting characterization; rock types joint and features classification; bench design stability; cracking impact on rock strength; laboratory testing of the different rock types, etc. Slope stability analysis is necessary to ensure that the open pit slopes are safe and movements are within acceptable limits

## GENERAL SETTING

With 82 big quarries, Setif province occupies a leader position in aggregates extraction in Algeria. The production exceeds 4 million $m^3$ of crushed stone and gravel; constituting 8.6 % of the overal national production. Jebel Gustar open pit is among the most important career of aggregates. It is situated at 24 km South of Setif city (36°00’ 43.82″N, 05°32′43.99″E), (Fig. 1a). The quarry is operated by ENOF company and extends over 19 ha with an installed production capacity up to 200t/h and an annual production of 350,000 $m^3$. Reserves are estimated at 21 million tons, conferring to the quarry an average life span of 60 years with the actual exploitation rate. The career of Jebel Gustar exploited lead and zinc from 1905 to 1973; where the efficiency of the unit becomes insufficient for the zinc and lead concentrate. So it was decided to convert the mine into aggregate quarry. The limestone deposit have a hardness ratio between 5 and 6 according to Protodiakonov scale.

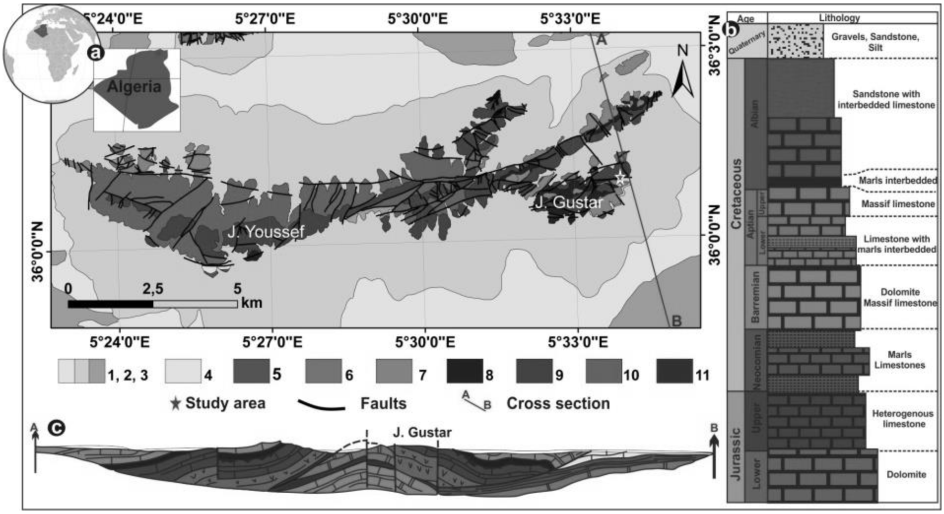


Fig. 1. a – Geographical location and the Geological map of the study area;
b – Stratigraphic column of the study area, c – Geological cross section in the study area
1; 2; 3 (Q) : Quaternary: Gravelus, Sandstones, Silts; 4(c12): Cenomanian–Turonian: Limestones with interbedded Marls; 5(n6): Albian: Sandstones with interbedded limestones ;6(n5): Aptian: (lower) Limestones with interbedded Marls; (Upper) Massif Limestones; 7(n4): Barremian: Dolomite, Massif Limestones; 8(n1-3): Neocomian: Marnl, Limestones; 9(J6): Upper Jurassic: heterogeneous limestones; 10(dJ): Lower Jurassic: Dolomites; 11(φ):Silicified and mineralized rocks (Cu)

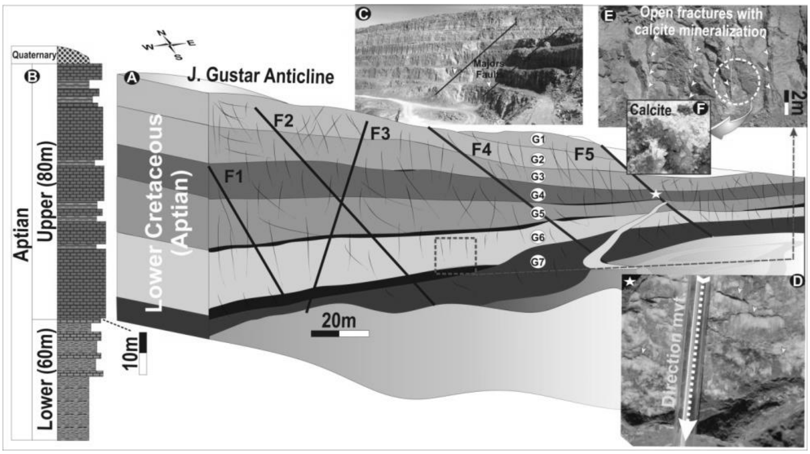


Fig. 2. a – Panoramic view of Jebel Gustar career; b – Litho-stratigraphic column;
c – Photography of the study site; d – Direction of the blocks movement;
e – fractures with calcite mineralization; f – Calcite crystals

The study area belongs to the Northestern Algeria Atlas chain. It inherited from Triassic to middle Cretaceous rifting periods related to the opening of the southern

Tethyan margin (Guiraud et al., 2005). Tethyan extensional structures of the Algerian Atlas (South Setefian alloctonous unit) have been reactivated during lower Cretaceous. Jebel Gustar ended the massif of Jebel Youssef from the Southeast (Fig. 1a). It reveals an NE-SW anticline structure with 10° to 45° dip. The stratigraphic serie consists on an alternation of carbonate formations, ranging from Jurassic to Holocene (Fig.1b,c). Quaternary covers the Aptian formations on slopes. It consists of boulders and, sand, and gravel.

The wall of the quarry is composed of thick limestones layers with *Orbitolines* (≈32 m), topped by a metric massive gray limestone intercalated by thin marl beds. And ended by limestones in benches (≈17 m) with some marl levels (Fig. 2b). The Aptian limestones are locally Pb, Zn, Fe, Cu mineralized and constitute the formation actualy exploited (in seven benches, G1 to G7) (Fig. 2a).

The study site is crossed by two faults groups with Cretaceous age and NW-SE, NE-SW orientation (Fig. 2c,d). They are characterized by an intense grinding with striated plane and calcite mineralization (Fig. 2e,f). The oldest fractures are composed of joints/veins strik, which are related to an early Cretaceous tectonic that affected North Africa. A recent ones striking mainly E-W has been tentatively related to the late Cretaceous flexural evolution of the study area.

The elevation in the study area ranges from 906 to 1,437 m asl in Jebel Youssef. The climate is semi-arid, characterized by a dry-hot summer and a cold-rainy winter. December is the wettest month with 39.3 mm, and July is the hottest (26.3°C).

## MATERIAL AND METHODS

In this study, a combination of four approaches have performed to assess slope stability in open pit mines and applied in Jebel Gustar career, as is explained in fig. 3.

The first step consist on data acquisition, along the wall working side of the career. The sampling method is that of usual traverses data (Hadjigeorgious et al., 1995). All discontinuity characteristics were plotted on an atribute table. A directory of azimuths and dips of discontinuities identified across the working face has been established. The orientations of fractures (direction/dips) are measured using a standard "Brunton" compass. The measurement of the opening is carried out perpendicular to the wall and that of the persistence on the height of the bench. The spacing is measured between two successive fractures along the orientation line (Priest, 1993). The roughness is estimated by comparing the appearance of the discontinuity surface with standard profiles published by Barton (1978), and the alteration according to the classification of Barton (1974). The RQD (Rock Quality Designation) is determined on the basis of a series of carrots boxes obtained from the exploration drilling performed by ORGM. To determine the physico-mechanical parameters, many compression tests were performed in the laboratory on intact cylindrical samples of 148mm length and 74mm diameter. The density was calculated for each sample by immersion.

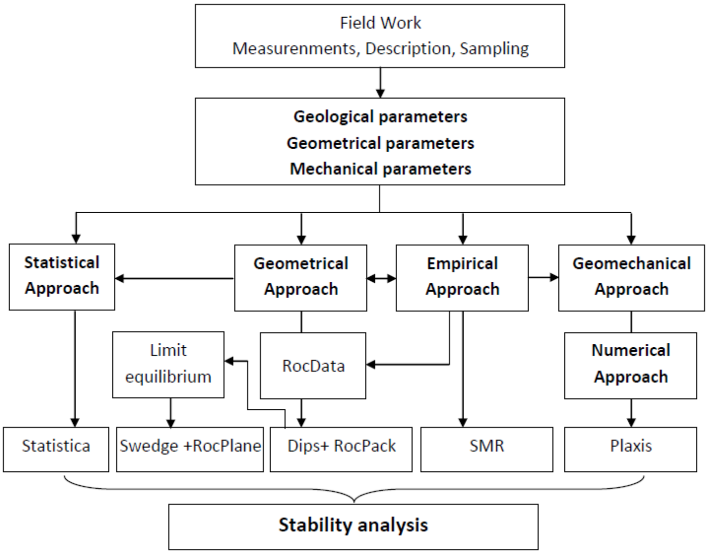


Fig. 3. The methodological chart of the used approach in the study

The geometric approach was largely exploited (Martin, 2000). The use of the stereographic projection allows interpretation of the structural data obtained from the first step (Goodman, 1989) For this task DIPS V.5.1 software is used to identify the joint sets for the stability analysis and rock type of interest. The kinematic study uses RocPack software, for the visualization of the preferential discontinuities and instability modes such as planar, wedge and toppling failures. The mechanic characteristics of rock are calculated using Rocdata software.

The use of the limit equilibrium methods allows to quantify the rock mass stability, with a safety factor assessment. The required data in this approach are based on the results obtained from the geometric approach. Use of Swedge, Rocplane software proves to be effective to evaluate deterministically the possibilities of developing a planar and/or wedge faillures within a rock mass. In this analysis, a safety factor of 1.3 was used as the limit between the stability and instability (Hook et al. 1995).

The statistical analysis (Dezayes, 2007) of discontinuities parameters (orientation, spacing, opening fractures and persistence) allows to discriminate and quantify each of the sets defined in the kinematic study, using STATISTICA 8.0 software.

The results of the previous step are used in the third step in assessing the career slope stability. This empirical approach uses mainly RMR, GSI and SMR, (Bieniawski, 1976; Romana 1985; Hoek and Brown, 1997) classification systems:

- The RMR classification (Rock Mass Rating), evaluates the properties/characteristics of each of its basic parameters by a rate. This system includes five parameters such as: *i*) the uniaxial compressive strength of the rock, and *ii*) the value of the index RQD for rock mass, *iii*) the spacing of the discontinuities, *iv*) the state of discontinuities, and *v*) hydraulic conditions. The sum of these coefficients determines a unique description of the RMR (number between 0 and 100);
- The GSI index (Geological Strength Index) is based on field observations of the rock mass structure and determined empirically by an *in situ* visual-examination of the rock mass quality. Its rate is ranging from 5 and 85. The SMR classification (Slope Mass Rating), is obtained by applying the RMR system and using adjustment factors that rely on the relation between the slope and the joints, yet another factor depends on the method of excavation as follows:

$$SMR = RMR_{basic} + (F_1 . F_2 . F_3) + F_4 \qquad (1)$$

$F_1$ – depends on the angle between the joints direction and the slope: $F_1=(1\text{-}\sin A)^2$;
$F_2$ – depends on the dip angle of joints in the plane failure mode;
$F_3$ – related to the angle between the slope and the dip of the joints (Bieniawski, 1976);
$F_4$ – is an adjustment factor depending on the slope excavation (Romana, 1993).

The SMR system classify the rock into five classes showing their stability, potential failure modes and recommended retaining structures.

The numerical approach is based on the method of finite elements operates the Plaxis software by exploiting geotechnical toolsavailable in this code. It allows us to model the realistic deformation characteristics and to simulate the behaviour of the career.

The mechanical parameters required for modeling are derived from the empirical relationships of the RMR system (Ozturk, 2013). Thus the massif properties are determined by equivalent characteristics. The Eq. (2, 3, 4) determine the equivalent Young's modulus ($E_{eq}$), cohesion ($C_{eq}$) and the internal friction angle ($\varphi_{eq}$) of rocks:

$$E_{eq}\ (\mathrm{GPA}) = 10^{(RMR-10)/40} \quad \text{(Serafim and Pereira, 1983)} \qquad (2)$$

$$C_{eq}\ (\mathrm{kPa}) = 5\ RMR \quad \text{(Bieniawski, 1976)} \qquad (3)$$

$$\varphi_{eq}\ (\mathrm{deg}) = 0.5\ RMR + 8.3 \pm 7.2 \quad \text{(Trunck and Hönisch, 1989)} \qquad (4)$$

We notice the close similarity of prediction of the four approaches both on the level of statements of problems and the interpretation of results. Their comparison allows the assessment of the slope stability of the quarry.

## RESULTS AND DISCUSSIONS

### GEOMETRIC APPROACH

Results of the geometric approach shows that the formation currently exploited dips toward South, according to the opening mode of the career. This parallelism helps the triggering of planar type of instability. The statistical compilation of a set of 312 single or multiple discontinuity identified along the working wall of the career reveals four main sets of discontinuities (Figs. 4 a,b,c,d). Measurements identifies five major faults with directions ranging between 120° and 192°.

Sampling were compiled and processed in DIPS 5.1. Results are reported in table 1.

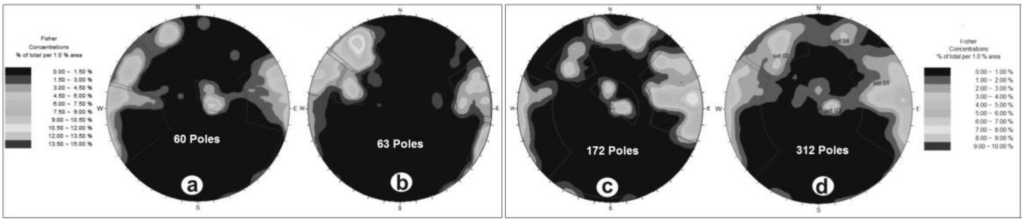


Fig. 4. Stereographic projection of discontinuities poles: a – Interbedded limestone, b – Massive limestone, c – Limestones with Orbitolines d – Front edge of the career

Tab. 1.Orientation of discontinuity sets

| | Interbedded limestone | | Massive limestone | | Limestone with Orbitolines | |
|---|---|---|---|---|---|---|
| | Dip(°) | Dip direction (°) | Dip(°) | Dip direction (°) | Dip(°) | Dip direction (°) |
| Set 1 | 21 | 240 | 76 | 144 | 77 | 260 |
| Set 2 | 79 | 121 | 85 | 114 | 12 | 122 |
| Set 3 | 89 | 83 | 78 | 259 | 79 | 189 |
| Set 4 | 82 | 154 | 58 | 113 | 64 | 141 |

The kinematic analysis was used to determine the various failure modes such as planar, weidge, and toppling failures (Figs. 5 b,c,d). The stereographic projection represents discontinuities, slope orientations and the friction angles. The results of this analysis are summarized in table 2.

Tab. 2. Failure modes compilation, according to the kinematic analysis

| | Planar failure | Wedege failure | Toppling failure |
|---|---|---|---|
| Interbedded limestone | - | F2&F3 | F3 |
| Massive limestone | - | F2&F3. F1&F2. F1&F3 | F2 |
| *Orbitolines* Limestone | F3 | F1&F3. F4&F3. F1&F4 | - |

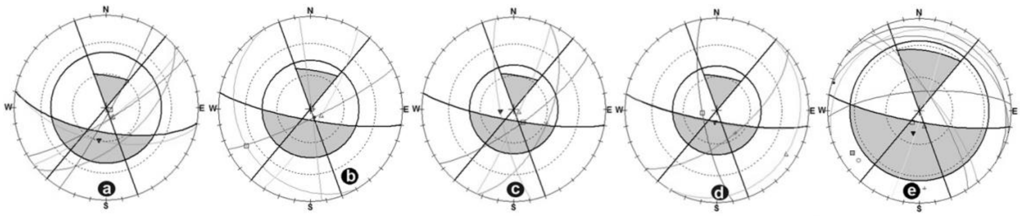

Fig. 5. Stereographic projection of failure modes: a – Faults sets, b – Interbedded limestones, c – Massive limestone d – *Orbitolines* Limestone e – Front edge of the career

Note here, that the toppling cases, indicated in table 2, have so far involved in only small volumes which can be retained by the security berms. The figure 4d shows concentration poles for the career slope corresponding to the four discontinuities sets. A dip of 82° and a dip direction of 264° for the set 1, (75°/145°) for set 2; (16°/262°) for set 3: and (78° /199°) for set 4.

Discontinuity planes are represented by their poles. The line on which the poles are drawn is turned until the two poles lie on the same large circle. The pole of this circle defines the intersection line. The evaluation of the stability relates to a slope of 80°, dips of 190° and a friction angle of 25°. According to measurements, we can project the poles of the four sets in addition to the pole of the stratigraphic joint with a dip of 18° and a direction of 205°. The intersection lines is defined in figure 5e. The most critical combinations are represented by poles [1, dipping 78° towards 209°], [2, 76°/160°], [3, 69°/192°] which are located in the shaded area favouring wedge failure.

The results obtained from the equilibrium limit analysis are summarised in table 3 and illustrated in the figure 6a. An interesting fact to note is that when the safety factor obtained was less than 1.3 (0.633 in our case). The evaluation of the number of active bolts necessary for the retaining is available using the software, (20 meters of length and 32 tonnes of capacity). Regarding to the *Rocplane* software analysis, a single case of planar failure was identified in *Orbitoline* limestones (Fig. 6b). A safety factor of 0.163 requires a single bolt with the same features mentioned above.

Tab. 3. The main results on the wedge failures possibilities

| | Wedege failure | Sliding on line | *F*s without bolt | bolts *F*s >1.3 | Weight (t) |
|---|---|---|---|---|---|
| Interbedded Limestone | F2/F3 | 170/74 | 0.679 | 1 | 40 |
| Massive limestone | F1/F2 | 190/70 | 0.973 | 1 | 112 |
| | F2/F3 | 194/63 | 1.260 | 1 | 55 |
| | F1/F3 | 199/67 | 0.633 | 4 | 154 |
| Limestone with Orbitolines | F1/F3 | 231/75 | 0.266 | 11 | 158 |
| | F1/F4 | 189/54 | 1.020 | 1 | 64 |
| | F3/F4 | 189/79 | 0.634 | 3 | 32 |

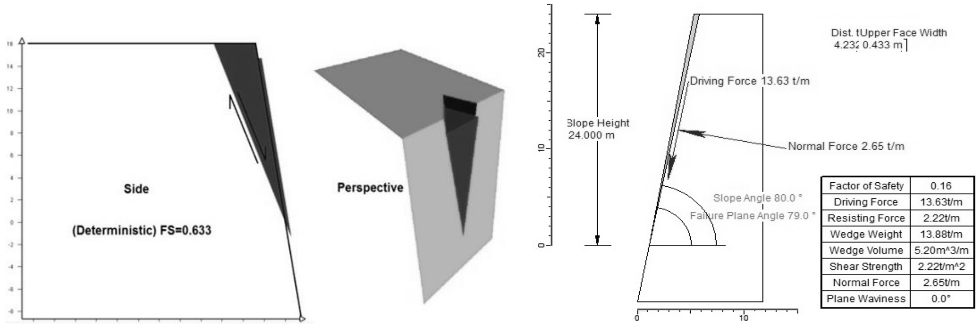


Fig. 6. Models of different failure modes. a – Failure model using Swedge software, b – Failure model using Rocplane Software

STATISTICAL APPROACH

The statistical analysis allows the comparison of different parameters of discontinuities with the variations of structural conditions observed during the sampling work. The analysis of the results of each of the discontinuities sets defined in the previous approach quantifies their orientation, openness, persistence and spacing for the whole site. The orientation of the predominant set in the career (set 1) is 174 (Fig. 7a). This direction is parallel to the fold axis of Jebel Gustar which is the result of North-South compressive stresses closely linked to the Atlasic chain genesis.

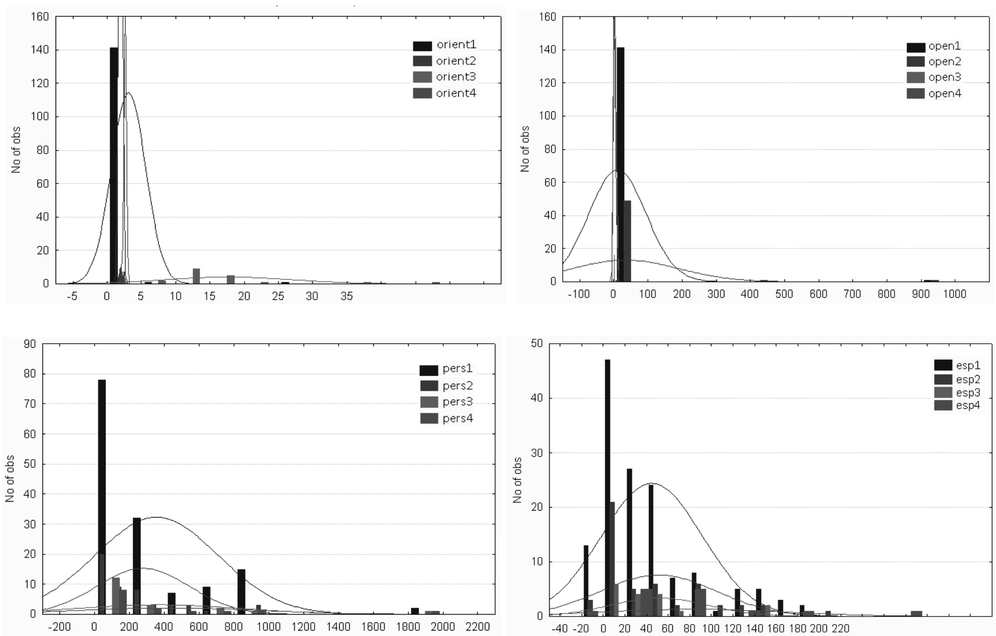


Fig. 7. Geometric parameters of discontinuities. a – orientation, b – oepning, c – persistance, d – spacing

According to the description suggested by ISRM (International society of Rock Mechanics), the rock mass is cut into blocks of various shapes and wedges because the quarry slope has more than three discontinuities sets that intersect. This geometric condition increases the possibilities of potential sliding along joints. Especially since the opening histogram shows openings more large (≈30 mm) in First and second sets, followed by third and fourth ones (with an average 20 mm), (Fig. 7b).

The persistence histogram (Fig. 7c) shows that the set N°1 is the most dominant with a main value over 3.5m (30 samples). The set N°2 has an average of 0.20m while the minor persistence corresponds to the set N°4. The spacing histogram (Fig. 7d) shows a single mode with a maximum on the set N°1 which is the most dominant (main value of 40 cm corresponding to 48 samples). The sets N° 2 and 3 have an average spacing of 50cm.The toppling failures are critical when all fractures are characterized by continuity of over 10 meters and a spacing of less than 2 meters. The sets N°1, 2 and 3 have an average spacing less than two meters. They can potentially generate failures with small volumes which can be damped by the security berms.

## EMPIRICAL APPROACH

The results of the empirical approach (table 4), shows that the career presents a risk of instability with plane and wedge failure modes, especially in marl intercalations. The results of the numerical approach are expressed as total displacement, shear stress and shear strain plastic points. This highlight the behaviour of the whole wall and of each edge. For the initial conditions, the displacements are fixed as nil and the initial stresses are equal to the stresses generated by the ground under its own weight. Mohr-Coulomb law and equivalent carachteristics were used (four settings + dilatancy).

Tab. 4. RMR, GSI classification of rock mass formations, SMR classes description

| | Interbedded limestone | Massive limestone | Limestone Orbitolines | Marl |
|---|---|---|---|---|
| Uniaxial compressive strength | 7 | 7 | 7 | 2 |
| RQD | 13 | 13 | 13 | 8 |
| Spacing between discontinuity | 20 | 20 | 20 | 5 |
| Condition of discontinuities | 6 | 12 | 20 | 6 |
| Goundwater in joint | 15 | 15 | 15 | 15 |
| *RMR* | 61 | 67 | 75 | 36 |
| SMR | 41.7 | 47.7 | 55.7 | 16.7 |
| Description | Fair | | | Bad |
| Stability | Partially stable | | | Unstable |
| Failure | Some joints or many wedges | | | Planar/wedge |
| Support | Systematic | | | correctif |
| GSI | 56 | 62 | 70 | 29 |
| Rock mass quality | Medium | | Good | Bad |

## NUMERICAL APPROACH

The table 5 shows the values of the rheological and intrinsic characteristics of the various formations of the quarry. The model is calculated in bidimensional plane strain in the cross section of a slope. It consists of 4989 triangular elements at 15 nodes. After observing the results obtained by (2D) modeling and the graphs of displacement, several outcomes can be determined.

Tab. 5. Physical and mechanical parameters of rock mass in the career

| Mohr-Coulomb | | Limestone orbitolines | Massive limestone | Interbedded limestone | Marl |
|---|---|---|---|---|---|
| $\gamma_{unsat}$ | kN/m³ | 26.000 | 25.700 | 25.000 | 19.000 |
| $\gamma_{sat}$ | kN/m³ | 27.000 | 26.560 | 25.500 | 21.000 |
| $E_{ref}$ | kN/m² | 42.170 | 26.610 | 18.840 | 4.470 |
| N | - | 0.230 | 0.250 | 0.280 | 0.400 |
| $G_{ref}$ | kN/m² | 17.142 | 10.644 | 7.359 | 1.596 |
| $E_{oed}$ | kN/m² | 48.887 | 31.932 | 24.085 | 9.579 |
| $c_{ref}$ | kN/m² | 375.000 | 335.000 | 305.000 | 180.000 |
| Φ | ° | 53.000 | 49.000 | 46.000 | 33.500 |

It was observed that under the influence of their own weight, the upper benches of the slope are unstable with a metric displacements (Ux, Uy) giving a maximum value in the edge N°6, (Fig. 8a). This movement is due to the plane and toppling failures. The reduction of the friction values in the limestone marl interface causes an increase in the displacement. The shear deformation show extreme values along the marl joints, especially in the first joint intersecting the bench N°1. The second joint produces also an acceptable values, but less than the previous one. The two remaining joints are relatively stable (Fig. 8b).

The evaluation of the shear stress is required in our case. The shear strength can be defined as the stress along the failure plane at the breakage time. It is clearly too high (higher RC) in the base of the slope and along the marly joint intersected with the first bench (Fig.8c). The maximum extensional deformations appear in the same places where we can see the initial crack (at the lower base and in the first marly joint). Plastic points are denoted as plastic failure point. If it is currently on the Mohr-Coulomb envelope at the undergone irreversible deformations. If they exceed the Mohr-Coulomb envelope the deformation becomes clear. The tension cut-off points are concentrated in the upper and lower tiers (Fig. 8d).

A whole slope stability/design requires consideration of a large number of geological, geotechnical mechanical and operational factors. The use of a single model, do not provide a reliable solution to open pit slope stability. The study of the slope stability analysis should always be considered in association with comparative approaches and should be checked wherever possible by analysis of displacements and slope failures. A slope stability calculation should never be treated as an end in itself but rather as a contribution to the overall.

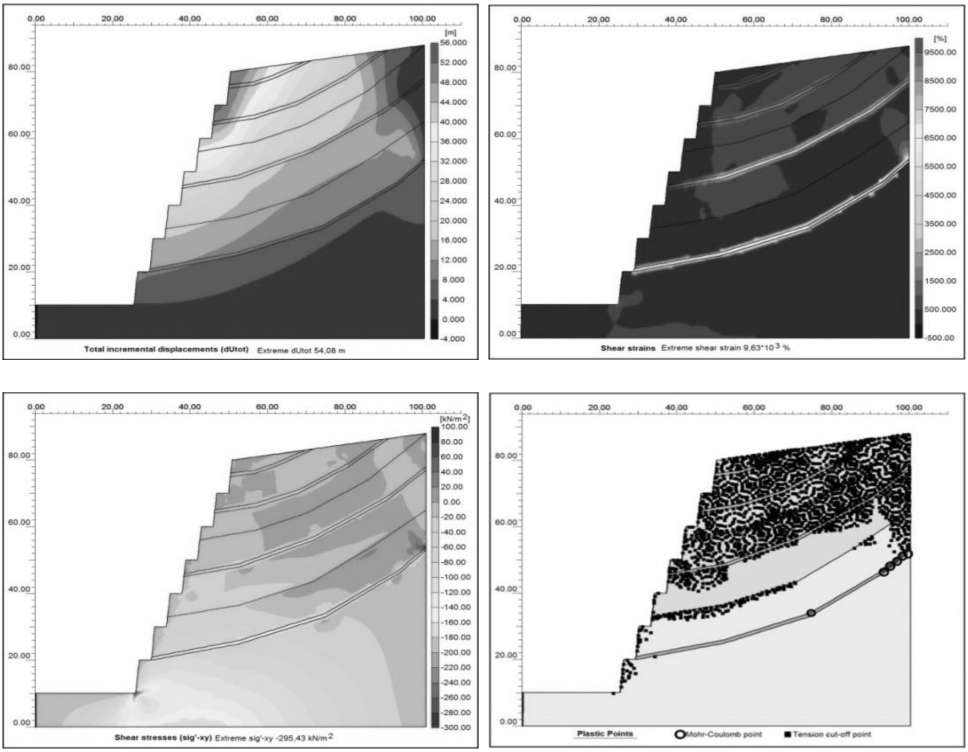


Fig. 8. a – Total incremental displacements of the studied profile; b – Shear deformations; c – Shear stresses; d – Plastic points in the studied profile

## CONCLUSIONS AND RECOMMENDATIONS

ENOF/Jebel Gustar open pit is the largest Aggregate career in Setif province and it is situated on the eastern limb of Jebel Youssef. The major discontinuities reflect the tectonic history, the four main joint sets having no obvious relation with rock types. Five intersecting fault sets are continuous throughout the pit. Geological and geotechnical data at the pit has been obtained by mapping faces and from exploration drill-holes and from blastholes. A number of uncertainties and practical problems in using statistical, geometrical, empirical, geomechanical and numerical processing have been addressed in this paper. An attempt has been made to provide a rigorous method for analysing slope stability in open pit mines. This method have been depeneds in numerical softwares such as RocData, Swedge, RocPlane, Dips, RocPack, Plaxis, Statistica, etc. This programs includes tables, diagrams, charts and rosette for estimating the necessary parameters for the study. The method compiles four separate approaches to predict the behaviour of a potentially unstable slope. This allows identifying diverse failure modes that may develop in the pit. The geometric approach distinguishes four major discontinuity sets. The kinematic analysis revealed eight possibilities of wedge failures. The sole case of plane failure can be initiated by the fault N°3 (80/142). Toppling failures have tended to be small and are only likely to cause failure of a single bench. They have so far involved a fall of undersized rocks volumes that can be retained by berms. Different potential failure modes can be deduced by the kinematic analysis in the geometric approach. Thereafter, each failure potential has been studied using the limit equilibrium method. Swedge program was largely utilized for analysing wedge failures and Rocplane program for the planar breakdown. This allows the identification of seven circumstance of wedge sliding, and just a sole likelihood of planar breakdown (in Orbitolines limestones). The statistical processing of algebraic data of discontinuities allows the quantification of their geometrical trend based on the ISRM catalog. It clearly shows the possibilitiy of a toppling failure mechanism and that the orientation of the prevailing discontinuity sets is analogue to Jebel Gustar fold axis. The empirical approach reveals a mediocre stability of the career. Hence planar and wedge failure modes, can develop in marl intercalations, who! the critical joints on the highwall require monitoring. In this connection, a rigorous MEF data analysis (by means of the Plaxis modelling), was undertaken on the hangingwall to assess aspects of stability on bench, stack and overall slope angles. This proved a critical displacements, stress and plastic deformations in benches. The Comparison of this multi-steps approach results, confirms the poor stability in the Jebel Gustar career. The finding of this study were make sure by a post verification in a greater scale along Jebel Youssef structure. The recognition of variations in rock mass quality and different types of slope failure has meant that slope design has not been tailored to suit the geological conditions.

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