JOURNAL OF ROCK MECHANICS

VOL. 7, NO. 4 , PP. 73-88.

https://doi.org/10.22034/IRSRM.2024.466658.0411

Slope stability analysis using a distinct element method considering the effects of fluid flow in open pit mines

Mohammad Shekari Nejad[1], Mohammad Fatehi Marji[2]*, Manouchehr Sanei[2]

1. Department of Mining Engineering, Si.C., Islamic Azad University, Sirjan, Iran.

2. Department of Mining and Metallurgical Engineering, Yazd University, Yazd, Iran.

Received: 04. February. 2024 Accepted: 19. March. 2024

(*Corresponding author: mfatehi@yazd.ac.ir)

Keywords

Fluid flow
Slope stability analysis;
Distinct element method
Effective stress
Golgohar mine

Abstract

The groundwater and subsurface flows may cause instability in the open pit mines. The water in pores leads to applying pressure to the rocks, decreasing the effective stress and reducing the shear strength of rock slopes. It means that water pressure causes instability in the benches of open pits. In the present study, we used the versatile and sophisticated distinct element method to investigate the water flow influence on the stability of the pit wall of one of the Golgohar mines, in Kerman, Iran. Numerical results showed that the smaller the distance of the water level from the crest of the first bench of the mine, i.e. the ground level, the higher the amount of flow in the discontinuities. Also, the results showed that the slope's overall safety factor increases with the water level reduction, that is, drainage. For a water level with a height of 57 meters compared to the ground level (the crest of the first bench), the safety factor is estimated to be 0.78. The same issue for a water level with a height of 150 meters shows a safety factor of 1.1, which its safety factor has increased compared to the previous case. The safety factor obtained from the numerical method compared with the results obtained from the Janbu and Bishop analytical methods confirms the validity of the modeling. In addition, the failures in benches indicated, there are planar sliding and toppling occurrences in this mine slope. For this case, it is proposed to decrease the water table level to reach a stable state in this mine.

1. INTRODUCTION

Many factors such as geology, slope height, groundwater pressures, and rock strength affect slope design. When the instability is due to water pressure, it is required and effective to install a drainage system to reduce water pressure. So far, several researches have been done showing the relation between slope angle, geology, and slope height for both open pit mine slopes and natural slopes [1].

Due to the importance of this issue, numerous studies have been carried out considering the slope stability of open pit mines and effective factors on stability. Jiao et al. studied the influence of groundwater on the stability of slopes in weathered igneous rocks in Hong Kong [2]. Predrag et al. investigated the impact of weathering on slope stability in soft rock mass [3]. Rabie studied the slope and compared traditional and finite element methods in slopes that are under heavy rainfall [4]. Zhiguo et al. did the stability analysis of the dike slope in the Bdg reservoir under the seepage of the flood [5]. Shao et al. coupled a dual-permeability model with a soil mechanics model for landslide stability evaluation on a hill slope scale by using the COMSOL Multiphysics software [6]. Gao et al. investigated the index system of rock slope safety for open pit mines by using fuzzy evaluation and the analytic hierarchy process [7]. Zhao et al. improved the method of using a random angle to generate a random sliding surface for stability analysis of complex slopes [8]. Ahmadi-Adli et al. showed the prediction of seepage and slope stability in a flume test and an experimental field case [9]. Setyananda et al. analyzed the Influence of Groundwater Level on slope stability at Highwall, South Kalimantan, the results showed that the reduction of water level caused to increase in the safety factor [10].

Previous studies showed that the stability analysis of the pit mine wall is very complicated, especially by considering the underground water table, on the other hand, due to the anisotropic nature of the rock mass, the studies conducted by others cannot be considered as the best path for new mines. Therefore, it is necessary to follow this issue and determine the stability of the mine wall based on its conditions.

Therefore, the purpose of this research is to do a stability analysis of the mine wall based on the distinct element numerical method. In the aforementioned numerical model, the subject of hydromechanics was followed, and in the mentioned model, the effect of the underground water level on the stability of the mine wall was analyzed. Also, the validation of this numerical model was done by comparison with the results of analytical methods. The results of the research showed that the safety factor of the mine wall increases with the reduction of underground water level, i.e., drainage of the mine.

2. Geological and hydrogeological evidence of the Golgohar mine

From a geological point of view, the Golgohar mineral zone is situated in the southern part of the Sanandaj-Sirjan zone. This zone is a beam from the southwest of central Iran to the northeast of the Zagros' main thrust. This zone is approximately 1500 km long. Due to the existence of several metamorphism phenomena, magmatism, and successive tectonic processes in this zone, it is considered the most unstable geo-structural zone in Iran.

3. Geomechanical characteristics of rocks and discontinuities

To analyze the stability of the mine wall, analytical and numerical methods should be used. To do the numerical modeling of the pit wall, firstly it is necessary to select the type of numerical method and then select and determine the essential modeling parameters. Therefore, these parameters for doing a distinct element analysis are the geomechanical parameters that can show the mechanical behavior of the rock mass. In this research, the Mohr-Coulomb criterion is used to express the behavior of rock mass and calculate the safety factor.

The Mohr-Coulomb model is an elastoplastic criterion that is very important in many topics related to mining geomechanics, geotechnics, and rock mechanics [11]. The Mohr-Coulomb consists of three key principles, namely: (a) the elastic law, (b) the yield criterion., and (c) the flow rule [12].

Therefore, the required parameters such as Young's modulus, Poisson's ratio, density, bulk modulus, and shear modulus were determined for this study. Table 1 shows the geomechanical characteristics of the studied zone and the geomechanical properties related to the joint sets observed in the studied area are presented in Table 2.

Table 1. Geomechanical characteristics of rock in Golgohar mine

Parameter	value
Density	2700 kg/m^3
Compressive strength	164 MPa
Yang's modulus	5 GPa
Poisson's ratio	0.23
Cohesion	1.53 MPa
Friction angle	36 degree

Table 2. Geomechanical properties of joint sets

	J set 1	J set 2	J set 3	J set 4
Dip (°)	85	51	54	8
Dip direction (°)	110	215	8	250
Joint persistence(m)	15	12	13	14
Spacing(m)	0.6	1	1	1
Cohesion (MPa)	0.33	0.33	0.33	0.33
Friction angle (°)	26	26	26	26

4. Geomechanical characteristics of rocks and discontinuities

The limit equilibrium method (LEM) is a powerful tool for solving many engineering problems. Several LEM methods have been developed for slope stability analysis. Fellenius [13] introduced the first one, referred to as the Ordinary or the Swedish method, for a circular slip surface. Bishop [14] advanced the first method introducing a new relationship for the base normal force. The equation for the FOS hence becomes non-linear. At the same time, Janbu [15] developed a simplified method for non-circular failure surfaces, dividing a potential mass into several vertical slices. The generalized procedure at the same time developed the simplified method [16]. Later, Morgenstern-Price [17], Spencer [18], Sarma [19], and several others made future contributions with different assumptions.

4.1. Janbu's method

In Janbu's method the failure surface is divided into some slides and then calculations are done for each slide using the following equations:

$$X_i = \left[\acute{C}_i + (\gamma\, h_i - \gamma_w h_w)\tan\acute{\varphi}_i\right]\Delta x_i (tan^2_{\alpha_i} + 1)$$
$$Y_i = \tan\acute{\varphi}_i * \tan\alpha_i \qquad (1)$$
$$Z_i = \gamma h_i \Delta x_i * \tan\alpha_i$$
$$Q = \frac{1}{2}\gamma_w Z_i^2$$

Thus, the safety factor is:

$$F = \frac{\left[\sum \frac{X_i}{(1 + \frac{Y_i}{F})}\right] f_0}{\sum Z_i + Q} \qquad (2)$$

$$f_0 = 1 + k\left(\frac{d}{l} - 1.4\left(\frac{d}{l}\right)^2\right) \qquad (3)$$

Where:

If $\acute{C}_i = 0$ $\quad K = 0.31$

If $\acute{\varphi}_i < 0$ and K=0.5 $\acute{C}_i > 0$

Fig.1 shows all the parameters used in this method. Janbu's method is applied for materials in which failure is defined by the Mohr-Coulomb failure criterion (Eq.4) [20].

$$\tau = C + \tan\varphi . \sigma_n \qquad (4)$$

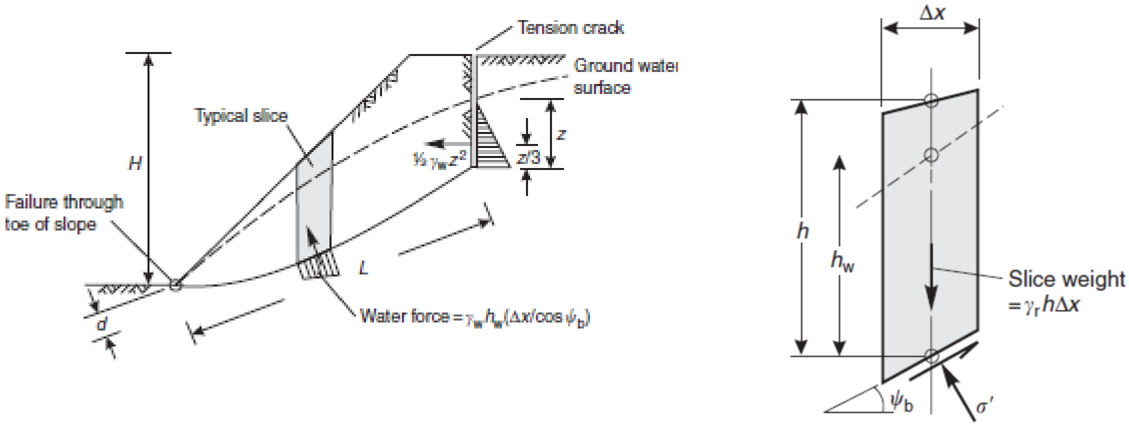


Fig. 1. Janbu's method of slope stability analysis [20]

4.2. Bishop's method

In Bishop's method a circular slide and horizontal side forces are assumed. This method of analysis is used for material in which strength is defined by non-linear Hoek-Brown ($\tau = f(\sigma_n)$) criterion. The safety factor is obtained by Eq. 5.

$$F = \frac{\sum(c_i' + \sigma_i' \tan\varphi_i') \dfrac{\Delta x_i}{\cos\alpha_i}}{\sum \gamma_i\, h_i \sin\alpha_i + \frac{1}{2}\gamma_w Z^2 \dfrac{a}{R}} \qquad (5)$$

Where Fellenius's solution gives:

$$\sigma_i' = \gamma_i\, h_i\, cos^2\alpha_i - \gamma_w h_{wi} \qquad (6)$$

The friction coefficient and cohesion are:

$$\tan\varphi_i' = AB\left(\frac{\sigma_i'}{\sigma_{ci}} - T\right)^{B-1} \qquad (7)$$

$$C_i' = A\sigma_{ci}\left(\frac{\sigma_i}{\sigma_{ci}} - T\right)^B - \sigma_i' \tan\varphi_i' \qquad (8)$$

$$\sigma_i'' = \frac{\gamma_i h_i - \gamma_w h_{wi} - \dfrac{c_i' \tan\alpha_i}{F}}{1 + \dfrac{\tan\varphi_i + \tan\alpha_i}{F}} \qquad (9)$$

This process is done till $|F_n - F_{n+1}| \leq 0.001$.The conditions must be satisfied for each slice:

$\sigma_i'' > 0$

$$\cos\alpha_i\,(1 + \tan\alpha_i \tan\varphi_i)/F > 0.2 \qquad (10)$$

The conditions and required parameters for obtaining safety factors are shown in Fig. 2 [20].

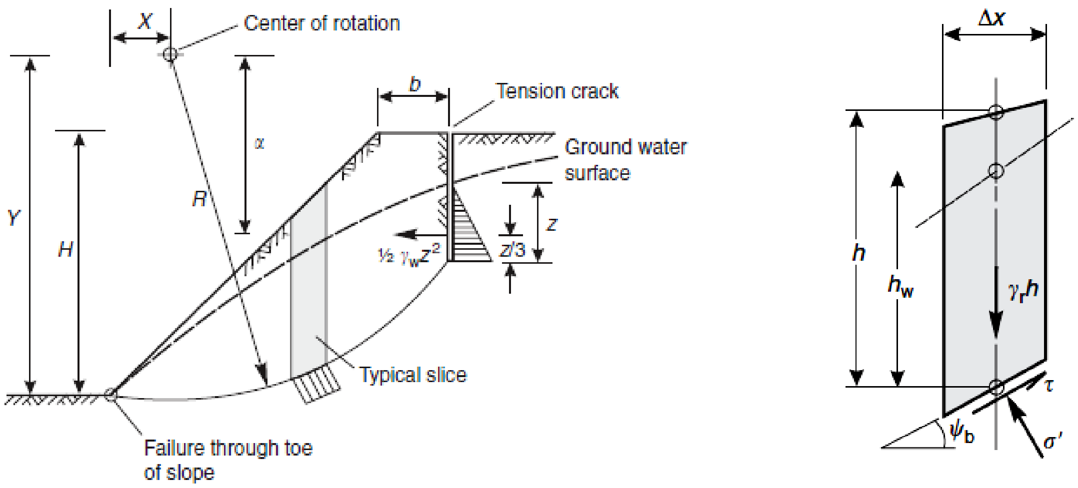


Fig. 2. Bishop's method of slope stability analysis [20]

4.3. Morgenstern-Price's method

The Morgenstern-Price method satisfies both force and moment equilibriums and assumes the interslice force function. The interslice force inclination can vary with an arbitrary $f(x)$ as:

$$T = f(x)\,\lambda\,E \tag{11}$$

Where $f(x)$ is interslice force function, λ is the scale factor of the assumed function.

The method suggests assuming any type of force function, for example, half-sine trapezoidal or user-defined. The relationships for the base normal force (N) and interslice forces (E, T) are the same. For a given force function, the interslice forces are computed by iteration procedure until, F_f is equals to F_m.

$$F_f = \frac{\sum(c'l + (N - ul)\tan\phi')\sec\alpha}{\sum(W + (T_2 - T_1)\tan\alpha)\sum\Delta E} \tag{12}$$

$$F_m = \frac{\sum(c'l + (N - ul)\tan\phi')}{\sum W\sin\alpha} \tag{13}$$

Where ΔE is net interslice forces, c' and ϕ' are cohesion and friction angle, α is the inclination of the slip surface at the middle of slice, u is the pore pressure, l is the slice base length, W is the weight of sliding mass, $T_2 - T_1$ is the interslice forces.

4.4. Spencer's method

Spencer's method is basically a modified and extended version of the Bishop's method. The Bishop's F is defined as the ratio of total strength available S on the slip surface to the total shear strength mobilized S_m:

$$F = S/S_m \tag{14}$$

In Spencer's analysis, the derived resultant Q of pair of interslice forces:

$$Q = \gamma H b\left(\frac{\frac{c'}{F\gamma H} + \frac{h\tan\phi'}{2HF}(1 - 2r_u + \cos 2\alpha) - \frac{h\sin 2\alpha}{2H}}{\cos\alpha\cos(\alpha-\theta)\left[1 + \frac{\tan\phi'}{F}\tan(\alpha-\theta)\right]}\right) \tag{15}$$

Where F is safety factor, S and S_m are the total strength available and total shear strength mobilized, respectively, Q is the resultant of pair of interslice forces, b and h width and mean height of slice, respectively, α is the slope of base of slice, r_u is the pore-pressure coefficient, θ is the slope of resultant Q of pair of interslice forces, γ is the bulk density, H is the height of embankment, ϕ' is the angle of shearing resistance with respect to effective stress, c' is the cohesion with respect to effective stress.

And if the external forces on the embankment are in equilibrium, the vectorial sum of the interslice forces must be zero. Hence:

$$\sum[Q\cos\theta] = 0 \tag{16}$$

$$\sum[Q\sin\theta] = 0 \tag{17}$$

5. MODELING

As mentioned in this research, the mine wall stability has been analyzed analytically and numerically. Analytical methods were performed to validate the numerical modeling. Also, numerical modeling has been used to investigate the effect of fluid flow on wall stability. The analytical and numerical modeling will be presented as follows:

5.1. Safety factor obtained using Bishop's and Janbu's methods

The water level in the studied mine is located at a depth of 57 meters from the first mine bench or ground level. To consider the effect of water level on the wall stability, it was decided to perform modeling with 3 different water levels that are measured relative to the ground surface, i.e. 57, 100, and 150 meters. The safety factor of the studied mine wall has been obtained by the method of Bishop and Janbu and is presented in Table 3. In these methods, it is not possible to define joint sets directly in analysis, but we can define parameters related to rock properties and its joints which show discontinuities. Bishop and Janbo's ability to capture the water level made it possible to consider the effects of available water on pit wall stability.

Therefore, the safety factor was estimated using the two mentioned methods while applying all the required parameters. The geometry of the pit wall and the three water table levels considered in this model are shown in Fig. 3.

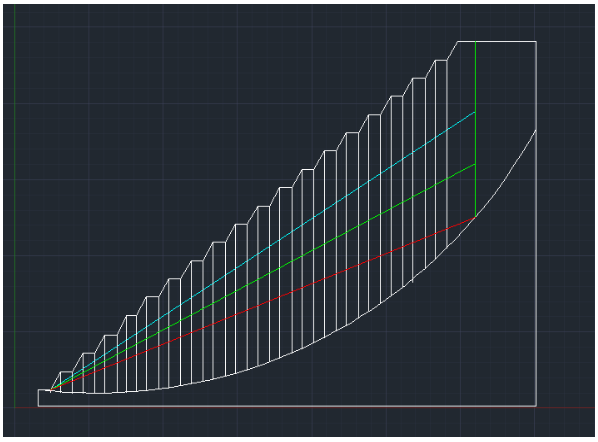


Fig. 3 Geometry of the Golgohar mine pit wall and its slices for Bishop's and Janbu's method analysis

Table 3 shows the safety factors obtained by Bishop's and Janbu's methods by considering 3 water tables. It's observed that in present conditions the slope is unstable, and to achieve the stability that is in mind it is essential to reduce the water table level to a depth of 157 meters from the ground surface using the mine drainage.

Table 3. Safety factors were obtained from Bishop's and Janbu's methods

Water table	Janbu	Bishop	Morgenstern-Price	Spencer
57 meter	0.9	0.91	0.87	0.88
100 meter	1.06	0.99	1.03	0.96
150 meter	1.11	1.15	1.08	1.12

5.2. Probable sliding in Golgohar mine

There are two main types of numerical models, continuous and discontinuous. The selection of the most adequate numerical approach to simulate the behavior of rock slope will depend on the overall behavior of the rock mass under operation which could be either continuous, homogeneous, and isotropic or discontinuous, inhomogeneous, and anisotropic [21, 22, 23]. Fig. 4 summarizes the cases when either continuous or discontinuous numerical modeling is used in rock engineering design. Generally, continuous methods are used either when the rock material is completely intact and has no defects; when there are just a few main planes of weakness (fractures, joints, and discontinuities); or when the rock mass is so highly fractured that its behavior can be assumed equivalent continuous. Discontinuous modeling is usually used when there are a few main discontinuities that could cause instability or when the failure in the system is mainly governed by the orientation, persistence, size, and strength of the discontinuities.

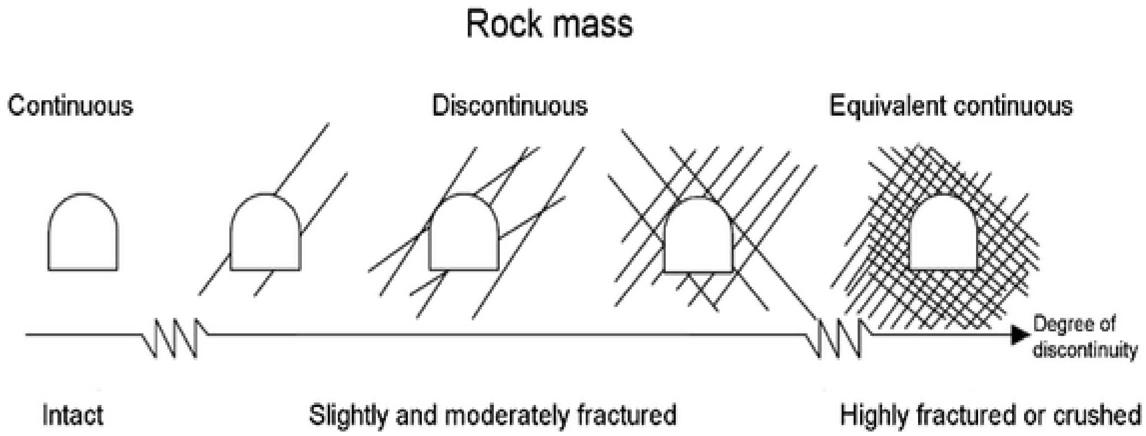
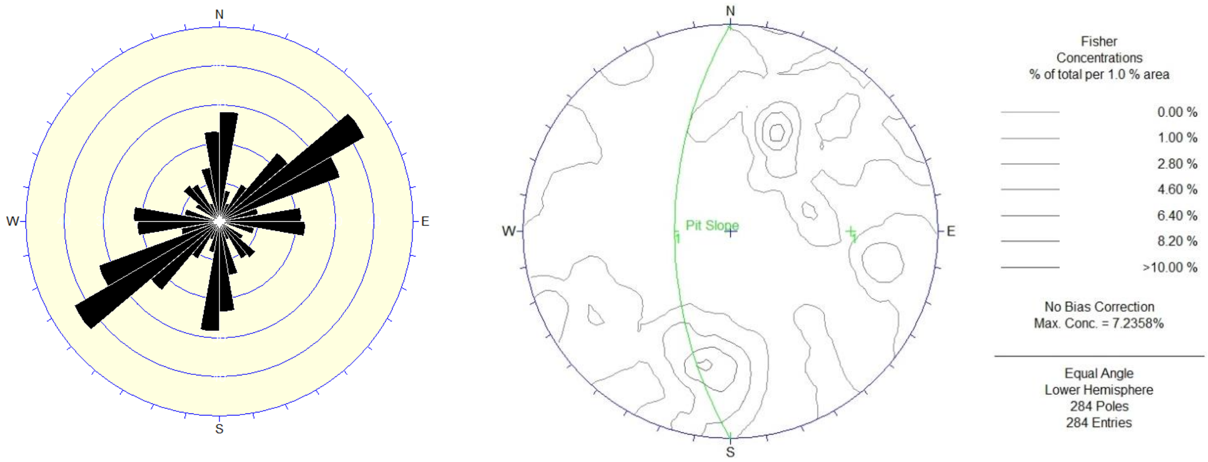


Fig. 4. Continuous and discontinuous rock mass behaviors [24]

The main purpose of this research is to perform numerical modeling to analyze the stability of the Golgohar mine wall. Selecting the type of numerical method is essential to perform the numerical model. From field surveys and data analysis of the Golgohar mine wall, it was obtained that the probable failure in the mine was mainly because of the orientation, persistence, size, and strength of the joints. The results in Fig. 5 and Fig. 6 showed that there 4 sets of joints in which this classification was formed based on the approximate similarity of the dip and dip directions of joints.

Fig 5(a) presents the Rose diagram of joints scanned in the studied area. In Fig 5(b) the pit slope plane and joints (discontinuities) contour lines are illustrated in the stereo net.



(a) (b)

Fig. 5. (a) Rose diagram of joints, and (b) joints contour lines in the stereonet

To analyze the possible failures of the pit wall, probable sliding should be considered. To accomplish this purpose, Goodman's method was used. The results of this investigation showed there is toppling sliding in a region with a dip angle of 0 to 160 degrees and dip direction of 248 to 290 (Fig 6(a)). In addition, the plane sliding occurred in this pit wall and no wedge sliding is illustrated (Fig 6(b) and (c)).

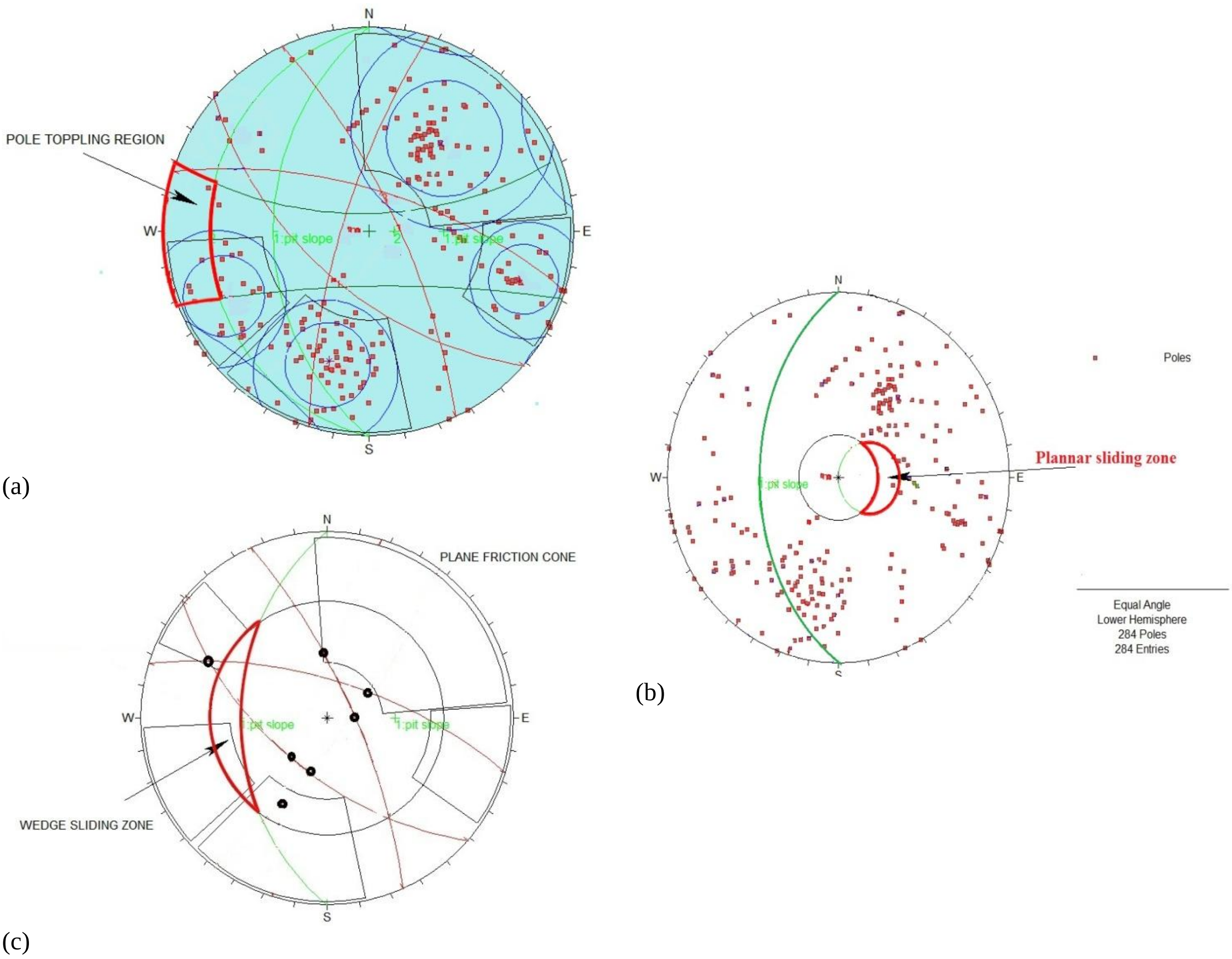


Fig. 6. (a) Toppling sliding, (b) plane sliding, and (c) wedge sliding zone in the stereonet

5.3. Numerical modeling

In this paper, the effect of underground water on the stability of the final pit wall of the Golgohar mine was analyzed numerically. To perform the numerical model, the Distinct Element method was selected to make the discontinuous numerical model because the rock mass of this pit wall behaves discontinuous. The numerical model was done using UDEC software. In this model, the four joint sets were imported as reported in Table 2. To consider the underground water on the stability of the pit wall, three different depths of 57, 100, and 150 meters of underground water which were measured from ground surface level, were selected.

The slope of the pit wall consisted of 19 benches with a height of 10m, width of 10m, and dip angle of 60 degrees (Fig. 7).

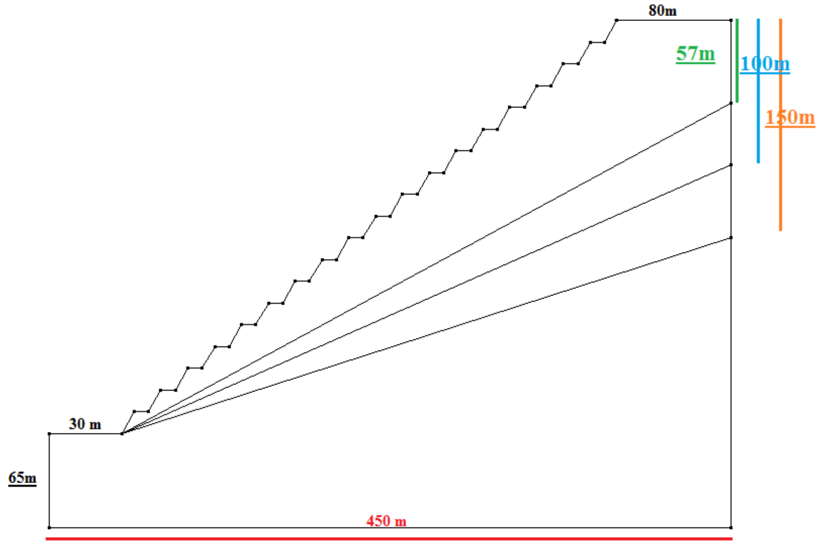


Fig. 7 The geometry of the final pit wall of the Golgohar mine

In addition to constructing the geometry of the final pit wall, individual benches were modeled for a more detailed analysis of the effect of underground water on stability. Fig. 8 shows the geometry of a single bench.

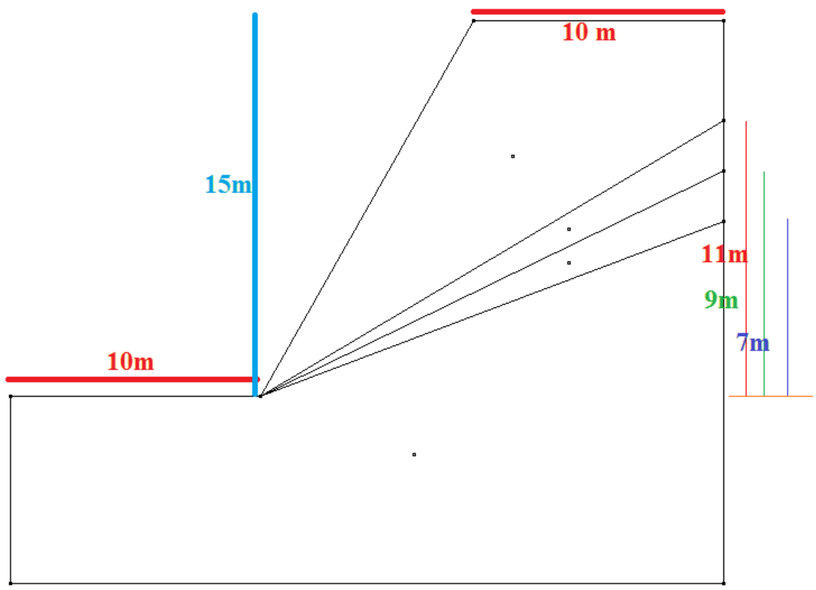


Fig. 8 The geometry of the single bench of the Golgohar mine

To make the distinct element analysis, the domain of the model should be meshed. In this numerical model, the triangular elements with three dimensions were used for meshing the model. The geomechanical properties of the rock mass and the joints of the pit wall of Golgohar mine are imported into the model using input data. Moreover, the initial and boundary conditions of this pit wall were applied in this model.
To be able to show the failure of the pit wall and the stability of its slope, it is essential to define the behavioral constitutive model. Thus, the Mohr-Coulomb criterion was used to perform slope and wall stability calculations. The geomechanical properties of rock mass are given in Table 2.

Table 4. The geomechanical properties of the rock mass of the pit wall of Golgohar mine

Parameters	Values
Density, [Kg/m^3]	2700
Uniaxial compressive strength, [MPa]	164
Young modulus, [GPa]	5
Poisson ratio	0.23
Cohesion, [MPa]	1.53
Friction angle, [°]	36

In addition, the information related to the joint's conditions of the environment such as number of joint sets and properties of the joints should be entered into the model. The joint properties of the Golgohar mine are reported in Table 5.

Table 5. The joint properties of the Golgohar mine

	Joint set 1	Joint set 2	Joint set 3	Joint set 4
Dip, [°]	85	51	54	8
Dip direction, [°]	110	215	8	250
Joint length, [m]	15	12	13	14
Joint spacing, [m]	0.6	1	1	1
Cohesion, [MPa]	0.33	0.33	0.33	0.33
Internal friction angle	26	26	26	26

In order to model the water flow, it is essential to apply fluid flow in hydromechanical boundary conditions. In this study, the fluid flow conditions are created by applying pore pressure on both sides of the model. The pore pressure is determined according to the following equation:

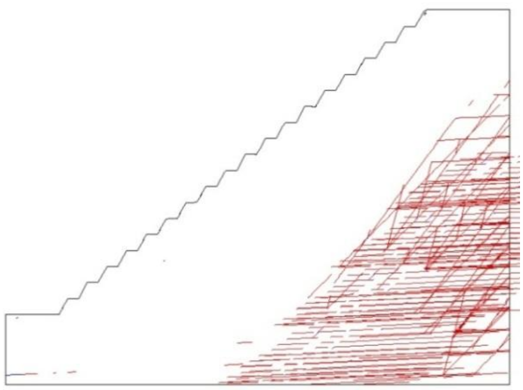
$$p = \rho_w \, g \, h \qquad (18)$$

ρ_w is the water density.

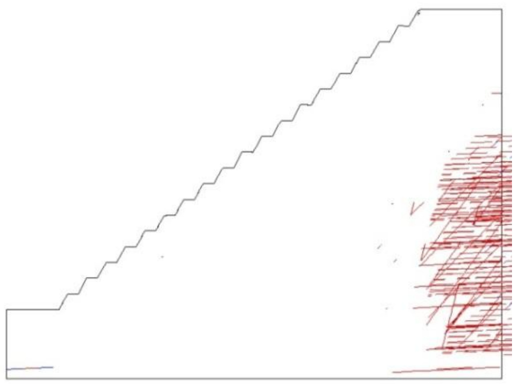
In this study, water pressure was applied as boundary conditions on three different levels to the left and right side of the model and then, the numerical model was built and implemented.

6. Discussion

The numerical modeling of the pit wall stability was done. In the continuation of this article, some of the results obtained from this model are assessed and analyzed.
To model the water flow, it is essential to apply boundary conditions for the flow on the right and left boundaries of the model. After applying the boundary conditions, the numerical model was run. The process reached equilibrium and the fluid flow can be seen in Fig. 9. Then, based on the developed model, the safety factor for the open pit mine wall is determined. This process is presented below.



Stage 2



Stage 1

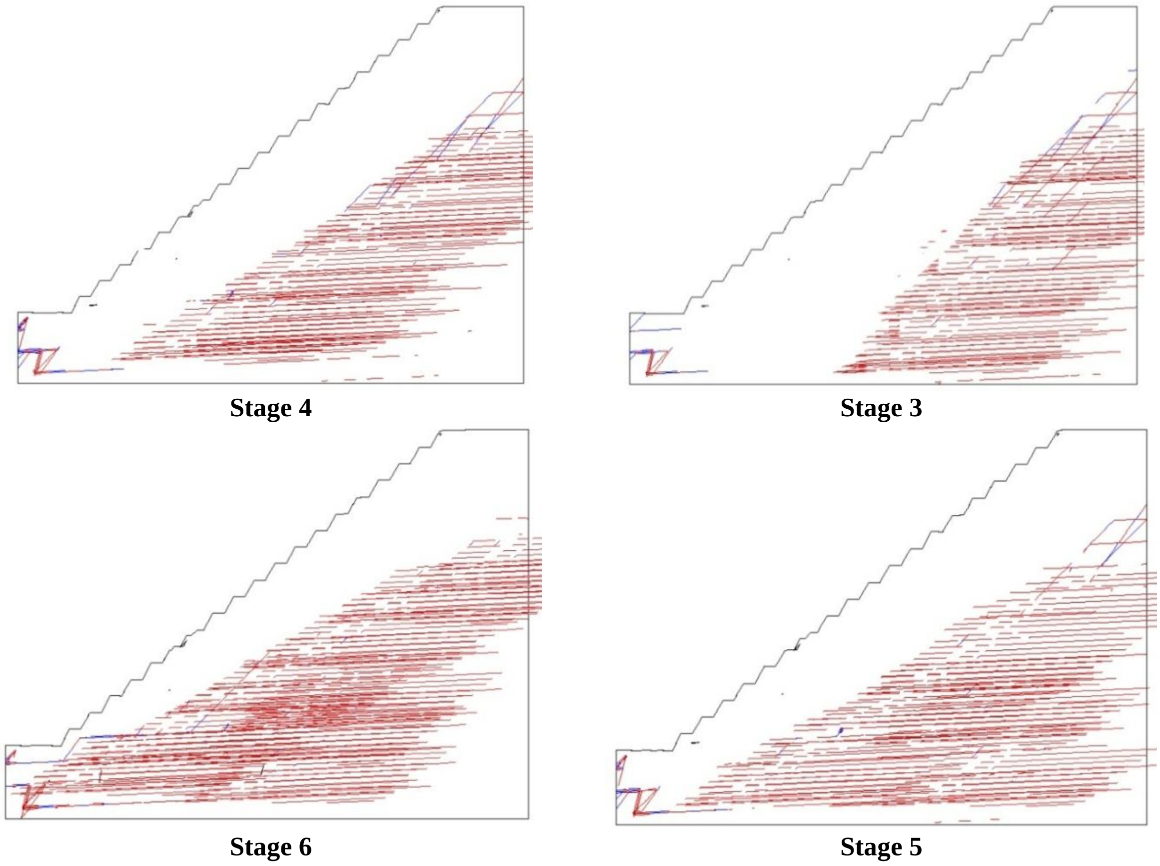


Fig. 9 Stages of reaching flow equilibrium at the final wall of the open pit mine

The diagram of flow rate in three levels of water table is drawn in Fig. 10. It’s seen from this figure that the maximum flow rate is obtained when the distance between water table and ground surface level is 57m. According to Fig. 10, it is noticeable that where the distance between water table and ground surface level is low, the flow rates increase. Fig. 11 shows the water pressure in discontinuities in three levels of water table. This parameter is obtained as 2.6, 2.5, and 1.97 MPa for water levels with a height of 57, 100, and 150m, respectively compared to the ground level.

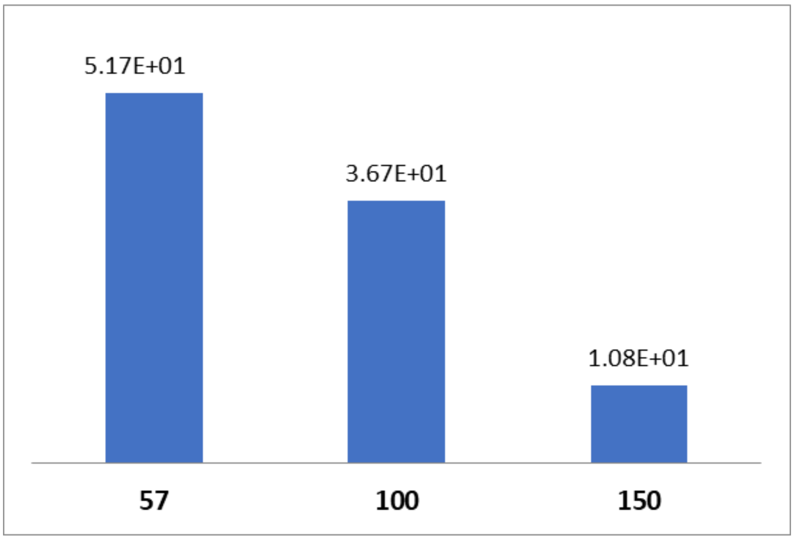


Fig. 10 Diagram of flow rate for water tables of 57,100 and 150m

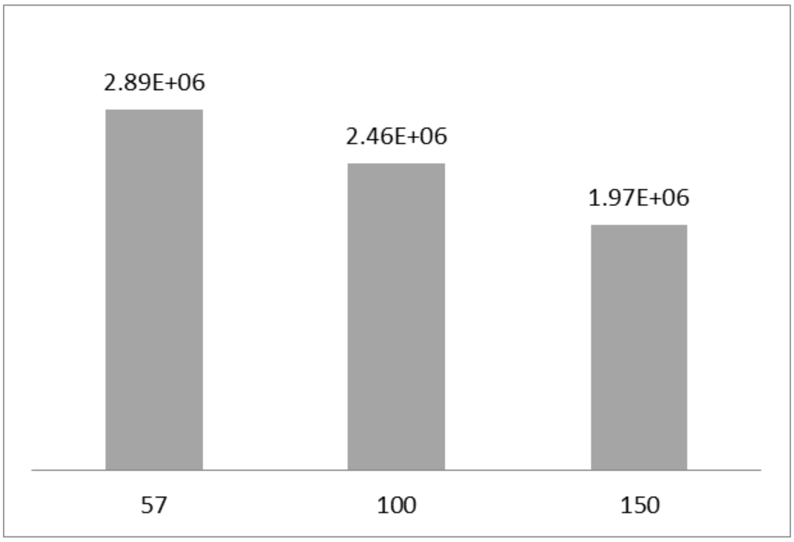


Fig. 11 Diagram of water pressure for water tables of 57,100 and 150m

The maximum displacement values for water tables are shown in Fig. 12. The displacement value for water table of 57 is 6.55 mm and it is larger than the two other cases.

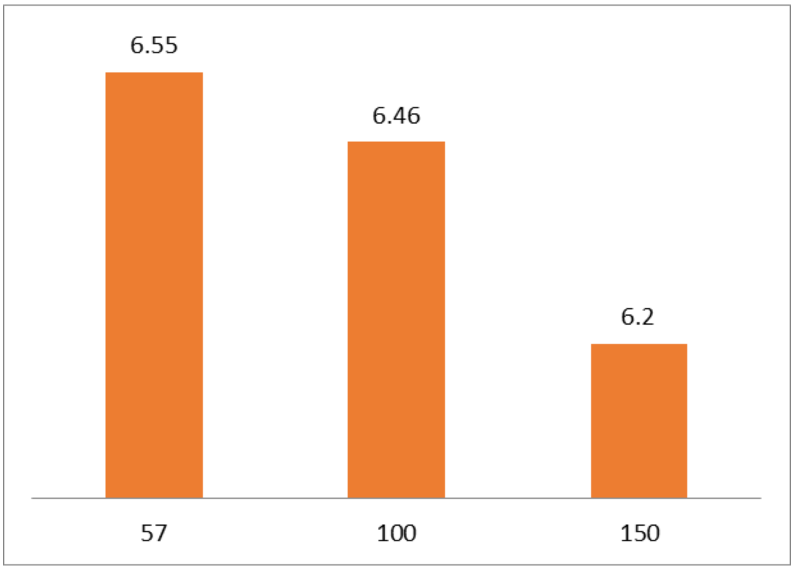


Fig. 12 Maximum displacement in slope for three water tables of 57,100 and 150m

As shown in Fig. 13, as the depth of water table decreases, horizontal component of velocity also decreases and the probabilistic sliding on slope becomes lower. Therefore, a drainage system is required to lower the water table to 150m (presented from ground level) in this open pit. The same variation is observed in vertical component too.

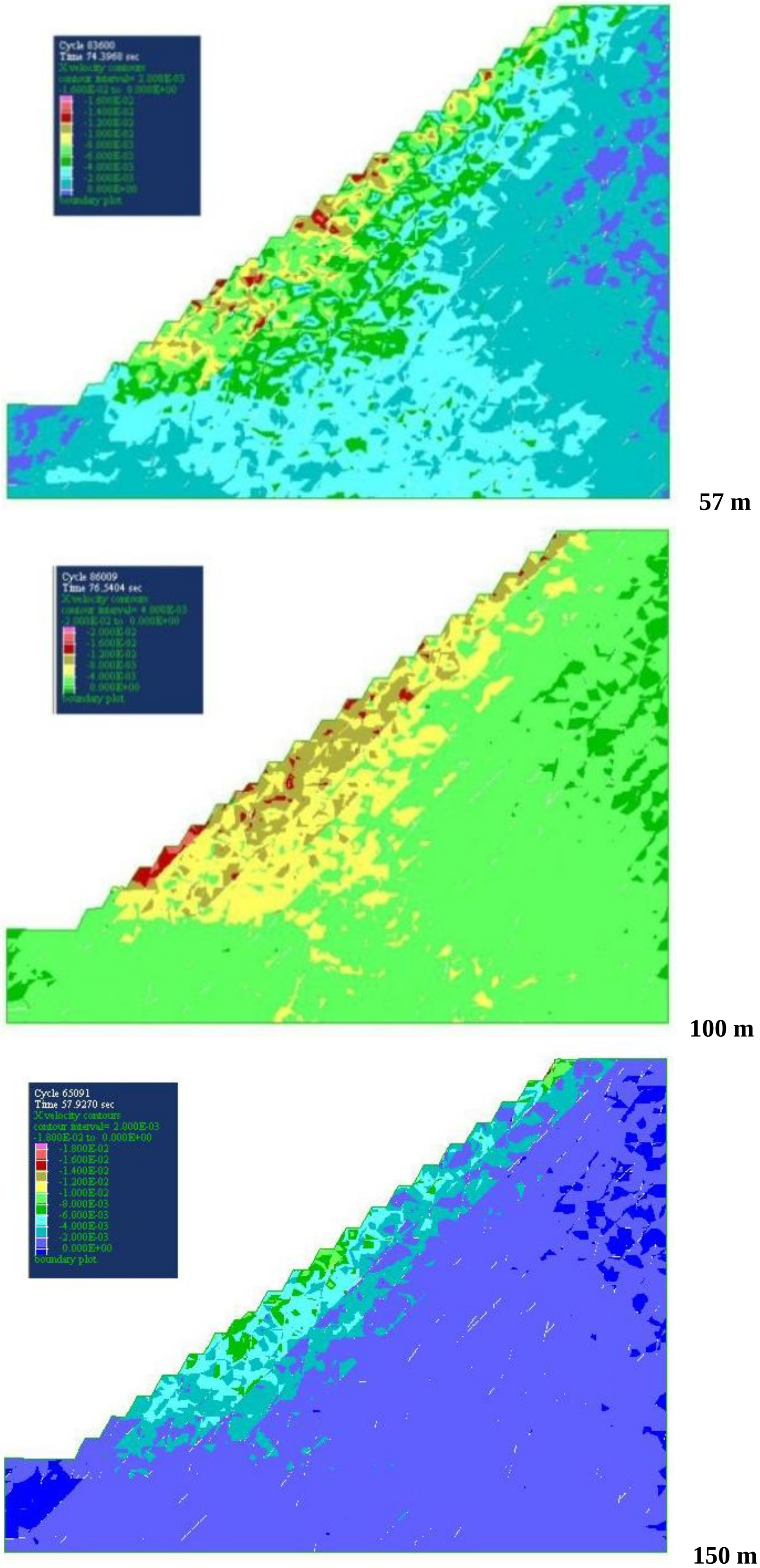


Fig. 13 Horizontal velocity contour in pit wall for three levels of water table

After building the model, it is necessary to express the safety factor of the wall. The safety factor was obtained, which is presented below as the safety factor separately for three water levels. The results showed that there is pit wall instability for the water table of 57 and 100m and it's necessary to decrease the water table to 150m. The safety factors obtained from this numerical model for each water table are given in Table 6. The shear strain rate and safety factor at 57 meters of water depth are shown in Fig. 14. Also, the shear strain contour in XY direction and the safety factor are indicated in Fig. 15.

Table 6. Safety factors obtained by numerical modeling

	WT 57m	WT 100m	WT 150m
Safety factor	0.78	0.92	1.1

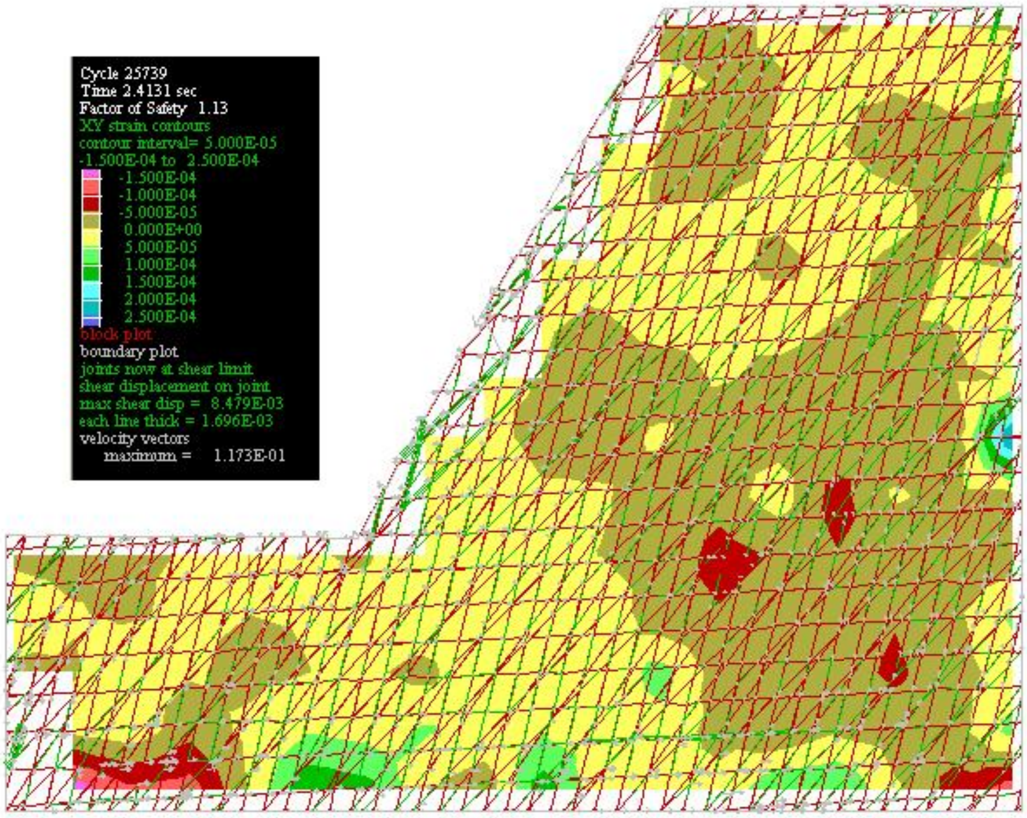


Fig. 14 Shear strain rate and safety factor at 57 meters of water depth

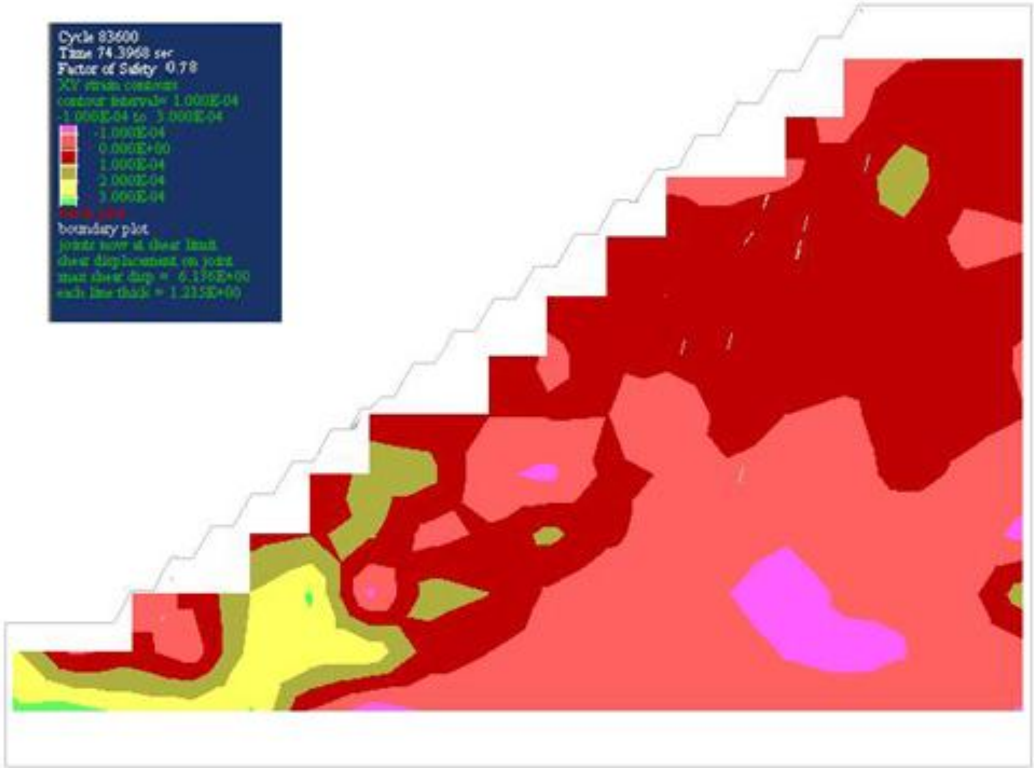


Fig. 15 Shear strain contours and the safety factor for water table 57m

Table 7 shows the safety factors obtained from numerical and analytical methods. As expected, there are differences between the results of the safety factor value obtained from UDEC software and the results of Bishop and Janbu calculation methods. Since fluid flow in discontinuities is well modeled in UDEC software, the effect of underground water flow at different depths is more evident. However, in both numerical and computational methods, it is possible to observe water's effect on reducing the slope's stability and the value of the safety factor. It should also be noted that the calculated safety factor values were obtained in Bishop and Janbu methods for circular or spoon failure mode.

Table 7. Comparison of safety factors obtained from analytical and numerical methods

	Safety factor				
	Bishop	Janbu	Morgenstern-Price	Spencer	Numerical result
57 m	0.91	0.9	0.87	0.88	0.78
100 m	0.99	1.06	1.03	0.96	0.92
150 m	1.15	1.11	1.08	1.12	1.1

Numerical and analytical analysis of underground water in the pit wall of Golgohar mine presented that by reducing the height of the water, for example, by using a drainage system, stability can be increased and a safe safety factor can be increased as well.

The results obtained emphasize that for optimal mining and reducing problems, the drainage process should be done well. Proper drainage can prevent mine collapse and mineral dilution and increase the profitability of the project. This issue is emphasized to be done well in mines and the management of mine drainage and the effect of fluid on the stability of a single bench and the final slope of the mine should be investigated.

7. Conclusion

Numerical modeling of the final pit wall stability of the Golgohar mine was done using UDEC software, and the effect of underground water flow on slope stability was investigated. The analyses performed in this research are based on the effect of underground water on the stability of the slope and its flow in discontinuities. Moreover, the safety factor value for three different water table depths was obtained through the numerical model and calculations of Bishop and Janbu analytical methods. The results obtained from this article are summarized as follows:

1) The lower the water depth measured from the ground surface level, the higher the flow rate in discontinuities. This difference is due to the water pressure created inside the discontinuities.

2) Some local sliding in types of toppling and plane sliding were probable in this pit wall. Hence the overall dip of slope should be decreased. There was a possibility of slip in the upper benches of the mine.
3) The effect of underground water depth on the stability of the mine wall is evident. The lowest value of the safety factor was obtained by using the numerical method for the water depth of 57 meters from the ground surface level as 0.78. With the decrease in the water level, the value of the safety factor increased until the value of 1.1 which was obtained at a water depth of 150 meters measured from ground surface level.
4) Bishop and Janbu methods showed a good verification of safety factor values compared to numerical modeling. The safety factor obtained by Janbu method for three water depths of 57, 100, and 150 was obtained as 0.9, 1.06, and 1.11 respectively. The safety factor values obtained from the Bishop method for these three depths were 0.91, 0.99, and 1.15, respectively.
5) The results of analytical and numerical models of pit wall stability of Golgohar mine indicate that to reach a stable and safe state in the final wall, it is necessary to reduce the underground water level.
6) Numerical modeling showed that instability occurred in the current level of water. Thus, a drainage system was required to decrease water table to 150m. The safety factor was around 0.78 and after drainage raised up to 1.1.

REFERENCES

[1] Hoek ,E and Bray,J. Rock slope engineering, A.A. Balkema (1981).

[2] Jiao, J.J., X.S. Wang, and S. Nandy, Confined groundwater zone and slope instability in weathered igneous rocks in Hong Kong. Engineering Geology,. 80(1): p. 71-92 (2005).

[3] Predrag Miscevic*,. Goran Vlastelica,"'Impact of weathering on slope stability in soft rock mass "Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 240e250.

[4] M. Rabie,. "Comparison study between traditional and finite element methods for slopes under heavy rainfall". HBRC Journal (2014) 10, 160–168

[5] Niu Zhiguo,.et al." The stability analysis of the dike slope in Bdg reservoir under the seepage of flood". Procedia Engineering 15 (2011) 5263 – 5267

[6] W. Shao, Th. Bogaard, M. Bakker. "How to Use COMSOL Multiphysics for coupled dual-permeability hydrological and slope stability modeling" Procedia Earth and Planetary Science 9 (2014) 83 – 90.

[7] GAO Yu-kun, Bao Na, ZHANG Ying-hua, JIANG Li-ming, HUANG Zhi-an,. "Research on index system of rock slope safety evaluation for open pit mine",. Procedia Engineering 26 (2011) 1692 – 1697

[8] Zhao Weifeng, Zhao Lianheng, Deng Dongping,. "Improved Sliding Surface Search Method for Stability Analysis of Complex Slopes". 2012 International Conference on Structural Computation and Geotechnical Mechanics.

[9] Mohammed Ahmadi-Adli, N. Kartal Toker, Nejan Huvaj,. "Prediction of seepage and slope stability in a flume test and an experimental field case ".Procedia Earth and Planetary Science 9 (2014) 189 – 194

[10] Setyananda, A., Novi Hartami, P., Maulana, Y., Jamal Tuheteru, E., Korra Herdyanti, M., & Putra, D. (2024). Analysis of the Influence of Groundwater Level on Slope Stability at Highwall PT. X, South Kalimantan. In IOP Conference Series: Earth and Environmental Science (Vol. 1339, Issue 1, p. 012029). IOP Publishing. https://doi.org/10.1088/1755-1315/1339/1/012029.

[11] Sanei, M. (2023). Development of Mohr-Coulomb criterion elastoplastic integration algorithm scheme for rock. Journal of Petroleum Geomechanics. https://doi.org/10.22107/jpg.2023.413537.1209.

[12] Sanei, M., Devloo, P. R. B., Forti, T. L. D., Durán, O., & Santos, E. S. R. (2021). An Innovative Scheme to Make an Initial Guess for Iterative Optimization Methods to Calibrate Material Parameters of Strain-Hardening Elastoplastic Models. In Rock Mechanics and Rock Engineering (Vol. 55, Issue 1, pp. 399–421). Springer Science and Business Media LLC. https://doi.org/10.1007/s00603-021-02665-y.

[13] Fellenius, W. (1936) "Calculation of the stability of earth dams." In proceeding of the 2nd congress on large dams, Washington, D.C., Vol. 4, U.S. Government Printing Office.

[14] Bishop, A.W. (1955) "The use of the slip circle in the stability analysis of slope." Geotechnique, 5(1), 7-17.

[15] Janbu, N. (1954) Stability analysis of slopes with dimensionless parameters Harvard Soil Mech. Ser.

[16] Janbu, N. (1973) Earth pressures and bearing capacity calculations by generalized procedure of slices.

[17] Morgenstern, N. R., Price, V. E. (1965) The analysis of the stability of general slip surfaces. Geotechnique, 15, 79-93.

[18] Spencer, A. (1967) "A method of analysis of the stability of embankments assuming parallel interslice forces." Geotechnique, Vol.17(1), 11- 26.

[19] Sarma, S. K. (1973). Stability analysis of embankments and slopes. In Géotechnique (Vol. 23, Issue 3, pp. 423–433). Thomas Telford Ltd. https://doi.org/10.1680/geot.1973.23.3.423.

[20] Hoek ,E and Bray,J. Rock slope engineering, A.A. Balkema (1981).

[21] Hudson, J., & Harrison, J. (2000). Engineering Rock Mechanics: An Introduction to the Principles (Vol. Second Impression 2000, p. 114). London: Elsevier Science Ltd.

[22] Sanei, M., Faramarzi, L., Goli, S. et al. Development of a new equation for joint roughness coefficient (JRC) with fractal dimension: a case study of Bakhtiary Dam site in Iran. Arab J Geosci 8, 465–475 (2015). https://doi.org/10.1007/s12517-013-1147-3.

[23] Sanei, M., Faramarzi, L., Fahimifar, A., Goli, S., Mehinrad, A., & Rahmati, A. (2015). Shear strength of discontinuities in sedimentary rock masses based on direct shear tests. International Journal of Rock Mechanics and Mining Sciences (Oxford, England: 1997), 75, 119–131. doi:10.1016/j.ijrmms.2014.11.009.

[24] Eldebro C (2003) Rock mass strength—a review. Technical Report, Lulea˚ University of Technology, Lulea.

نشریه‌ی مکانیک سنگ
JOURNAL OF ROCK MECHANICS
دوره هفتم، شماره۴، زمستان ۱۴۰۲، صفحه ۷۳ تا ۸۸
https://doi.org/10.22034/IRSRM.2024.466658.0411

تحلیل پایداری شیب با استفاده از روش المان مجزا با در نظر گرفتن اثرات جریان سیال در معادن روباز

محمد شکاری نژاد [۱]؛ محمد فاتحی مرجی [۲*]، منوچهر صانعی [۲]
۱- دانشکده مهندسی معدن، دانشگاه آزاد اسلامی، واحد سیرجان، سیرجان، ایران.
۲- دانشکده مهندسی معدن و متالورژی، دانشگاه یزد، یزد، ایران.

دریافت : ۱۴۰۲/۱۱/۱۵؛ پذیرش: ۱۴۰۲/۱۲/۲۹
(*نویسنده مسئول: mfatehi@yazd.ac.ir)

چکیده

جریان آب زیرزمینی و زیرسطحی ممکن است باعث ناپایداری در معادن روباز شود. آب موجود در منافذ منجر به اعمال فشار به سنگ ها، کاهش تنش موثر و کاهش مقاومت برشی شیب سنگ ها می شود. یعنی فشار آب باعث ناپایداری در نیمکت های روباز می شود. در پژوهش حاضر، ما از روش عناصر متمایز همه کاره و پیچیده برای بررسی تأثیر جریان آب بر پایداری دیواره گودال یکی از معادن گل گهر کرمان، ایران استفاده کردیم. نتایج عددی نشان داد که هر چه فاصله سطح آب از تاج نیمکت اول معدن یعنی سطح زمین کمتر باشد میزان جریان در ناپیوستگی ها بیشتر می شود. همچنین نتایج نشان داد که ضریب ایمنی کلی شیب با کاهش سطح آب یعنی زهکشی افزایش می یابد. برای سطح آب با ارتفاع ۵۷ متر نسبت به سطح زمین (تاج نیمکت اول) ضریب ایمنی ۰/۷۸ برآورد می‌شود. همین موضوع برای سطح آب با ارتفاع ۱۵۰ متر ضریب ایمنی ۱/۱ را نشان می دهد که ضریب ایمنی آن نسبت به مورد قبلی افزایش یافته است. ضریب ایمنی به‌دست‌آمده از روش عددی در مقایسه با نتایج به‌دست‌آمده از روش‌های تحلیلی *Janbu* و *Bishop* اعتبار مدل‌سازی را تأیید می‌کند. علاوه بر این، خرابی‌های نیمکت‌ها حاکی از وقوع لغزش و واژگونی مسطح در این شیب معدن است. برای این مورد پیشنهاد می‌شود سطح سطح ایستابی را کاهش داده تا به حالت پایدار در این معدن برسد.

واژگان کلیدی جریان سیال؛ تحلیل پایداری شیب؛ روش المان مجزا؛ تنش موثر؛ معدن گل گهر