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Assessment of the Slope Stability Under Geological Conditions Using FDAHP-TOPSIS (A Case Study for Sungun Open Pit Mine)

Morteza Niromand[1], Reza Mikaeil[2*], Mehran Advay[3]

1. Ph.D. Student, Department of Mining, Ahar Branch, Islamic Azad University, Ahar, Iran
2. Associate Professor, Faculty of Environment, Urmia University of Technology, Urmia, Iran
3. Assistant Professor, Department of Mining, Ahar Branch, Islamic Azad University, Ahar, Iran

Corresponding author: *reza.mikaeil@uut.ac.ir*

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ABSTRACT

Determining the degree of slope stability is one of the most important steps in the design of open pit mines that are affected by other mining activities. So that the collapse of a part of the wall will lead to irreparable human and compensatory damages. Slope stability is affected by natural factors such as lithology, tectonic regime, rock mass conditions, climatic conditions and design factors including slope angle, slope height, pattern and blasting method. In the present study, using a combination of fuzzy approach and multi-criteria decision models, the stability and ranking of the slope stability has been investigated. For this purpose, the stability of 28 slopes of 8 large open pit mines was evaluated. In the first step of the research, after identifying the parameters affecting the slope stability and recording their values for the studied mines, the degree of importance of these parameters were determined by experts using the Fuzzy Delphi Analytical Hierarchy Process. Then the slopes were evaluated and ranked using the technique of order preference similarity to the ideal solution technique. The slope A23 with similarity index 0.742 was selected as the most desirable alternative and the slope A15 with similarity index 0.335 as the most undesirable alternative in terms of slope stability. Meanwhile, Sungun copper mine with a similarity index of 0.399 was ranked 12th in the second half of the slope stability classification table. The results showed that, the matching of research results and field observations shows the applicability of the model in the initial evaluation of slopes to determine its stability.

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1. Introduction

Assessing the slope stability plays an important role in design, planning and mining costs. For example, increasing the angle of slope will reduce waste disposal or increase mineral extraction, resulting in higher profits and shorter payback periods. A high angle of slope also reduces the safety factor and increases the cost of failure. Factors influencing failure include lithology, tectonic regime, rock mass conditions, climatic conditions and design factors including slope angle, slope height, pattern and blasting method. Fractures in rocks occur at discontinuous surfaces, including joints and faults, and in the form of plates, wedges, overturns, and two blocks, and spoon or circular fractures in rocks. Intensity of weathering or earthen slopes occurs. Instability in open pit mines occurs mainly in the form of gradual or sudden falls. Sudden failure or collapse, which usually has warning signs, is one of the most dangerous types of falls and usually causes a lot of damages Including causing (irreparable) casualties and extensive direct financial damages (especially damage to the devices, which sometimes causes the devices to go completely out of service), mixing minerals with tailings that in most cases, it will cause a large volume of mineral loss, stop or reduce production in the mine, which will be directly related to the volume of the fall (Angoran mine fall is a good example in this regard), impose additional costs to remove the volume of fallow soil , Incurring ancillary costs for cleaning and repairing the stairs or stairs on which the collapse has taken place (need to redesign the end walls) can be mentioned. The use of rating systems and models is one of the common and basic methods to evaluate the stability of a slope.

Hack, R., et al., developed A new approach to rock slope stability–a probability classification (SSPC) [1]. Taherynia, et al. 2014 studied the slope instability and risk analysis of road slopes in Lashotor Pass, Iran [2]. Fereidooni, et al. 2015 investigated a modified rock mass classification system for rock slope stability analysis in the Q-system [3]. Azarafza, et al., 2017, studied the rock slope stability by slope mass rating (SMR) in the gas flare site in Assalouyeh, South of Iran [4]. Baghbanan, et al. 2017, studied Numerical probabilistic analysis for slope stability in fractured rock masses using DFN-DEM approach [5]. Haghshenas et al. (2017), used fuzzy and classical MCDM techniques to rank the slope stabilization methods in a rock-fill reservoir dam [6]. Azarafza et al. (2017), studied the discontinuous rock slope stability using block theory and numerical modeling for the South Pars Gas Complex, Assalouyeh, Iran [7]. Sujatha, and Thirukumaran, 2018, studied the rock slope stability assessment by using geomechanical classification and its application for specific slopes along Kodaikkanal-Palani Hill Road, Western Ghats, India [8]. Zhang et al. (2018), developed a risk assessment model of expansive soil slope stability based on Fuzzy-AHP method and its engineering application [9]. Chen et al. (2018), studied the bedding rock slope based on random seismic response and dynamic fuzzy reliability analysis based on pseudo excitation method [10]. Zhou et al. (2018), investigated the slope stability under uncertain circumstances[11]. Xu et al. (2019), evaluated the rock slope stability by using the hierarchically weighted rough-set genetic algorithm in the freeze–thaw mountains[12]. Zhou et al. (2019): investigated the highway slope stability based on hierarchical fuzzy comprehensive evaluation method [13]. Moayedi et al. (2019), Monitored and evaluated the slope stability by using novel remote sensing based on fuzzy logic [14]. Wang et al. (2019), studied the characterization of rock slope stability using key blocks within the framework of

GeoSMA-3D [15]. Azarafza et al. (2020), investigated the discontinuous rock slope stability analysis under blocky structural sliding by using fuzzy key-block analysis method [16]. Xia et al. (2020), studied the slope stability analysis based on group decision theory and fuzzy comprehensive evaluation[17]. Chen et al. (2021), investigated the application of group decision-making AHP of confidence index and cloud model for rock slope stability evaluation [18]. Zhao et al. (2021) developed a new stability forecasting model for goaf slope based on the AHP–TOPSIS theory [19]. Spanidis et al. (2021) used a Fuzzy-AHP for planning the risk management of natural hazards in surface mining projects[20].

One of the most important goals of this research is to investigating and evaluating the application of decision models in important engineering topics such as slope stability analysis according to the characteristics of the rock mass. Comparing the stability of sloping walls of large mines with each other and with Sungun copper mine is one of the important innovations of this research.

2. Research significance

In the present study, a decision model has been proposed to rank the evaluated slopes and select the walls prone to instability by combining Fuzzy Delphi Analytical Hierarchy Process (FDAHP) and Technique of Order Preference Similarity to the Ideal Solution (TOPSIS). For this purpose, 28 slopes of 8 mines were studied. Finally, in order to evaluate the accuracy of the model, the results were evaluated with the actual behaviors of the slopes. Investigating the stability of slops with FDAHP and TOPSIS is one of the important innovations of this research.

To present the model in the first step, the degree of importance of the criteria was determined based on the opinions of experts. At this stage, first a questionnaire form was sent to experts in the field of slope stability and after collecting the questionnaire forms, the degree of importance of each criterion was calculated using FDAHP. Finally, the slopes were ranked using the TOPSIS. The results of model were compared with the actual behavior of the studied slopes. The flowchart of study is shown in Figure 1.

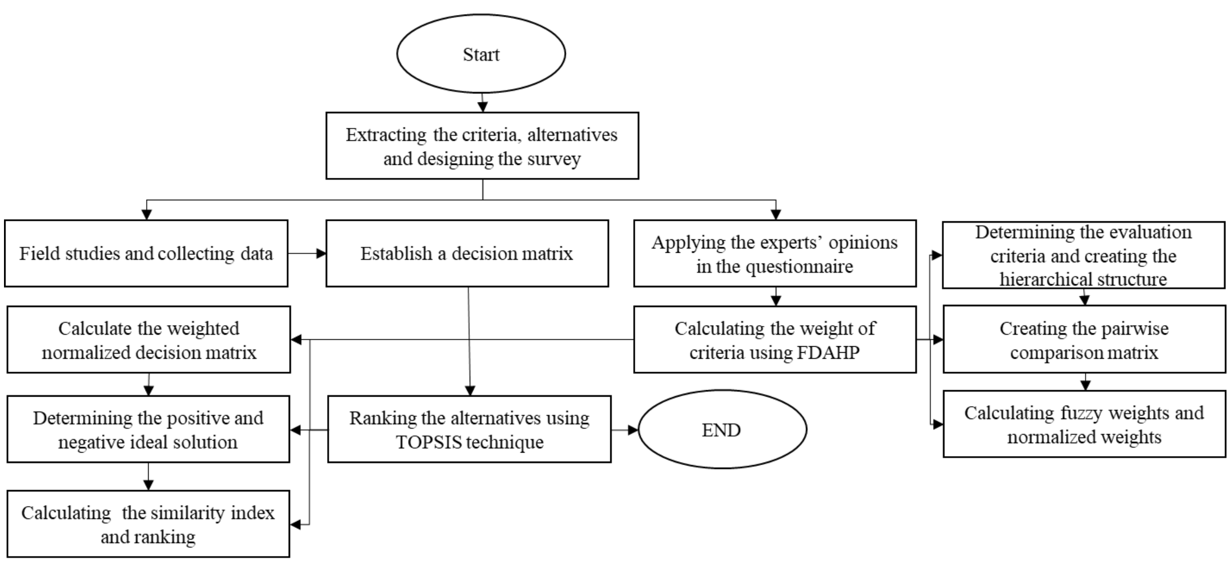

Fig. 1. Flowchart of research.

3. Methods

3.1. FDAHP method

Fuzzy theory and fuzzy sets were first introduced by Zadeh in a treatise entitled "Fuzzy Sets" in 1965 to analyze complex systems[21]. In the theory of classical collections, the membership of members in a collection is determined as binary sentences based on a binary condition that a member either belongs to the collection or not, and the boundaries of a collection are quite clear and sharp, and therefore they are clearly defined. In fuzzy theory, the relative degrees of membership of the members in the set are allowed and the boundaries are blurred and soft. Fuzzy sets are generalizations of the characteristic {0,1} to all numbers in the range [0,1][22]. In fact, in fuzzy sets, unlike classical sets, elements are not divided into two categories: member and non-member; rather, according to the defined functions, the membership of different elements in fuzzy sets varies between zero and one.

In the following, some researches related to this method are briefly described. Hosseini et al. (2009) presented a new classification system for assessing permeability using the FDAHP method [23]. Mikael et al. (2013) also classified the ability of cutting building blocks using the FDAHP method [24]. Que et al. (2016) also assessed the risk of water pollution in a coal mine located in China by the combined method of FDAHP and gray dependence analysis[25]. The results of the mentioned researches show the capability of FDAHP method in classifications related to different issues. Based on the results of research conducted with this method, it is clear that it can be used in analyzes and classifications related to mining engineering issues. The reason for the compatibility of this method and the results of its applications, which are very compatible with real conditions, shows this combined method has all the advantages of AHP methods, fuzzy theory and Delphi method, and the disadvantages of each of these methods, when combined will be minimized. On the other hand, the use of aggregation of the advantages of the above three methods in the form of the combined FDAHP method causes not only the results of its application for the simulated data to have acceptable results. However, the results of the mentioned method are significantly similar to the real conditions and its results can be used for executive and operational applications. Therefore, in order to implement the above method in classifying the stability of sloping walls, first it is necessary to determine the importance of effective criteria based on the opinions of experts.

After forming the pairwise comparison matrices, the results were used to form a fuzzy pairwise comparison matrix. In forming this matrix, the triangular membership function and as a result, triangular fuzzy numbers have been used. Calculations related to this method include the following steps:

Calculation of fuzzy numbers: To calculate fuzzy numbers (αij), the opinions obtained from the survey of experts are directly considered. In this study, fuzzy numbers were calculated based on the triangular membership function. Figure (2) shows the calculation of fuzzy numbers by the triangular method. According to Figure (2) in the Delphi fuzzy method, a fuzzy number can be calculated using equations (1) to (4):

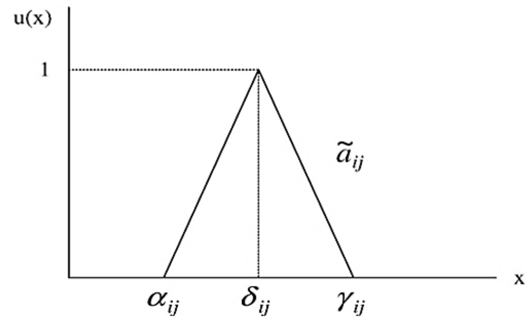

Fig. 2. Triangular membership function in Delphi fuzzy method [26].

$$a_{ij} = (\alpha_{ij}, \delta_{ij}, \gamma_{ij}) \tag{1}$$

$$a_{ij} = Min(\beta_{ijk}) \ \ , \ k = 1,2, \dots, n \tag{2}$$

$$\delta_{ij} = \left(\prod_{k=1}^{n} \beta_{ijk}\right)^{\frac{1}{n}} \ \ , \ k = 1,2, \dots, n \tag{3}$$

$$\gamma_{ij} = Max(\beta_{ijk}) \ \ , \ k = 1,2, \dots, n \tag{4}$$

In the above relations, γij and αij represent the upper limit and the lower limit of expert opinions, respectively. The parameter βijk also indicates the relative importance of the parameter i relative to the parameter j from the kth' s point of view [26].

Formation of fuzzy pairwise comparison matrix: In this step, using the fuzzy numbers obtained from the previous step, a fuzzy pairwise comparison matrix between different parameters is formed using Equation (5):

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{5}$$

$$\tilde{a}_{ij} \times \tilde{a}_{ij} \approx 1 \ \ , \ \forall i, j = 1,2, \dots, n$$

$$\tilde{A} = \begin{bmatrix} (1,1,1) & (\alpha_{12}, \delta_{12}, \gamma_{12}) & (\alpha_{13}, \delta_{13}, \gamma_{13}) \\ \left(^1/_{\gamma_{12}}, ^1/_{\delta_{12}}, ^1/_{\alpha_{12}}\right) & (1,1,1) & (\alpha_{23}, \delta_{23}, \gamma_{23}) \\ \left(^1/_{\gamma_{13}}, ^1/_{\delta_{13}}, ^1/_{\alpha_{13}}\right) & \left(^1/_{\gamma_{23}}, ^1/_{\delta_{23}}, ^1/_{\alpha_{23}}\right) & (1,1,1) \end{bmatrix}$$

At this stage, the fuzzy weight belonging to each parameter can be determined using Eqs. (6) and (7) [26]:

$$\tilde{Z}_i = [\tilde{a}_{ij} \otimes \dots \otimes \tilde{a}_{in}]^{\frac{1}{n}} \tag{6}$$

$$\widetilde{W}_i = \tilde{Z}_i \otimes (\tilde{Z}_i \oplus \dots \oplus \tilde{Z}_n) \tag{7}$$

In the above relations, is the multiplication sign of fuzzy numbers and ⊕ is the sum of fuzzy numbers. Finally, the parameter W̃i, which is a linear vector, represents the fuzzy weight of the parameter i-m.

De-fuzzy weighting of fuzzy numbers: After finding the fuzzy weights related to each of the parameters, all numbers are converted to non-fuzzy using Eq. (8) [26]:

$$\widetilde{W}_i = \left(\prod_{i=1}^{3} \omega_j\right)^{\frac{1}{3}} \tag{8}$$

3.2. TOPSIS technique

The method of similarity to the ideal option was proposed by Yoon and Hwang in 1981. In this method, the options are ranked based on the similarity to the ideal solution, so that the more similar an option is to the ideal solution, the higher it ranks. If there are n criteria and m options in a multi-criteria decision problem, in order to select the best option using the similarity method to the ideal solution, the steps of the method are as follows [27]:

Step 1- define the decision matrix

According to the number of criteria and the number of options and the evaluation of all options for different criteria, the decision matrix is formed as follows:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

Where x_{ij} is the function of option i ($i = 1,2,...,m$) in relation to criterion j ($j = 1,2,...,n$)

Step 2 - Unscaling the decision matrix

In this step, we tried to convert criteria with different dimensions into dimensionless criteria and the R matrix is defined as follows:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \cdots & \cdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix}$$

There are several methods for scaling, but usually we use the following equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{9}$$

If the distance between the measured values is not large, the following equations can be used to scale the positive and negative criteria, respectively:

$$r_{ij} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \tag{10}$$

$$r_{ij} = \frac{\max\{x_{ij}\} - x_{ij}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \tag{11}$$

Step 3- Determine the weight vector of the criteria

At this stage, according to the coefficients of importance of different criteria in decision making, the weight vector of the criteria is defined as follows:

$$W = [w_1 \quad w_2 \quad \cdots \quad w_n]$$

The elements of the vector W are the coefficient of importance of the relevant criteria.

Step 4- Determine the weighted unmatched decision matrix

Weighted unmeasured decision matrix is obtained by multiplying the unmeasured decision matrix by the weight vector of the criteria:

$$v_{ij} = w_j r_{ij} \qquad j = 1, \dots, n\,;\, i = 1, \dots, m. \tag{12}$$

Step 5 - Find the positive-ideal and negative-ideal solution

The positive-ideal with and negative -ideal is shown as follows:

$$A^* = \left\{ v_1^*, v_2^*, \dots, v_j^*, \dots, v_n^* \right\} \tag{13}$$

$$A^- = \left\{ v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^- \right\} \tag{14}$$

Where v_j^* is the best value of j among all the options and v_j^- is the worst value of the criterion j of all the options. The options in A^* and A^- represent the better and the worse, respectively.

Step 6- Calculate the distance from the ideal and anti-ideal solution

In this step, for each option, the distance from the positive-ideal solution and the distance from the negative-ideal solution are calculated from the following relations, respectively:

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^*\right)^2} \tag{15}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^-\right)^2} \tag{16}$$

Step 7- Calculate the similarity index

In the last step, the similarity index is calculated from the following equation:

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \tag{17}$$

The value of the similarity index varies between zero and one. The closer the option is to the ideal, the closer the value of its similarity index will be to one. It is quite clear that if an option matches the ideal option, then its distance to the ideal solution is equal to zero and its similarity index is equal to one, and if an option matches the counter-ideal solution, then its distance to the counter-ideal solution is equal to zero. Its similarity index will be equal to zero. Therefore, to rank the options based on the value of the similarity index, the option that has the most similarity index is in the first rank and the option that has the lowest similarity index is in the last rank.

4. Data collection and analysis

In rock engineering system, in order to develop a rank system, selecting the most effective parameters are the most important issues. In rank system, as a very important and basic rule, the number of parameters that are used should be small. Therefore, using all of parameters in the rank system is inconvenient from the practical and engineering point of view. Thus, in the rank system, for selecting the final main parameters, the two assumptions have been considered: (a) the number of parameters that are used should be small, and (b) equivalent parameters should be avoided. Considering these two assumption, 18 parameters such as Rock Type (C1), Rainfall (C2), Intact Rock Strength-UCS (C3), RQD (C4), Weathering (C5), Tectonic Regime (C6), Groundwater Conditions (C7), Number of Major Discontinuity Sets (C8), Discontinuity Persistence (C9), Discontinuity Spacing (C10), Discontinuity Orientation (C11), Discontinuity Aperture (C12), Discontinuity Roughness (C13), Discontinuity Filling (C14), Slope (pit-wall) Angle (C15), Slope (pit-wall) Height (C16), Blasting Method (C17), Convexity/Concavity (C18), that have been chosen for assessing the rank system. In this study, data related to 28 slopes from 8 open pit mines in the world have been used to assess and rank sustainability. Table 1 shows the sloping walls studied in this study. Completion of information about each wall is done either in the field or by reading pre-recorded reports [28].

Table 1
The studied slopes.

Case No.	Name	Case No.	Name
A1	Sarcheshmeh-Iran- East wall	A15	Aznalcollar- Spain- South wall
A2	Sarcheshmeh-Iran- North wall	A16	Aznalcollar- Spain- West wall
A3	Sarcheshmeh-Iran- South wall	A17	Aznalcollar- Spain- North wall
A4	Sarcheshmeh-Iran- West wall	A18	Cadia Hill- Australia- Northeast wall
A5	Angoran-Iran- Southeast wall	A19	Cadia Hill- Australia- East wall
A6	Sangan-Iran-Baghak wall	A20	Cadia Hill- Australia- West wall
A7	Sangan-Iran- Anomaly A	A21	Cadia Hill- Australia- North wall
A8	Chuquicamata- Chile- Northwest wall	A22	Cadia Hill- Australia- South wall
A9	Chuquicamata- Chile- South wall	A23	Aitik- Sweden- East wall
A10	Chuquicamata- Chile- West wall	A24	Aitik- Sweden- Northeast wall
A11	Chuquicamata- Chile- North wall	A25	Aitik- Sweden- Northwest wall
A12	Chuquicamata- Chile- East wall	A26	Aitik- Sweden- Southeast wall
A13	Aznalcollar- Spain- Southeast wall	A27	Aitik- Sweden- Southwest wall
A14	Aznalcollar- Spain- Southwest wall	A28	Sungun- Iran- Southwest wall
A1 to A28: Considered alternatives (large open pit)			

4.1. Case study

One of the most important goals of this research is to compare the stability of Sungun copper mine wall with other large mines in the world. In fact, the stability of this mine along with other large mines whose stability status has been evaluated can be a specific way to assess the stability of large mines according to the characteristics of the rock mass. This mine is one of the largest open pit mines in Iran. Sungun copper mine is one of the most important copper mines in Iran and the Middle East which is located in 105 km northeast of Tabriz, 75 km northwest of Ahar and 28 km north of Varzaghan, in the vicinity of the Republic of Azerbaijan and the Republic of Armenia. Its longitude is 46 degrees and 43 minutes east, and the latitude is 38 degrees and 42 minutes north, and the average height of the region is 2000 m from sea level (maximum 2700 m) which is located on the global copper belt. This mine is located on the Arasbaran mountain range (Gharadagh) in the form of a penetrated mass. This mountain range with 80 km width is a part of the Alpine-Himalayan orogenic belt. The probable reserve of this mine is more than one billion tons, the extractable reserve (given the discoveries made) is about 796 million tons, and the total amount of the definitive, probable and possible reserves in the surrounding area of Varzaghan Sungun mine is about 1.7 billion tons of copper ore at a grade of 0.61%. Figure 3, shows the location and view of Sungun copper mine.

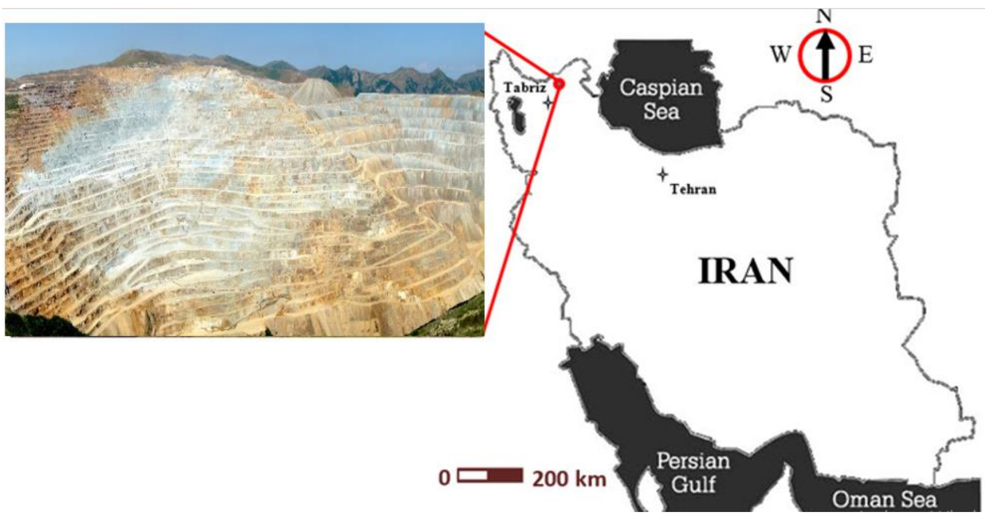

Fig. 3. The location of Sungun Copper Mine.

Field studies were conducted to evaluate the stability of this mine. Figure 4 and 5 show the geological map and the discontinuity characteristics of the mine levels. The Sungun copper deposit is in the northwestern part of a NW-SE trending Cenozoic magmatic belt (Sahand-Bazman) where porphyry copper deposits are located [29].

The Sungun porphyry (reportedly Miocene in age, based largely on regional geological relationships) has intruded a sequence of Cretaceous limestone and calcareous sedimentary units following collision of the Persian sub-continent with Europe and closure of the Neotethys in the Oligocene – Miocene. The intrusion and related post-mineralization dykes are a product of magmatic activity, the location of which is controlled by regional fault zones which strike WNW and are compartmentalized by a series of transfer faults which strike NNE-to-NE.

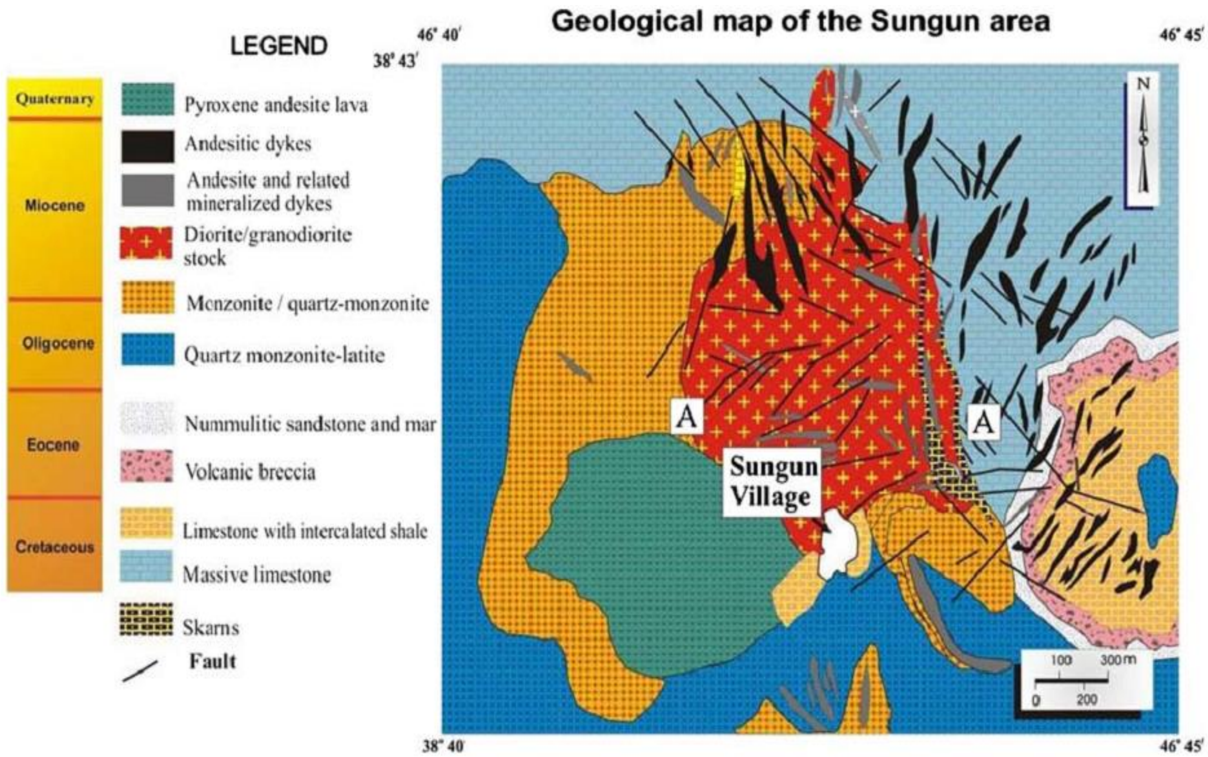

Fig. 4. Geological map of Sungun copper deposit [29].

The structure and regional tectonics can be used to constrain the chronology of alteration and mineralization at Sungun. The following points are suggested;

1. ~20–15 Ma, intrusion of the Sungun porphyry,
2. Propylitic alteration (predominantly meteoric fluids driven by thermal perturbation),
3. Locally developed silica (± kaolinite) acidic alteration as a result of exsolution of magmatic fluids,
4. locally developed sericite + pyrite ± quartz alteration which is fault controlled and found associated with WNW, NW and NE striking faults as well as a number of shallowly west dipping faults,
5. Intrusion of DK1a dykes (possibly synchronously with the sericitic alteration, which is also controlled by locally active faults.
6. 14–10 Ma, quartz + sulphide (including copper) vein mineralization with a NW preferred orientation.
7. Post mineralization, emplacement of NW and WNW striking dykes.
8. < 10 Ma, Late fault movement.

Stages 1 to 5 can be constrained to the period when there was a southwestward shortening as a result of the collision of Persian terranes with Europe. Stages 6 and 7 occurred during south eastward shortening from about 14 Ma as a result of plate reorganization at that time. Stage 8 may have occurred during several tectonic events in the Pliocene and Quaternary, including Quaternary tecto magmatic activity that resulted in the extrusion of sequences of intermediate tephra and volcanic [29].

a B

Fig. 5. a) View of a joint located at level of 2250 with a slope of 70 degrees, extension 25, in the direction of slope 295, which is severely crushed. b) View of a joint located at the level of 2287.5 with a slope of 80 degrees, extension 150, direction of the slope of 240 and an average opening of about 1-2 cm.

Table 2 shows field study information taken from the southwestern wall of the Sungun copper mine.

Table 2
Field study information recorded from the southwest wall of Sungun copper mine, Iran.

NO	Parameters	SW Sungun
C1	Rock Type (Major)	Quartz Monzonite (SP) & Diorite (Dk-1)
C2	Rainfall (mm/year)	300-450
C3	Intact Rock Strength-UCS (MPa)	30-80
C4	RQD (%)	50-75
C5	Weathering	W3
C6	Tectonic Regime	Strong
C7	Groundwater Conditions	Damp
C8	Number of Major Discontinuity Sets	1
C9	Discontinuity Persistence (m)	10-30
C10	Discontinuity Spacing (m)	0.06-2
C11	Discontinuity Orientation	Favorable
C12	Discontinuity Aperture (mm)	0.5-1
C13	Discontinuity Roughness (JRC)	Smooth
C14	Discontinuity Filling	Hard Filling
C15	Slope (pit-wall) Angle (deg)	30-40
C16	Slope (pit-wall) Height (m)	450
C17	Blasting Method	Modified production
C18	Convexity/Concavity	Concave

C1 to C18: Considered criteria (Geotechnical and geomechanical properties)

Table 3 shows the quantitative characteristics affecting the stability of the studied slopes. During this research, it was tried to evaluate all the characteristics affecting the stability capability quantitatively or qualitatively.

Table 3
Characteristics of sloping walls of studied mines.

Name	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
A1	80	135	60	45	90	60	100	3	12.5	5.3	40	3	90	60	35	390	40	60
A2	80	135	70	55	90	60	100	3	6.5	350	90	3	90	60	35	420	40	60
A3	80	135	55	45	90	60	60	4	10	350	60	3	80	40	35	620	40	60
A4	80	135	55	45	90	60	60	4	10	300	40	3	80	50	35	800	40	60
A5	40	497	73	41	90	60	100	4	20	75	40	3	40	50	30	170	40	60
A6	60	155	105	45	85	75	100	1	7.5	125	40	0.55	90	50	41	50	40	60
A7	60	155	90	40	60	75	60	3	15	85	40	0.55	40	50	45	65	40	60
A8	80	35	59	48	60	60	100	3	5	200	40	0.55	40	60	32	210	40	60
A9	80	35	52	59	40	60	100	4	2.75	325	60	0.55	90	60	31	700	40	60
A10	80	35	48	23	60	60	60	5	5.75	325	15	3	60	50	32	750	40	60
A11	80	35	67	44	40	60	100	5	5.75	400	60	0.55	60	60	31	750	40	60
A12	60	35	85	46	60	60	100	6	7.75	240	10	3	80	50	42	780	40	60
A13	80	650	55	60	100	40	100	3	3	225	80	0.1	80	60	34	240	40	60
A14	40	650	24	25	100	40	60	4	10	165	15	3	60	60	34	210	40	60
A15	40	650	20	25	60	40	60	4	10	90	40	3	60	40	34	210	40	60
A16	40	650	35	40	60	40	60	5	15	115	40	3	40	40	32	210	40	60
A17	60	650	35	40	100	40	60	3	7.5	60	60	0.55	60	60	32	240	40	60
A18	95	800	87	60	100	60	100	3	6.5	415	60	0.55	90	40	58	500	80	90
A19	95	800	53	56	100	60	100	2	4.5	375	60	3	90	40	58	500	80	60
A20	95	800	50	60	100	60	100	3	4.5	105	40	0.55	90	40	46	500	80	60
A21	95	800	89	68	100	60	100	3	3	175	80	3	100	40	58	500	80	60
A22	60	800	46	65	90	60	60	4	5.5	75	40	3	80	40	52	500	80	90
A23	95	680	133	78	60	60	60	4	2.25	350	80	0.55	80	80	42	125	60	90
A24	60	680	75	80	60	60	60	5	9.5	150	40	3	80	80	47	230	60	90
A25	95	680	138	82	100	60	100	5	3	325	60	0.55	90	40	51	250	60	90
A26	95	680	124	78	60	60	100	4	2.5	325	80	0.1	90	40	49	325	60	60
A27	95	680	138	85	60	60	100	4	3.5	150	60	0.55	90	40	53	325	60	90
A28	95	375	75	30	60	60	100	1	20	100	90	0.75	40	80	35	475	60	90

C1 to C18: Considered criteria, A1 to A28: Considered alternatives

5. Results

The first step in data analysis is to determine the degree of importance of the criteria for creating a new classification system. The importance of each of the mentioned criteria was determined based on the opinions of experts and specialists. At this stage, first the questionnaire form was completed by experts and then the degree of importance of each criterion was calculated using the FDAHP method. Table (4) shows an example of a questionnaire.

Table 4
Sample of the questionnaire, answered by the first expert.

Parameters affecting the slope stability	Importance of each parameter				
	Very Strength	Strength	Moderate	Weak	Very weak
Rock Type (Major)	✓				
Rainfall (mm/year)					✓
Intact Rock Strength-UCS (MPa)	✓				
RQD (%)		✓			
Weathering			✓		
Tectonic Regime				✓	
Groundwater Conditions				✓	
Number of Major Discontinuity Sets			✓		
Discontinuity Persistence (m)			✓		
Discontinuity Spacing (m)		✓			
Discontinuity Orientation		✓			
Discontinuity Aperture (mm)			✓		
Discontinuity Roughness (JRC)			✓		
Discontinuity Filling				✓	
Slope (pit-wall) Angle (deg)	✓				
Slope (pit-wall) Height (m)	✓				
Blasting Method		✓			
Convexity/Concavity				✓	

Then, the pairwise comparison matrix was formed based on the opinions of experts using the Saaty' s scale [30]. At this stage, the elements of each level were paired and compared to their other existing elements at a higher level and paired comparison matrices were formed. Allocation of numerical scores related to pairwise comparison of the importance of two indicators was done based on Table (5).

Table 5
Quantitative and qualitative classification for pairwise comparison of criteria.

Definition	Intensity of Importance
Extreme importance	9
Very strong or demonstrated importance	7
Strong importance	5
Moderate importance	3
Equal Importance	1
Weak, Moderate plus, Strong plus and Very, very strong	2, 4, 6 and 8

The pairwise comparison matrix is an n × n matrix in which n is the number of elements compared. For each n × n pairwise comparison matrix, the elements on the diameter are equal to one and do not need to be evaluated, but in other matrix components they must be determined based on pairwise comparisons. Symmetries with respect to diameter are inversely proportional to each other. The pairwise matrix based on the opinion of the first expert is listed in Table (6).

Table 6
Pairwise matrix based on the opinion of the first expert.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
C1	1.00	9.00	1.00	3.00	5.00	7.00	7.00	5.00	5.00	3.00	3.00	5.00	5.00	7.00	1.00	1.00	3.00	7.00
C2	0.11	1.00	0.11	0.14	0.20	0.33	0.33	0.20	0.20	0.14	0.14	0.20	0.20	0.33	0.11	0.11	0.14	0.33
C3	1.00	9.00	1.00	3.00	5.00	7.00	7.00	5.00	5.00	3.00	3.00	5.00	5.00	7.00	1.00	1.00	3.00	7.00
C4	0.33	7.00	0.33	1.00	3.00	5.00	5.00	3.00	3.00	1.00	1.00	3.00	3.00	5.00	0.33	0.33	1.00	5.00
C5	0.20	5.00	0.20	0.33	1.00	3.00	3.00	1.00	1.00	0.33	0.33	1.00	1.00	3.00	0.20	0.20	0.33	3.00
C6	0.14	3.00	0.14	0.20	0.33	1.00	1.00	0.33	0.33	0.20	0.20	0.33	0.33	1.00	0.14	0.14	0.20	1.00
C7	0.14	3.00	0.14	0.20	0.33	1.00	1.00	0.33	0.33	0.20	0.20	0.33	0.33	1.00	0.14	0.14	0.20	1.00
C8	0.20	5.00	0.20	0.33	1.00	3.00	3.00	1.00	1.00	0.33	0.33	1.00	1.00	3.00	0.20	0.20	0.33	3.00
C9	0.20	5.00	0.20	0.33	1.00	3.00	3.00	1.00	1.00	0.33	0.33	1.00	1.00	3.00	0.20	0.20	0.33	3.00
C10	0.33	7.00	0.33	1.00	3.00	5.00	5.00	3.00	3.00	1.00	1.00	3.00	3.00	5.00	0.33	0.33	1.00	5.00
C11	0.33	7.00	0.33	1.00	3.00	5.00	5.00	3.00	3.00	1.00	1.00	3.00	3.00	5.00	0.33	0.33	1.00	5.00
C12	0.20	5.00	0.20	0.33	1.00	3.00	3.00	1.00	1.00	0.33	0.33	1.00	1.00	3.00	0.20	0.20	0.33	3.00
C13	0.20	5.00	0.20	0.33	1.00	3.00	3.00	1.00	1.00	0.33	0.33	1.00	1.00	3.00	0.20	0.20	0.33	3.00
C14	0.14	3.00	0.14	0.20	0.33	1.00	1.00	0.33	0.33	0.20	0.20	0.33	0.33	1.00	0.14	0.14	0.20	1.00
C15	1.00	9.00	1.00	3.00	5.00	7.00	7.00	5.00	5.00	3.00	3.00	5.00	5.00	7.00	1.00	1.00	3.00	7.00
C16	1.00	9.00	1.00	3.00	5.00	7.00	7.00	5.00	5.00	3.00	3.00	5.00	5.00	7.00	1.00	1.00	3.00	7.00
C17	0.33	7.00	0.33	1.00	3.00	5.00	5.00	3.00	3.00	1.00	1.00	3.00	3.00	5.00	0.33	0.33	1.00	5.00
C18	0.14	3.00	0.14	0.20	0.33	1.00	1.00	0.33	0.33	0.20	0.20	0.33	0.33	1.00	0.14	0.14	0.20	1.00

C1 to C18: Considered criteria , A1 to A28: Considered alternatives

Table 7 shows the degree of importance of the criteria affecting the stability of sloping walls using Delphi fuzzy hierarchical analysis.

Table 7
The degree of importance of the parameters affecting the slope stability.

Criteria	Weight	Criteria	Weight
C1	0.140	C10	0.033
C2	0.051	C11	0.035
C3	0.123	C12	0.039
C4	0.064	C13	0.027
C5	0.047	C14	0.038
C6	0.045	C15	0.058
C7	0.018	C16	0.078
C8	0.022	C17	0.090
C9	0.033	C18	0.059

C1 to C18: Considered criteria

In the next step, the studied slopes are evaluated and ranked according to the various steps described in the similarity model to the ideal solution. The computational steps performed for this purpose are given below.

Step 1. define unscaled decision matrix

The decision matrix is scaled according to the values in Table 4 according to Eq. 5. Table 8 shows the unscaled decision matrix.

Step 2. define a weighted unscaled decision matrix

According to the weight vector determined for the problem criteria, a weighted unscaled matrix was formed. Table 9 shows the unmeasured weighted matrix.

Table 8
Unscaled matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
A1	0.159	0.149	0.145	0.154	0.257	0.0041	0.263	0.163	0.047	0.1959	0.213	0.195	0.218	0.134	0.224	0.211	0.141	0.165
A2	0.159	0.149	0.169	0.1882	0.133	0.2697	0.263	0.176	0.047	0.1959	0.213	0.195	0.218	0.302	0.224	0.211	0.141	0.165
A3	0.159	0.198	0.133	0.154	0.205	0.2697	0.263	0.259	0.047	0.1959	0.213	0.195	0.131	0.201	0.199	0.141	0.141	0.165
A4	0.159	0.198	0.133	0.154	0.205	0.2312	0.263	0.334	0.047	0.1959	0.213	0.195	0.131	0.134	0.199	0.176	0.141	0.165
A5	0.136	0.198	0.177	0.1403	0.411	0.0578	0.263	0.071	0.174	0.0979	0.213	0.195	0.218	0.134	0.099	0.176	0.141	0.165
A6	0.186	0.05	0.254	0.154	0.154	0.0963	0.048	0.021	0.054	0.1469	0.201	0.244	0.218	0.134	0.224	0.176	0.141	0.165
A7	0.204	0.149	0.218	0.1369	0.308	0.0655	0.048	0.027	0.054	0.1469	0.142	0.244	0.131	0.134	0.099	0.176	0.141	0.165
A8	0.145	0.149	0.143	0.1642	0.103	0.1541	0.048	0.088	0.012	0.1959	0.142	0.195	0.218	0.134	0.099	0.211	0.141	0.165
A9	0.141	0.198	0.126	0.2019	0.056	0.2504	0.048	0.293	0.012	0.1959	0.095	0.195	0.218	0.201	0.224	0.211	0.141	0.165
A10	0.145	0.248	0.116	0.0787	0.118	0.2504	0.263	0.314	0.012	0.1959	0.142	0.195	0.131	0.05	0.149	0.176	0.141	0.165
A11	0.141	0.248	0.162	0.1505	0.118	0.3082	0.048	0.314	0.012	0.1959	0.095	0.195	0.218	0.201	0.149	0.211	0.141	0.165
A12	0.19	0.297	0.206	0.1574	0.159	0.1849	0.263	0.326	0.012	0.1469	0.142	0.195	0.218	0.034	0.199	0.176	0.141	0.165
A13	0.154	0.149	0.133	0.2053	0.062	0.1734	0.009	0.1	0.228	0.1959	0.237	0.13	0.218	0.269	0.199	0.211	0.141	0.165
A14	0.154	0.198	0.058	0.0855	0.205	0.1271	0.263	0.088	0.228	0.0979	0.237	0.13	0.131	0.05	0.149	0.211	0.141	0.165
A15	0.154	0.198	0.048	0.0855	0.205	0.0694	0.263	0.088	0.228	0.0979	0.142	0.13	0.131	0.134	0.149	0.141	0.141	0.165
A16	0.145	0.248	0.085	0.1369	0.308	0.0886	0.263	0.088	0.228	0.0979	0.142	0.13	0.131	0.134	0.099	0.141	0.141	0.165
A17	0.145	0.149	0.085	0.1369	0.154	0.0462	0.048	0.1	0.228	0.1469	0.237	0.13	0.131	0.201	0.149	0.211	0.141	0.165
A18	0.263	0.149	0.21	0.2053	0.133	0.3198	0.048	0.209	0.28	0.2326	0.237	0.195	0.218	0.201	0.224	0.141	0.281	0.247
A19	0.263	0.099	0.128	0.1916	0.092	0.289	0.263	0.209	0.28	0.2326	0.237	0.195	0.218	0.201	0.224	0.141	0.281	0.165
A20	0.208	0.149	0.121	0.2053	0.092	0.0809	0.048	0.209	0.28	0.2326	0.237	0.195	0.218	0.134	0.224	0.141	0.281	0.165
A21	0.263	0.149	0.215	0.2327	0.062	0.1349	0.263	0.209	0.28	0.2326	0.237	0.195	0.218	0.269	0.249	0.141	0.281	0.165
A22	0.236	0.198	0.111	0.2224	0.113	0.0578	0.263	0.209	0.28	0.1469	0.213	0.195	0.131	0.134	0.199	0.141	0.281	0.247
A23	0.19	0.198	0.322	0.2669	0.046	0.2697	0.048	0.052	0.238	0.2326	0.142	0.195	0.131	0.269	0.199	0.282	0.211	0.247
A24	0.213	0.248	0.181	0.2737	0.195	0.1156	0.263	0.096	0.238	0.1469	0.142	0.195	0.131	0.134	0.199	0.282	0.211	0.247
A25	0.231	0.248	0.334	0.2806	0.062	0.2504	0.048	0.105	0.238	0.2326	0.237	0.195	0.218	0.201	0.224	0.141	0.211	0.247
A26	0.222	0.198	0.3	0.2669	0.051	0.2504	0.009	0.136	0.238	0.2326	0.142	0.195	0.218	0.269	0.224	0.141	0.211	0.165
A27	0.24	0.198	0.334	0.2908	0.072	0.1156	0.048	0.136	0.238	0.2326	0.142	0.195	0.218	0.201	0.224	0.141	0.211	0.247
A28	0.159	0.05	0.181	0.1026	0.411	0.0771	0.066	0.199	0.131	0.2326	0.142	0.195	0.218	0.302	0.099	0.282	0.211	0.247

C1 to C18: Considered criteria , A1 to A28: Considered alternatives

Table 9
Weighted unscaled matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
A1	0.009	0.003	0.018	0.0099	0.008	0.0001	0.01	0.013	0.002	0.0274	0.01	0.009	0.004	0.005	0.006	0.008	0.013	0.01
A2	0.009	0.003	0.021	0.012	0.004	0.0089	0.01	0.014	0.002	0.0274	0.01	0.009	0.004	0.011	0.006	0.008	0.013	0.01
A3	0.009	0.004	0.016	0.0099	0.007	0.0089	0.01	0.02	0.002	0.0274	0.01	0.009	0.002	0.007	0.005	0.005	0.013	0.01
A4	0.009	0.004	0.016	0.0099	0.007	0.0076	0.01	0.026	0.002	0.0274	0.01	0.009	0.002	0.005	0.005	0.007	0.013	0.01
A5	0.008	0.004	0.022	0.009	0.014	0.0019	0.01	0.006	0.009	0.0137	0.01	0.009	0.004	0.005	0.003	0.007	0.013	0.01
A6	0.011	0.001	0.031	0.0099	0.005	0.0032	0.002	0.002	0.003	0.0206	0.009	0.011	0.004	0.005	0.006	0.007	0.013	0.01
A7	0.012	0.003	0.027	0.0088	0.01	0.0022	0.002	0.002	0.003	0.0206	0.007	0.011	0.002	0.005	0.003	0.007	0.013	0.01
A8	0.008	0.003	0.018	0.0105	0.003	0.0051	0.002	0.007	6E-04	0.0274	0.007	0.009	0.004	0.005	0.003	0.008	0.013	0.01
A9	0.008	0.004	0.015	0.0129	0.002	0.0083	0.002	0.023	6E-04	0.0274	0.004	0.009	0.004	0.007	0.006	0.008	0.013	0.01
A10	0.008	0.005	0.014	0.005	0.004	0.0083	0.01	0.024	6E-04	0.0274	0.007	0.009	0.002	0.002	0.004	0.007	0.013	0.01
A11	0.008	0.005	0.02	0.0096	0.004	0.0102	0.002	0.024	6E-04	0.0274	0.004	0.009	0.004	0.007	0.004	0.008	0.013	0.01
A12	0.011	0.007	0.025	0.0101	0.005	0.0061	0.01	0.025	6E-04	0.0206	0.007	0.009	0.004	0.001	0.005	0.007	0.013	0.01
A13	0.009	0.003	0.016	0.0131	0.002	0.0057	3E-04	0.008	0.012	0.0274	0.011	0.006	0.004	0.009	0.005	0.008	0.013	0.01
A14	0.009	0.004	0.007	0.0055	0.007	0.0042	0.01	0.007	0.012	0.0137	0.011	0.006	0.002	0.002	0.004	0.008	0.013	0.01
A15	0.009	0.004	0.006	0.0055	0.007	0.0023	0.01	0.007	0.012	0.0137	0.007	0.006	0.002	0.005	0.004	0.005	0.013	0.01
A16	0.008	0.005	0.01	0.0088	0.01	0.0029	0.01	0.007	0.012	0.0137	0.007	0.006	0.002	0.005	0.003	0.005	0.013	0.01
A17	0.008	0.003	0.01	0.0088	0.005	0.0015	0.002	0.008	0.012	0.0206	0.011	0.006	0.002	0.007	0.004	0.008	0.013	0.01
A18	0.015	0.003	0.026	0.0131	0.004	0.0106	0.002	0.016	0.014	0.0326	0.011	0.009	0.004	0.007	0.006	0.005	0.025	0.015
A19	0.015	0.002	0.016	0.0123	0.003	0.0095	0.01	0.016	0.014	0.0326	0.011	0.009	0.004	0.007	0.006	0.005	0.025	0.01
A20	0.012	0.003	0.015	0.0131	0.003	0.0027	0.002	0.016	0.014	0.0326	0.011	0.009	0.004	0.005	0.006	0.005	0.025	0.01
A21	0.015	0.003	0.026	0.0149	0.002	0.0045	0.01	0.016	0.014	0.0326	0.011	0.009	0.004	0.009	0.007	0.005	0.025	0.01
A22	0.014	0.004	0.014	0.0142	0.004	0.0019	0.01	0.016	0.014	0.0206	0.01	0.009	0.002	0.005	0.005	0.005	0.025	0.015
A23	0.011	0.004	0.04	0.0171	0.002	0.0089	0.002	0.004	0.012	0.0326	0.007	0.009	0.002	0.009	0.005	0.011	0.019	0.015
A24	0.012	0.005	0.022	0.0175	0.006	0.0038	0.01	0.008	0.012	0.0206	0.007	0.009	0.002	0.005	0.005	0.011	0.019	0.015
A25	0.013	0.005	0.041	0.018	0.002	0.0083	0.002	0.008	0.012	0.0326	0.011	0.009	0.004	0.007	0.006	0.005	0.019	0.015
A26	0.013	0.004	0.037	0.0171	0.002	0.0083	3E-04	0.011	0.012	0.0326	0.007	0.009	0.004	0.009	0.006	0.005	0.019	0.01
A27	0.014	0.004	0.041	0.0186	0.002	0.0038	0.002	0.011	0.012	0.0326	0.007	0.009	0.004	0.007	0.006	0.005	0.019	0.015
A28	0.009	0.001	0.022	0.0066	0.014	0.0025	0.003	0.015	0.007	0.0326	0.007	0.009	0.004	0.011	0.003	0.011	0.019	0.015

C1 to C18: Considered criteria , A1 to A28: Considered alternatives

Step 3. Find the positive-ideal and negative-ideal solution

In this step, the values of positive-ideal and negative-ideal solutions for the problem criteria were calculated and entered in Table 10.

Table 10
Positive-ideal and negative-ideal values for the problem criteria.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
a+	0.008	0.001	0.041	0.0186	0.002	0.011	0.01	0.002	6E-4	0.0326	0.011	0.011	0.004	0.011	0.007	0.011	0.025	0.015
a-	0.015	0.007	0.006	0.005	0.014	0.0001	3E-4	0.026	0.214	0.013	0.004	0.006	0.002	0.001	0.003	0.005	0.013	0.01

C1 to C18: Considered criteria , a+: the positive-ideal solution, a-: the negative-ideal solution

Step 4. Find the distance from the positive-ideal and negative-ideal solution

In this step, the distance values from the positive-ideal and negative -ideal solutions were determined for the studied options (Table 11).

Step 5. Determine the similarity index

According to the relationship, 13 similarity index values were determined. Table 11 shows the similarity indices for the 28 slopes, respectively.

Table 11
Values of distance from positive-ideal, negative -ideal solution and similarity index for the studied slopes.

Case No.	S-	S+	c	Rank
A1	0.0303	0.034	0.4703	15
A2	0.0348	0.029	0.5449	8
A3	0.029	0.037	0.4418	19
A4	0.0276	0.04	0.408	23
A5	0.0305	0.037	0.45	17
A6	0.0407	0.027	0.6049	5
A7	0.0359	0.031	0.5368	9
A8	0.0337	0.032	0.5099	11
A9	0.0294	0.039	0.4311	21
A10	0.0278	0.042	0.3961	24
A11	0.0299	0.038	0.442	18
A12	0.0297	0.038	0.4403	20
A13	0.0323	0.034	0.4856	14
A14	0.0253	0.047	0.3495	27
A15	0.0243	0.048	0.3353	28
A16	0.0244	0.045	0.3526	26
A17	0.0254	0.042	0.3775	25
A18	0.0375	0.029	0.563	7
A19	0.0343	0.035	0.4965	13
A20	0.0312	0.037	0.458	16
A21	0.0391	0.028	0.5828	6
A22	0.0271	0.039	0.4109	22
A23	0.0505	0.018	0.7421	1
A24	0.0334	0.03	0.5305	10
A25	0.0495	0.02	0.7155	2
A26	0.0453	0.022	0.6716	4
A27	0.0478	0.022	0.6852	3
A28	0.0327	0.033	0.4992	12

S-: Distance from negative -ideal solution,
S+: Distance from positive-ideal solution,
c: Similarity index

According to the results in Table 11, 4 slopes of the Spanish Asnalquier mine are in the bottom rows of the table with similarity indices less than 0.4. In contrast, the two eastern and northwestern slopes of the Itik mine in Sweden with indices above 0.7 were in the first and second ranks, respectively. Other options were ranked in the middle according to the value of the similarity index.

6. Discussion

In order to evaluate the accuracy of the research results, field reports were collected from all studied mines and then a comparison was made between their actual behavior and the predicted categories. The results of these studies are given in Table 12 and Figure 6.

Table 12
Actual behavior of studied slopes.

Case	Slope behavior (Actual)	Rank	Case	Slope behavior (Actual)	Rank
A1	Stable	15	A15	Overall failure	28
A2	Stable	8	A16	Overall failure	26
A3	Stable	19	A17	Failure in the set of benches	25
A4	Stable	23	A18	Stable	7
A5	Overall failure	17	A19	Stable	13
A6	Failure in the set of benches	5	A20	Stable	16
A7	Failure in the set of benches	9	A21	Stable	6
A8	Stable	11	A22	Failure in the set of benches	22
A9	Stable	21	A23	Stable	1
A10	Stable	24	A24	Failure in the set of benches	10
A11	Stable	18	A25	Stable	2
A12	Failure in the set of benches	20	A26	Stable	4
A13	Stable	14	A27	Stable	3
A14	Overall failure	27	A28	Stable	12

A1 to A28: Considered alternatives

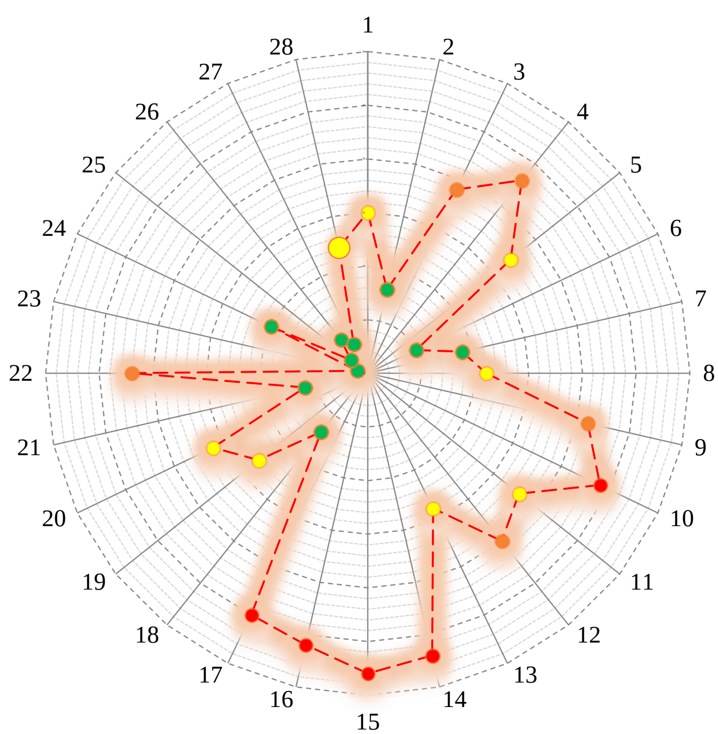

Fig. 6. Ranking of studied slopes according to similarity index.

The results of this study and its comparison with the actual behavior of slopes in all studied mines have shown the proper performance of the ranking system. So that the reports received from the slopes in the bottom rows of the table (slopes studied in the mine of Asnalquier, Spain), indicate the instability of the slopes in this mine and the total collapse of the walls. On the other hand, objective reports from the walls in the upper rows of the table indicate the stability of the walls. Also, with the examinations performed in some of the recorded reports, it was observed that in some of the slopes located in the middle ranks of the table, slight instability occurred in parts of the slope. So that the slopes located in the middle ranks can be prone to instability and the category of minor instabilities.

7. Conclusion

Slope stability is one of the most important challenges in large open pit mines. The occurrence of accidents may be accompanied by the occurrence of limited or large displacements, which in both cases, in addition to irreparable loss of life, cause problems or damages to structures located on the slope or lower parts. Instability of slopes may occur under natural conditions solely due to the weight of the unstable mass, or may be due to factors such as earthquakes, heavy and prolonged rains, or floods. Of course, in natural conditions, the presence of other factors such as erosion of the wall due to water or wind flow, gradual rise of groundwater level or even human activities, including the application of loading and unloading on the wall can make it unstable. Intensify. In the present study, we have tried to evaluate and rank 28 slopes from 8 large open pit mines in the world according to all identifiable influential factors on the slope stability. For this purpose, the TOPSIS and FDAHP with 18 criteria were used to rank the studied slopes. The slope: A23 with similarity index 0.742 was selected as the most desirable alternative and the slope: A15 with similarity index 0.335 as the most undesirable alternative in terms of slope stability. According to the results, 3 walls of Asnalquier mine in Spain are in the last 3 ranks of the ranking table with similarity index less than 0.4, in contrast to the 2 eastern and northwestern walls of Itik mine in Sweden with index Those above 0.7 were ranked first and second, respectively. In order to evaluate the accuracy of the research results, field reports were collected from all studied mines and then a comparison was made between their actual behavior and the predicted categories. The results showed that the slopes located in the bottom rows have a general collapse and the slopes located in the upper rows of the table are completely stable. Observations also show that the slopes located in the middle categories have slight falls in parts of the wall, which can be evaluated in the class of fair instability. Meanwhile, Songun copper mine with a similarity index of 0.399 was ranked 12th in the second half of the slope stability classification table. This indicates the acceptable stability of this mine compared to other mines in the half table. Finally, the results showed that, the matching of research results and field observations shows the applicability of the model in the initial evaluation of slopes to determine its stability.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

Morteza Niromand: Conceptualization; Data curation; Formal analysis; Reza Mikaeil and Mehran Advay: Project administration; and Writing, review & editing.

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