Al-Nahrain University, College of Engineering Journal (NUCEJ) Vol.19 No.1, 2016 pp.33 - 45

Determination of the Safe Orientation and Dip of a Rock Slope in an Open Pit Mine in Syria Using Kinematic Analysis

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Abstract:

This paper presents a method for choosing the orientation and the dip of an excavated rock slope, to safely serve the intended function of the slope or the excavation.

The investigated slope is a rock slope in an open pit mine in Knifes, Syria.This mine is a phosphate mine. The phosphate is covered with the sedimentary organic limestone rocks, which are the subject of this research.

The kinematic analysis method is adopted here to analyze the slope stability. This method uses stereographic projection principles and applies them in rock slope stability analysis. Open Stereo program of stereographic projection was used to obtain the required projections.

A particular case study was performed in order to ensure that the studied part of the slope is safe, and a general case study was performed to present a suggested procedure for choosing safe dip and dip direction to the face of the studied slope.

In this research, the results present the possible choices of the orientation and the dip of the excavated rock slope, to enlarge the open pitmine safely in future.

Key Words: Rock Slope Stability, Kinematic Analysis.

1- Introduction:

Open pit mines are large rock excavations that are usually intended mainly to strip away rocks from the required material,(such as phosphate). Most of the slopes of open pit mines are temporary, since the pits are ever enlarging. However, slopes of the cut should be designed to be absolutely safe during the work in the mine. Choosing safe angles for rock slopes requires that shear strength characteristics of the controlling discontinuity surfaces to be evaluated, but only minimal reference is made to the strength parameters of the rock, because the principal considerations are the orientations of the planar weaknesses in relation to the orientation of the excavation. However, if the strike of the excavation can be altered to suit the structural properties of the rock mass, it is often possible to choose an orientation for the excavation such that rock failure cannot occur, regardless of friction angle of the discontinuities. This is true because of the highly directional characteristics of failure modes along structural weakness planes [1].

2- Research purpose:

The main objective of this research is to optimizethe excavated rock slopes when enlarging the studied open pit mine.

3- Background:

Early applications of rock slope kinematic analysis were presented by Markland (1972), Hoek and Bray (1981), Giani (1988), Goodman (1989) and others, [2,3,4,1]. The kinematic analysis is performed using the stereographic projection method which is a strong tool to use for systematic data collection and presentation [5].Data required to perform the stereographic projection method are dip and dip direction of each discontinuity. Current kinematic analysis software such as Dips [6], Rock Pack III [7], and Dip Analyst [8] provide easy tools to perform kinematic analyses.

In this research, Open Stereo program of stereographic projection was used to obtain the required projections [9].

4- Stereographic projection:

Stereographic projection is a method to obtain projections of lines and planes that pass through the center of reference sphere, Fig. (1). Dip is the maximum inclination of a structural discontinuity plane to the horizontal, [3]. Dip direction is the direction of the horizontal trace of the dip line, measured clockwise from north. Strike is the trace of the intersection of an obliquely inclined plane with a horizontal reference plane and it is at right angles to the dip and dip direction of the oblique plane. Pole is the point at which the surface of the sphere is pierced by the radial line which is normal to the plane. The horizontal plane through the sphere center is termed the projection plane.

Each plane will intersect with the sphere by a great circle. It is convenient to plot the stereographic projection by tracing from a stereo net, Fig. (2), which is a stereographic projection of a set of reference planes and lines within one of the two hemispheres of the reference sphere [1].

5- Kinematic analysis principles:

"Kinematics" refers to the motion of bodies without reference to the forces that cause them to move [1]. Kinematic analyses concentrate on the feasibility of translational failures due to the formation of day lighting wedges or planes of sliding. As such, these analyses rely on the detailed evaluation of rock mass structure and the geometry of existing discontinuity sets that may contribute to block instability [10]. This assessment may be carried out by means of stereographic projection plots, that are drawn by hand using a stereo net or by a computer program such as open Stereo program, which is used in this research.

For some geometries of slopes and discontinuities, movement is possible (i.e., the system is kinematic ally feasible), and for other geometries, movement is not possible (i.e., the system is kinematic ally infeasible). A method based on checking the kinematic feasibility of a rock slope discontinuity system will provide a "first pass" analysis in a long line of design and analysis tools [11].

When there are multiple sets of discontinuity planes intersecting in oblique angles, kinematic model studies may be helpful in anticipating the most likely pattern of slope failure[1].

6- Rock slope failure mechanisms:

In weak and highly fractured rock masses, it is possible to see a circular slip, like that in soils. Failures involving movement of rock blocks on discontinuities combine one or more of the three basic modes; plane sliding, wedge sliding and toppling [1]. Figure (3) shows the four main types of rock failure mechanisms.

Rock sliding phenomena may be divided into plane sliding and sliding on an intersection line of two planes (i.e., wedge sliding). Plane sliding phenomenon occurs in natural slopes or in slope excavations and in stratified or jointed rock masses where beddings or joint sets have an average dip direction similar to the slope face dip direction [4].

In plane failure, movement of a rock block or mass occurs by sliding along a basal slip plane, while wedge slides can occur when two planes of weakness intersect to define a tetrahedral block [1].

Toppling failure involves overturning of rock layers like a series of cantilever beams inclined steeply into the hillside. Each layer (tending to bend downhill under its own weight) transfers force downslope. If the toe of the slope is allowed to slide or overturn, flexural cracks will form in the layers above, liberating a large mass of rock. If there are frequent cross joints, the layers can overturn as rigid columns rather than having to fail in flexure [1], so there are two types of toppling:

- Flexural toppling:

A discontinuity system, sub vertically oriented and plunging towards the slope, determines semi-continuous rock columns, Fig. (4,a). These columns, when loaded in the upper part by forward thrusts or when weight force falls outside the base tend to bend forward and to break in flexure.

- Block toppling:

Block toppling failure mechanism is shown in figure (4,b). Failure occurs when single rock columns are divided by widely spaced cross joints [4].

7- Kinematic conditions of failure:

Stereographic representation of the structural conditions which can determine a slope instability event is to draw a stereo plot involving the great circle that represents the slope face plane, the circle that represents the friction angle of the discontinuities in the rock mass,the poles of the discontinuities, the contour lines of pole concentrations and great circles that represent main planes of the discontinuity system exposed on the rock face (i.e., great circles that represent planes having poles corresponding to the centersof the main pole concentrations).Figures (5), (6), (7) and (8) illustrate the stereographic representation of each slope instability event of the four principal types of instability phenomena.

Afterthis representation, a discussion of kinematic conditions of failure can be presented.

Note: All of the stereoplots in this research were drawn by OpenStereo program.

7-1-Circular sliding:

For rotational sliding on a circular shear failure surface to be possible to occur, the poles that represent the discontinuities must be scattered, Fig. (5).

7-2-Plane sliding:

A plane sliding forms under gravity alone when a rock block rests on an inclined weakness plane that "daylights" into free space. The inclination of the plane of slip must be greater than the friction angle of that plane [1].

So in plane failure, for movement to occur, the following three basic conditions must be satisfied [12]:

- The dip direction of the slip plane must lie within approximately 20^0 of the slope face dip direction.
- The slip plane must "daylight" (outcrop) on the slope.
- The dip of the slip plane must exceed the friction angle on that plane.

Other factors such as the presence of water, the effect of water pressure and the necessity of lateral release surfaces to exist are ignored in this simple assessment [13].

Figure (6) illustrates the kinematical conditions for the plane sliding to occur. There is one concentration of poles of discontinuities. The center of this concentration is considered the pole of the main plane (P) of this discontinuity group.The point that represents the dip vector (D_p) of the plane of discontinuity (P) must lie on the shaded zone between the great circle of the slope face (S) and the friction circle (ø).

7-3- Wedge sliding:

In wedge failure, movement takes place by sliding along both planes in the direction of the intersection line. For failure to occur, two basic conditions must be satisfied [2]:

- The intersection line must "daylight" on the slope.
- The dip of the intersection line must exceed the friction angles of the planes.

Although this disregards the component of friction acting on both planes and possible water pressures, it is considered sufficiently accurate (and on the safe side) for preliminary assessments [13].

For wedge sliding to occur, the intersection of the two planes (I_{12}) must lie on the shaded zone that bounded by the great circle of the slope face (S) and the friction circle (ø), Fig. (7).

7-4- Toppling:

Toppling may occur when the dip direction of the slope face is approximately towards the opposite orientation of the dip direction of the discontinuity plane, but toppling will not occur when the difference (Δ) between the strike of the slope face and the strike of the plane of the discontinuities is relatively big; say more than 20^o, Fig. (8).

8- Site description:

The investigated site is the open pit mine of phosphate in Knifes, Syria. Some slopes in this mine may reach approximately 50 m height.

Site investigations were performed to determine the types of rocks in the site and to collect the required information and data. The collection of data involved rock mass characterization, field observation, in situ measurements and the sampling of rock materials for laboratory testing.

In this research, the studied rock is the sedimentary organic limestone rock. Figure (9) shows the structure of this rock, that consists mainly of shells cemented by the calcite mineral($CaCO_3$), and shows the multiple discontinuities in the rock mass. Figure (10) presents a zoomed photograph of this rock mass.

9- Laboratory tests:

Samples of the studied rock were brought to the rock mechanics laboratory of Al- Baath University - Syria, and tests were performed according to"American Standardsfor Testingof Materials"(ASTM) (D7263-09,D1558-10, D5779-14) [14],to determine the rock physical properties. Table (1) presents the results of these tests.

The portable rock shear box apparatus was used to determine the rock shear strength, Fig. (11), according to "International Society for Rock Mechanics" standards, ISRM (1974), [15]. The shear strength was presented according to Mohr-Coulomb criterion by the values of the shear strength parameters: the cohesion c and the internal friction angle Ø.Table (2) shows these shear strength parameters.

In kinematic analysis, the main property of rock is the internal friction angle.

10- A particular case study:

A particular case study was performed for a part of the studied slope.

The (dip direction/dip) of the slope face are ($145^0/70^0$), Fig. (12).

There are four discontinuities in the rock mass, have to be checked:

$J_1(145^0/25^0)$, $J_2(040^0/70^0)$, $J_3(200^0/35^0)$ and $J_4(045^0/75^0)$.

J_1 may act as a sliding surface, and J_2& J_3 may act as the release surfaces of the sliding block; if other kinematical conditions are corresponded.

Also, J_3& J_4 may form a wedge sliding block.

Figure (13) shows the stereoplot of this case. To perform the kinematic analysis of this case, the procedure was as follows:

1- The great circles of the rock slop face (S) and the four discontinuities (J_1, J_2, J_3& J_4) were constructed by measuring the dip direction on the perimeter of the stereonet, clockwise from the north; and measuring the dip angle inwards from the outer circle of the net, to get a point that represents the dip vector of the plane, and draw the great circle that passes from it. For example, the point D_{J1} stands for the dip vector of the plane J_1.
2- The friction circle(ø) was drawn having a radius corresponds the angle 90-ø=46^o; measured from the center of the stereonet.
3- The shaded area, in Fig. (13), is the critical zone that satisfies the kinematical conditions of planar and wedge sliding, but the dip vector of plane J_1 does not lie on the critical zone, so the planar sliding in this case is kinematicallyimpossible.
4- After drawing the two great circles of J_3& J_4, that form the sliding wedge, the

intersection line of these two planes was determined. The point I_{34} is the stereographic projection of the line of intersection, and it does not lie on the critical zone; so the wedge sliding in this case is also kinematically impossible.

11- A general case study:

A general case study was performed to determine the safe dip and dip direction of the general studied slope, Fig. (14),when enlarging the open pit mine; and the following procedure was suggested:

1- Site measurements were performed to determine the geological data of the discontinuities in the studied rock mass.Then, the great circlesand the poles of these discontinuitieswere drawn onstereoplots, Fig. (15).

Note: When constructing pole vectors, the dip angle of each plane is measured from the center of the stereonet.Otherwise, $dip_{(pole)}=90-dip_{(plane)}$; and the $dip_{(pole)}$ is measured from the circumference towards the center.

2- It is obvious that the discontinuities may be divided into five groups, Fig. (15).

3- The pole plot, Fig. (15, b), is used to prepare the contour diagram of the pole concentrations, Fig. (16, a), using OpenStereo program.

4- The main planes of the five discontinuity groups (i.e., the great circles that represent the planes having poles corresponding to the centers of the main pole concentrations) were drawn in Fig. (16, b). Table (3) presents the (dip direction/dip) of the five planes and (dip direction/dip) of the poles of these planes corresponding to the centers of the main pole concentrations.

5- The friction circle (ø) was drawn having a radius corresponds the angle $90-ø=46^{o}$,Fig. (17).

6- The intersection lines of these planes (i.e., I_{12}, I_{13}, I_{24}, I_{23}& I_{34}) were determined, Fig. (17).

7- All of the intersection lines (i.e., I_{12}, I_{13}, I_{24}, I_{23}& I_{34}) do not lie on the friction circle; so the kinematical conditions for wedge sliding are not satisfied.

8- The middle of each great circle drawn in the stereoplot, Fig. (17), represents the dip vector of the plane; for example: the dip vector of the plane J_2 is D_{J2},as shown in Fig. (17).

9- All of the dip vectors of the plane discontinuities do not lie on the friction circle except D_{J2}, Fig. (17); so there is only one possible planar sliding on the plane J_2.

10- For planar sliding, one of the kinematical conditions is that the dip direction of the slip plane must lie within approximately 20^{0} of the slope face dip direction; so two planes $J_2'(025^{o}/58^{o})$ &$J_2''(065^{o}/58^{o})$ were drawn in Fig. (18), in order to bound the dangerous zone for the dip vector of the slope face.

11- If the slip plane J_2 daylights on the slope face the dip vector of the slope face will lie on the critical zone (i. e., the shaded area) in Fig. (18).

12- After choosing a dip and dip direction of the slope face, to be excavated when enlarging the open pit mine, the dip vector of the slope face is plotted on the stereoplot, Fig. (18), to ensure that it does not lie on the critical zone, so the slope is considered safe.

12- Conclusions:

1- Kinematic analysis provides a very useful method to determine the possible mechanisms of failure in rock masses.

2- There are specific kinematical conditions of each main case of failure (i. e.,circular sliding, planar sliding, wedge sliding and toppling).

3- In a particular case study, when the slope face is existed and known, a critical zone of planar and wedge sliding have been constructed, and it has concluded that the particular studied slope is safe.

4- In a general case study, when the slope face is unknown and there is a need to choose an orientation and dip for a safe slope when enlarging the excavation; a procedure was suggested, and a critical zone of planar sliding have been constructed. In eachchoice, the slope is considered safe if the dip vector of the slope face does not lie on the critical zone.

5- No possible wedge slidingor toppling in the general studied case, because the required kinematical conditions are not satisfied.

13- References:

[1] Goodman, R. E. (1989), "Introduction to Rock Mechanics", University of California at Berkeley, 562 pages.

[2] Markland, J. T. (1972), "A Useful Technique for Estimating the stability of Rock Slopes when the Rigid Wedge Sliding Type of Failure Is Expected", Imperial College of Rock Mechanics Research Report No. 19, 10 pages.

[3] Hoek, E. and Bray, J. W. (1981), "Rock Slope Engineering", The Institute of Mining and Metallurgy, London, 548 pages.

[4] Giani, P. G. (1988), "Rock Slope Stability Analysis", (transl. from Italian), Balkema, Rotterdam, 345 pages.

[5] West, T. R. and Cho, K. H., (2007), "Rock Slope Stability of the Valdez Marine Terminal (VMT)", The Prince William Sound, Regional Citizen’s Advisory Council (RCAC), 107 pages.

[6] RocscienceD. ,(2014), last accessed:14.1.9 , URL:

[7] http://www.rocscience.com/products/1/Dips.

[8] RockWare RI. ,(2014), last accessed:14.1.9 , URL:

[9] http://www.rockware.com/product/overview.php?id=119.

[10] Admassu Y., (2014), last accessed:14.1.9 , URL:

[11] http://www.dipanalyst.com/.

[12] Grohmann, C. H. and Campanha, G. A., (2009-2015) ," OpenStereo Program", software for structural geology analysis, Institute of Geosciences - University of São Paulo, Brazil, URL:

[13] http://www.igc.usp.br/openstereo.

[14] Eberhardt, E. (2005), "Rock Slope Stability Analysis – Utilization of Advanced Numerical Techniques", Geological Engineering / Earth and Ocean Sciences, University of British Columbia, 41 pages.

[15] Hudson, J. A. and Harrisson, J. P. (1997), "Engineering Rock Mechanics – An Introduction to the Principles", Imperial Collage of Science, Technology and Medicine University of London, UK, 444 pages.

[16] Matherson, G. D. (1983), "Rock Stability Assessment in Preliminary Site Investigations – Graphical Methods", Department of the Environment, Department of Transport, Transport and Road Research Laboratory, Crowthorne, Berkshire, 30 pages.

[17] Simons, N.,Menzies, B. and Matthews, M. (2005), "Soil and Rock Slope Engineering", Thomas Telford Publishing, London, 432 pages.

[18] ASTM (D7263-09, D1558-10, D5779-14), "American Standards for Testing of Materials",annual books of ASTM standards (2009,2010 and 2014).

[19] ISRM (1974), "Suggested Methods for Determining Shear Strength Rock Characterization Testing and Monitoring", International Society for Rock Mechanics, pp. 129-140.

— **Table 1:** Physical properties of the organic limestone

Physical property	Value
Specific gravity	2.627
Porosity	0.142
Void ratio	0.167
Dry unit weight	22.53 kN/m^3
Saturated unit weight	23.96 kN/m^3

Table 2**: Shear strength modules of the organic limestone**

Module	Value
Internal friction angle	44^o
Cohesion	0.3 MPa

Table 3: The data of the main planes of the five discontinuity groups

Group	Dip vector	Pole
J_1	144^o/20^o	324^o/70^o
J_2	045^o/58^o	225^o/32^o
J_3	206^o/29^o	026^o/61^o
J_4	324^o/20^o	144^o/70^o
J_5	143^o/1^o	323^o/89^o

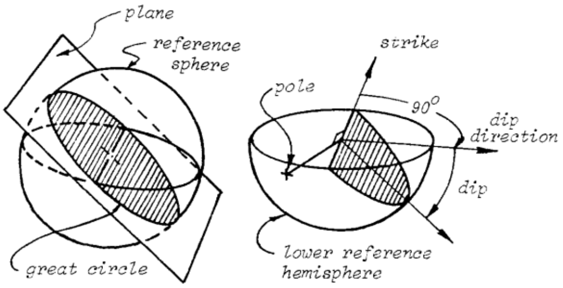


Figure 1: Definition of some geometrical terms [3]

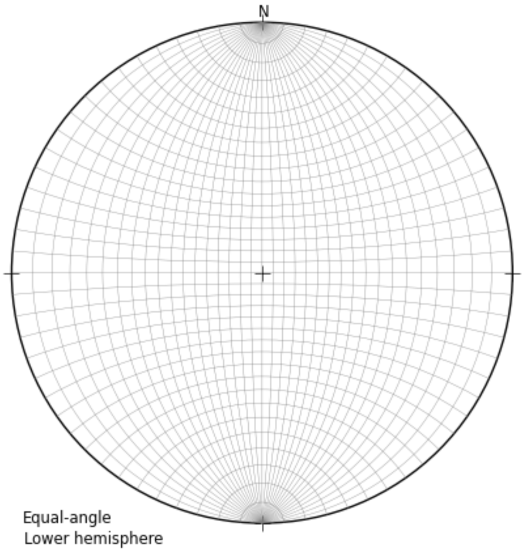


Figure 2: A stereonet drawn by OpenStereo program

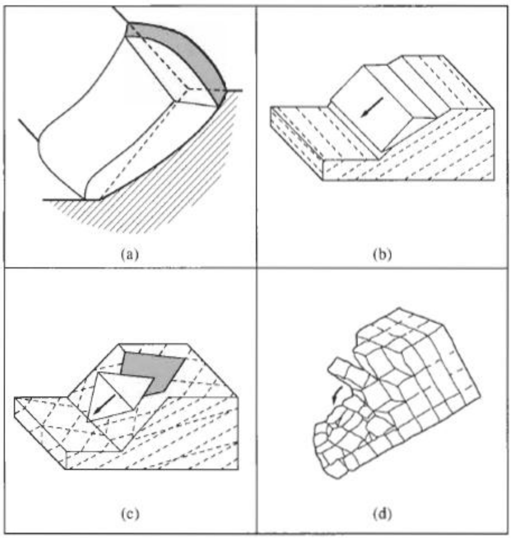
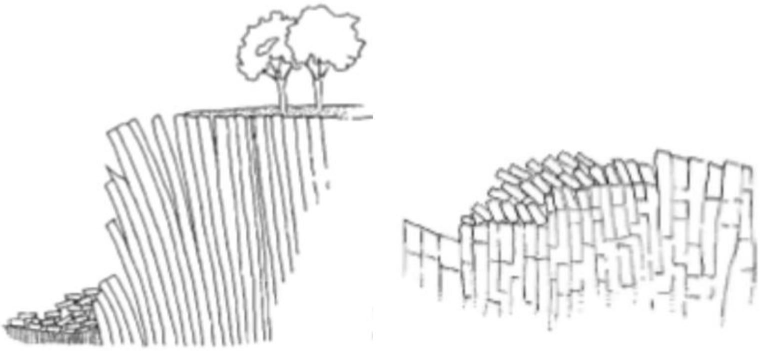


Figure 3: The four basic failure mechanisms:
(a) circular slip; (b) plane sliding; (c) wedge sliding and (d) toppling [12]



a) Flexural toppling **b**) Block toppling

Figure 4: The two types of toppling [4]

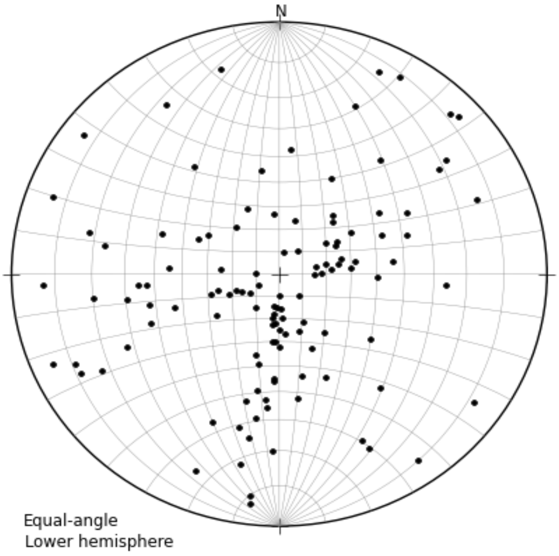


Figure 5: Stereographic representation of circular sliding phenomenon

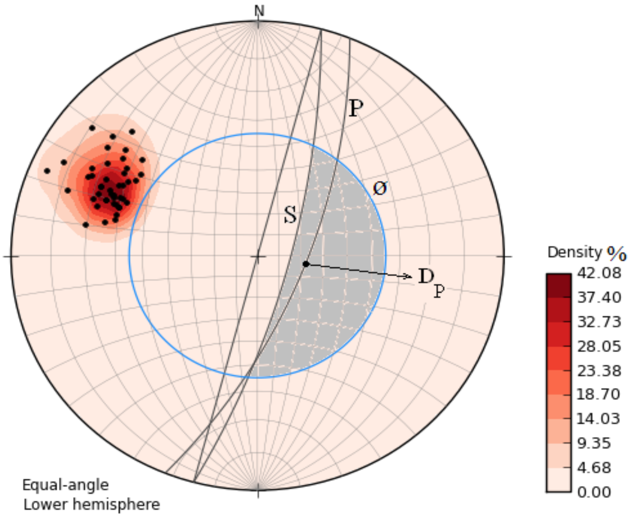


Figure 6: Stereographic representation of planar sliding phenomenon

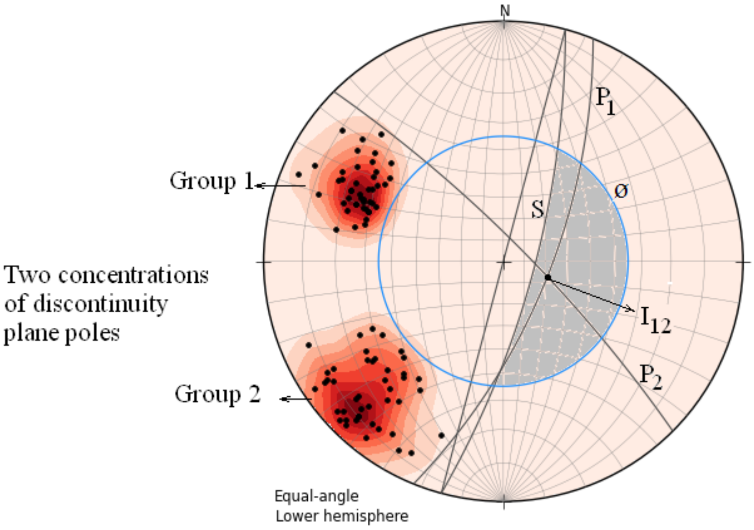


Figure 7: Stereographic representation of wedge sliding phenomenon

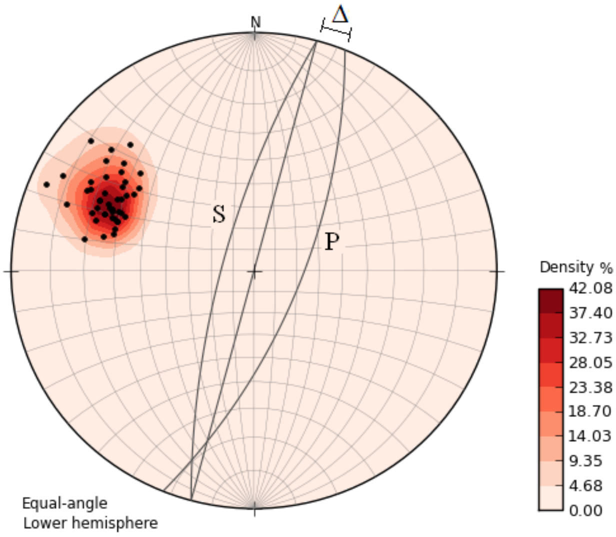


Figure 8: Stereographic representation of toppling phenomenon

Figure 9: The organic limestone rock in Khneifees, Syria

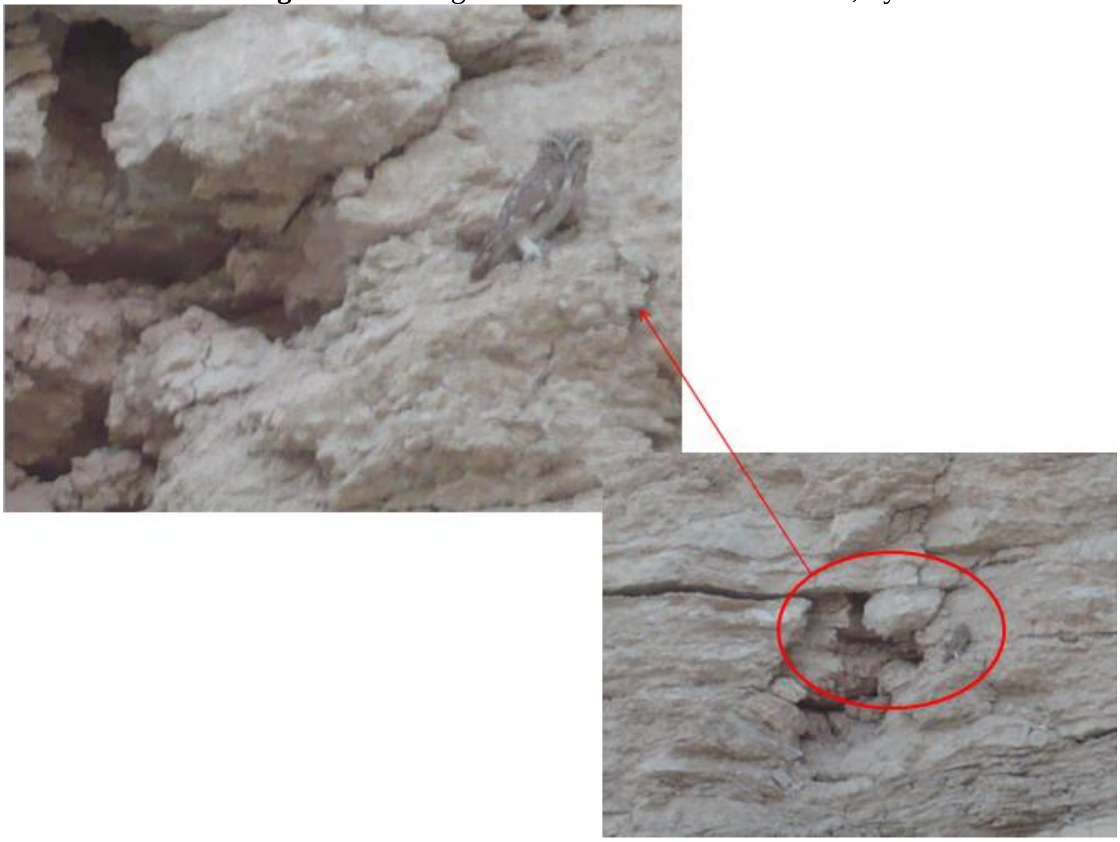


Figure 10: A zoomed photograph of the organic limestone rock in Khneifees mine, Syria

Figure 11: The portable rock shear box apparatus

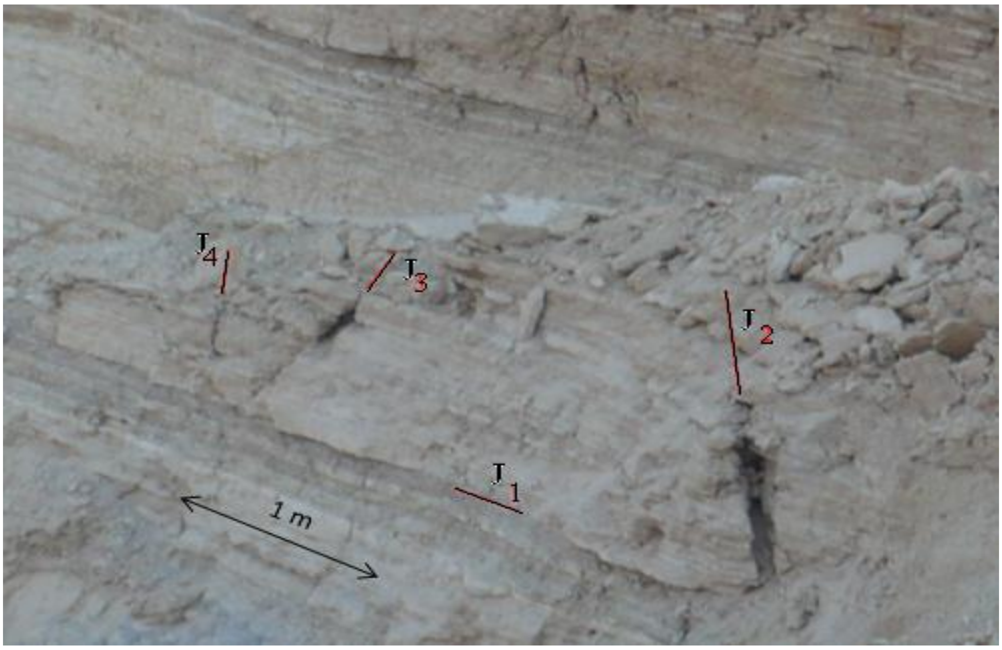


Figure 12: A sliding rock block from the particular studied slope face

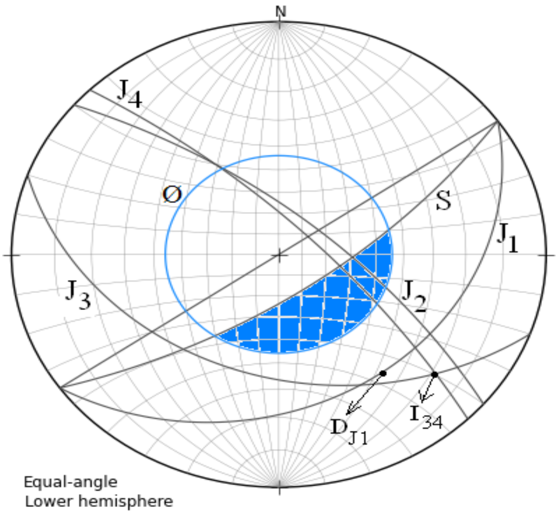
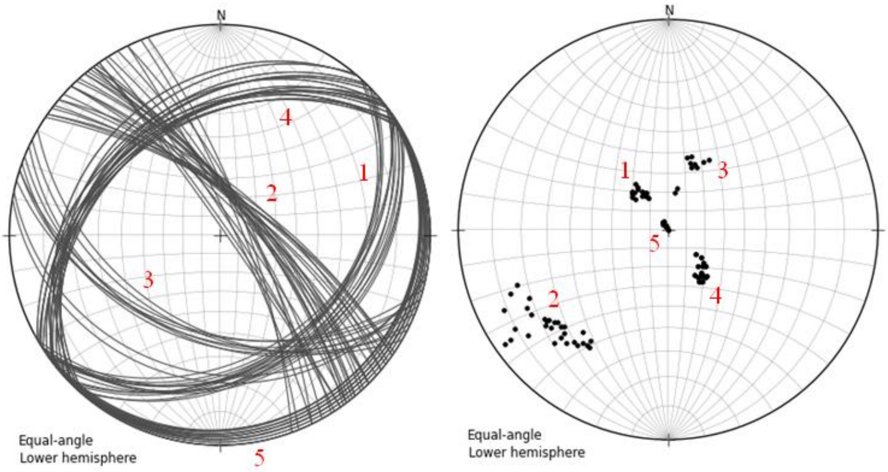


Figure 13: The stereoplot of the particular studied slope

Front view

Side view

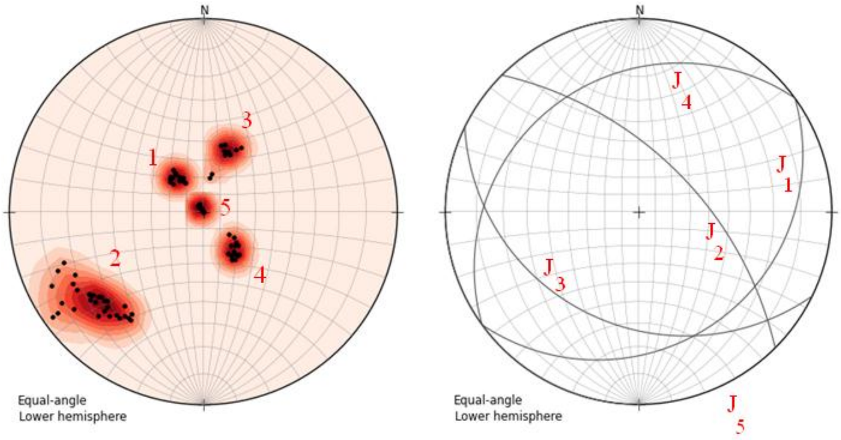
Figure 14: The general studied rock slope



(a)

(b)

Figure 15: The steroplots of great circles (a), and poles of the discontinuities (b)



(a) (b)

Figure 16: The contour diagram of the pole concentrations (a), and the main planes of the five discontinuity groups (b)

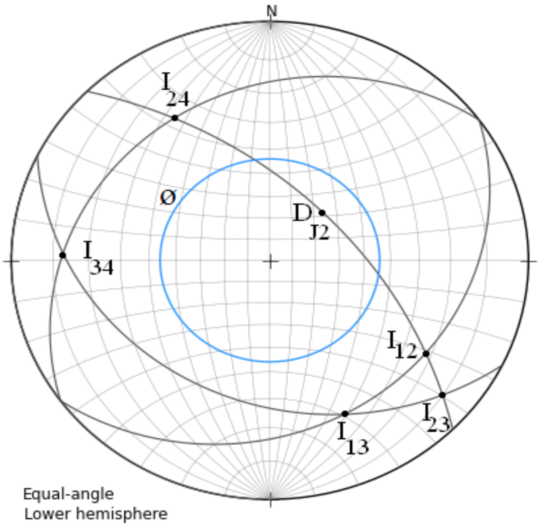


Figure 17**: The stereoplot of the general studied slope**

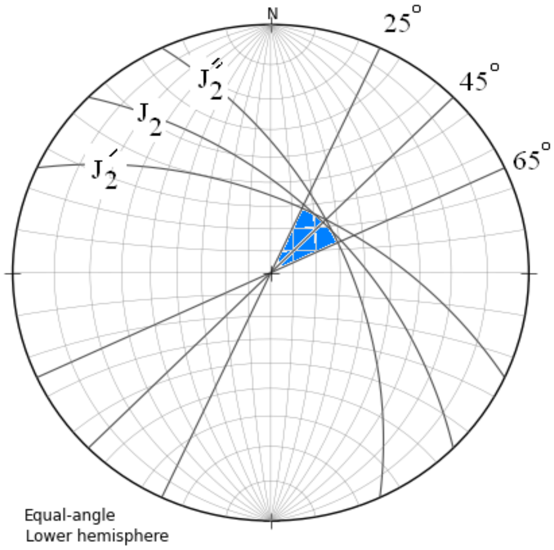


Figure 18: The stereoplot of the potential sliding on plane J_2

تحديدالاتجاه والميل الآمنين لمنحدر صخري في منجم من نوع الحفر المفتوحة في سورية باستخدام التحليل الحركي

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الخلاصة :

يقدم هذا البحث طريقة لاختيار اتجاه وميل منحدر صخري محفور، لكي يخدم الوظيفة المرادة من المنحدر أو الحفرية بشكل آمن.

إن المنحدر المدروس هو منحدر صخري في منجم من نوع الحفر المفتوحة في خنيفيس، سورية.

هذا المنجم هو منجم فوسفات، والفوسفات مغطى بالصخور الرسوبية الكلسية العضوية، التي هي موضوع دراسة هذا البحث.

تم اعتماد طريقة التحليل الحركي (الكينيماتيكي) هنا لتحليل توازن المنحدرات. تستخدم هذه الطريقة مبادئ الإسقاط الستيريوغرافي وتطبقها في تحليل توازن المنحدرات الصخرية، وقد تم استخدام برنامج OpenStereo للإسقاط الستيريوغرافي للحصول على المساقط المطلوبة.

تمت دراسة حالة جزئية للتأكد من أن الجزء المدروس من المنحدر هو آمن، وتمت دراسة حالة عامة لتقديم إجراء مقترح لاختيار ميل واتجاه ميل آمنين لوجه المنحدر المدروس.

تقدم نتائج هذا البحث الخيارات الممكنة لاتجاه وميل المنحدر الصخري المحفور، لتوسيع منجم الحفرة المفتوحة بأمان في المستقبل.

الكلمات المفتاحية: توازن المنحدرات الصخرية، التحليل الحركي.