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Research article

Cavability Assessment in Narigan IIX Mine Using Empirical and Numerical Methods

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Abstract

This paper introduces a comprehensive study of the cavability of rock mass in the Narigan IIX mine by applying empirical and numerical methods. Assessing caving requirements is crucial for ensuring the safety and efficiency of underground mining operations. First, this study integrates all needed data with field investigations and laboratory tests used in empirical approaches and advanced numerical modeling to evaluate the cavability of the rock mass. After that, employing Laubscher's chart and Mathews's stability graph, rock mass was classified, and the minimum required HR was calculated for all Narigan IIX mi tectonic blocks. On the other hand, to evaluate empirical approach results, endeavor to create a beneficial model by DEM and obtain more insights about the caving process. The findings from both empirical and numerical analyses led to a minimum HR equal to 18 m with a square shape for undercut and the cave angle near 70 degrees. The results of this study are anticipated to contribute to improved mining practices and enhanced safety measures in similar geological settings.

1. INTRODUCTION

In recent years, the mining industry has faced challenges with depleting surface deposits and increasing demand for ore and mining materials. As a result, there is a growing need to develop cost-effective methods for extracting deep ore deposits. Among underground mining methods, caving methods offer distinct advantages over other underground methods due to their large-scale and cost-effective operations, making them comparable to surface mining methods. Therefore, caving methods are being touted as a solution to the challenges faced in recent years.

Caving methods are chosen based on the ability of the orebody and hanging wall to cave. This can happen individually for the orebody and hanging wall, or sequentially for both. It is important to ensure that the rock mass can cave safely and efficiently. After ore extraction, the hanging wall should be caved to fill the gap. Therefore, it is essential to thoroughly investigate the ability of the rock mass to cave before planning caving operations. If the rock mass does not have good cavability, mining operations may encounter challenges and damage. Therefore, a comprehensive investigation of the rock mass's cavability is crucial to understand the suitability of caving methods.

The cavability of a rock mass depends on its geo-mechanical properties, in-situ stress, induced stress, and the dimensions of the extraction span. This study aims to investigate how the most important geo-mechanical parameters influence the cavability of rock masses[1].

Based on the mining industry conditions in Iran and the presence of large-scale deep ore deposits, underground cave mining methods are suitable for extracting the remaining ore in open pit mines and for accessing new deep deposits. Narigan IIX mine is one of the largest and deepest deposits located in the Central Iran Block and should be thoroughly examined for the potential application of underground cave mining methods.

2. LITERATURE ON CAVABILITY OF ROCK MASS

The caving process depends on the relationship between induced stress, rock mass strength, and the geometry and strength of discontinuities. According to Kendorski's studies [2, 3], the successful propagation of caving requires the presence of suitable expanded, and low-depth discontinuities and fractures are desirable parameters for the caving process. For instance, when a joint set with high depth intersects with two low-depth joint sets, it can create favorable conditions for rock block displacements [4].

Studies in the field of caving typically concentrate on the caving process and the cavability of rock masses. Therefore, this literature reviews and highlights all related research and studies.

Before the year 2000, there were several studies dedicated to predicting caving based on rock mass classification methods like RMR, RQD, and Q-system. The seminal work in quantifying caving and rock mass cavability was credited to Laubscher's studies [5-8], which gave rise to the development of the Mining Rock Mass Rating (MRMR) for assessing rock mass cavability. Kendorski [2, 3] also sought to characterize rock mass cavability using rock mass classification in block caving mines. Other notable studies from this period include those by Mathews et.al [9] Obert et al. [10], McDonough [11], Ghose and Dutta [12], Lacy [13], Lorig et al. [14], Wang [15], and Duplancic and Brady [16], which delved into caving in specific mines or addressed particular issues. In 1993, Hassen et al. [17] introduced a new approach to rock mass cavability modeling, marking the first instance of numerical methods being employed in this domain.

In recent years, there has been a significant increase in the adoption of innovative techniques for assessing the cavability of the rock mass. Some studies have concentrated on investigating the Longwall Top Coal Caving (LTCC) method, while others have explored mass mining, specifically focusing on the block caving mining approach. Additionally, the utilization of classification systems has become standard practice.

The MRMR development stands out as a crucial advancement in empirical methods for studying cavability. Researchers such as Jakubec and Laubscher [18] and Jakubec and Esterhuizen [19]have endeavored to apply the MRMR system to mining practices. Chitombo [20] has also sought to evaluate cave mining studies, drawing from Laubscher's influential paper [6] entitled "Cave mining-state of the art". Another well-regarded empirical method in this field is the Mathews Stability Chart (MSC) [9], which was first introduced in 1981. Justifications for the MSC were put forward by Stewart and Trueman [21], Mawdesley et al. [22], and Suorineni [23, 24], in line with the principles of empirical methods. After that, Jabinpour et.al [25] compared results of MRMR and MSC in cavability prediction.

Numerous studies have utilized a variety of methods, including numerical approaches, physical and probabilistic modeling, as well as heuristic methods, to model rock mass cavability and the parameters influencing it. The goal is to predict and assess the cavability of rock mass and the caving process in underground mining methods such as Block Caving (BC), Sub Level Caving (SLC), Mass Caving (MC), Longwall Caving (LC), and LTCC. To gain a comprehensive understanding of these studies, it is beneficial to categorize them based on the modeling method employed.

2.1. Numerical Modeling And Simulation

Research on rock mass and cavability investigation began with Hassen et al. [17], and since then, numerous studies have utilized numerical methods. Rance et al. [26] employed computational modeling to evaluate fragmentation for block cave mines. The paper presents a computational strategy incorporating the Elfen code to simulate block caving operations involving multiple fracture and flow phenomena. Feng et al. [27] investigated rock mass cavability using 3D simulation technology. Sainsbury et al. [28] analyzed caving behavior with the Ubiquitous Joint Rock Mass Modelling Technique. The researchers used the Particle Flow Code (PFC3D) to create synthetic rock masses that explicitly represent a discrete fracture network (DFN) embedded within an intact rock matrix. This allowed them to simulate the mechanical properties of rock masses, including strength anisotropy and brittleness. The UJRM model incorporates strain-softening and ubiquitous joint constitutive models to simulate the behavior of rock masses with joint networks. The UJRM model was implemented in FLAC3D to simulate large-scale caving operations. This approach allowed the researchers to account for the effects of joint orientation, density, and persistence on the rock mass behavior during caving. Jafari and Khishvand

[29] assessed orebody cavability with the Geometry Identification of Fracture Rock. The paper presents a computational algorithm to trace and identify rock blocks created by discontinuities in a rock mass. This is crucial for understanding the structural behavior of the rock mass. The researchers developed an algorithm that uses matrices with integer elements to represent vertices, edges, and faces of rock blocks. This helps in accurately identifying both convex and concave blocks formed by fractures. Blachowski and Ellefmo [30] utilized numerical modeling to study rock mass deformation in SLC systems. The paper describes a concept that combines numerical models of deformations with repeated geodetic measurements to provide reliable information on the state of the rock mass in a mining area. The researchers used FEM to simulate rock mass deformations due to sublevel caving (SLC) mining. This method helps predict the extent of deformation zones on the mining ground surface. The results of the numerical modeling and geodetic measurements are used to improve deformation models for successive stages of mining activity, ensuring safety and minimizing surface damage. Using numerical methods, Jabinpour et al. [31, 32] evaluated rock mass cavability in LW and BC. In these studies, researchers conducted studies to investigate the effects of rock mass parameters on the caving process and the cavability of rock mass in the context of caving methods. They modeled both the Block Cave (BC) and Longwall (LW) methods, performing a sensitivity analysis on the variability of the parameters. The caving process was studied using the Discrete Element Method (DEM) implemented through UDEC software from Itasca. Ren et al. [33] endeavored to investigate caving mechanisms based on in-situ conditions with numerical methods. In this study, they utilized RFPA 2D (Rock Failure Process Analysis), a numerical software, to investigate the mechanisms behind rock mass caving and surface subsidence. This software is based on the Finite Element Method (FEM) and is commonly used to simulate the behavior of rock masses under various conditions. Le et al. [34] presented a new cavability evaluation using Discrete Element Method (DEM) in LTCC. This numerical program is created to accurately simulate the essential characteristics of Longwall Top Coal Caving (LTCC) operations, including the regular assessment of overburden strata and the detailed caving of top coal and roof rock. The model is developed from a genuine LTCC face that functioned under standard geological and mining conditions in the Bowen Basin, Australia and was calibrated using the field observations of the distance at which top coal began to cave from the installation room. Rafiee et al. [35] studied cavability parameters in block caving using numerical simulation. This study utilizes PFC3D software to simulate a large block caving mine. The simulation is integrated with a discrete fracture network to evaluate the effect of six factors on the cavability of the rock mass: the compressive strength of unbroken rock, the orientation of joints, the persistence of joints, the density of joints (P32), the friction of joints, and the hydraulic radius (HR). Finally, a sensitivity analysis is performed to determine which parameters are the most influential. Merino and Tapia [36] predicted rock mass cavability in El Salvador Mine using FLAC Itasca software. Due to the cessation of mining operations in the El Salvador mine, this study aimed to conduct a comprehensive analysis of the situation and develop a work program to safely manage the caving in the affected area. Numerical modeling using FLAC3D was employed to investigate the issue, and a successful 3D model was created to predict the conditions under which the hang-up would fail. The analysis indicated that this collapse would be violent. Alipenhani et al. [37, 38] evaluated rock mass cavability using numerical modeling. The researchers used the Finite Element Method (FEM) to simulate the caving processes of rock masses in block caving mining operations. Their study compares various failure criteria to predict caving height. They found that shear and tensile failure criteria provide more accurate predictions. This underscores the importance of selecting appropriate numerical methods and criteria for effectively simulating and understanding the behavior of rock masses during block caving.

2.2. Rock Engineering Systems

Chang-Sheng [39] conducted a classification of cavability by examining the structural properties of rock masses. Vakili and Hebblewhite [40] introduced a new criterion for assessing the cavability of top coal, considering factors such as deformation modulus, vertical and horizontal stresses, coal thickness, and joint spacing. Rafiee et al. [41] evaluated the effective properties of rock mass cavability in BC using a rock engineering system. Cao et al. [42] focused on cavability assessment using an MRMR classification system. Jabinpour et al. [43] investigated rock mass cavability through geostatistical modeling based on the MRMR system. Sui et al. [44] analyzed the caving characteristics of inclined jointed rock masses in a caving mine using numerical methods.

2.3. Heuristic Methods

Rafiee et al. [45] introduced a new cavability index using a fuzzy rock engineering system for BC. Meanwhile, Gautam et al. [46] examined roof rock cavability using the parting plane approach. Rafiee et al. [47] proposed a simple approach based on a fuzzy RES to predict rock mass cavability in BC mines. Additionally, He et al. [48] developed a comprehensive fuzzy approach to investigate cavability in BC mines. Finally, Zhou et al. [49] presented a new method to assess fragmentation in BC using an unascertained measurement model and information entropy with a flexible credible identification criterion.

3. NARIGAN IIX MINE

The Narigan IIX mine is situated 25 kilometers to the northeast of Bafgh and 13 kilometers to the northeast of the Choghart iron ore mine. Accessible via the Bafgh-Bahabad road within a 30-kilometer distance, the mine is also close to the Sechahoon and Mishdovan iron ore mines [50].

The geophysical deposit is estimated to be 20,000,000 cubic meters based on the final deposit model and exploration drill hole results. With a density of 3.5 tons per cubic meter, the estimated ore deposit is more than 70,000,000 tons of iron ore. The iron ore is predominantly magnetite with an average grade of 40 percent total iron, along with sulfur (4.9%), phosphorus (0.185%), and silica (18.7%).

Petrological studies at Narigan IIX Mine revealed that the ore body is surrounded by biotite-schist and quartz-schist rocks. The orebody's geometry can be described as an inclined layer body with a dip ranging from 45 to 50 degrees oriented to the south and 30 to 40 degrees to the west. According to well-logging data, the uppermost level of the ore body is situated at a depth of 480 m and extends to 1000 m depth [50].

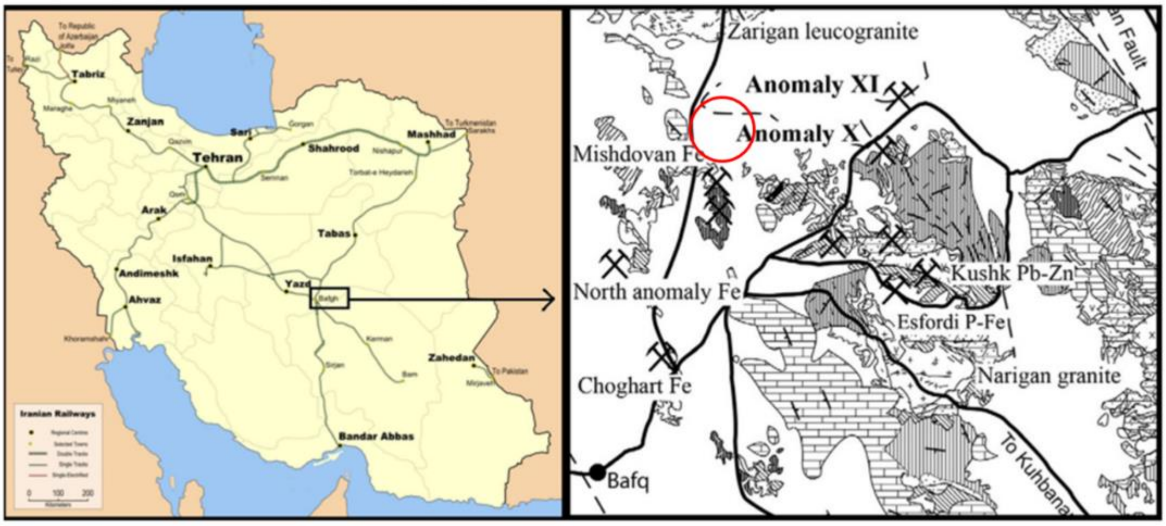


Fig. 1. Narigan IIX iron ore mine location.

4. PARAMETERS EFFECT ON CAVABILITY

The cavability of rock mass depends on natural parameters such as in-situ stresses and geo-mechanical properties, as well as mining-induced parameters such as induced stresses. Fig. 2 illustrates the number of effective parameters affecting the cavability of rock mass [41].

4.1. Uniaxial Compressive Strength (UCS)

The uniaxial compressive strength (UCS) is recognized as an important parameter in rock engineering classification systems like RMR and MRMR. Various characteristics, such as alteration rate, weathering rate, micro-cracks, density, and permeability, influence the UCS. It is known that an increase in UCS results in lower cavability in the rock mass [41].

4.2. Hydraulic Radius (HR)

The hydraulic radius (HR) is calculated by dividing the area of the exposed roof undercut by its perimeter. HR plays a crucial role in influencing the induced stress around the undercut. An increase in HR leads to a higher rate of caving. When choosing the HR, it is important to consider the MRMR classification system to facilitate caving [41, 51].

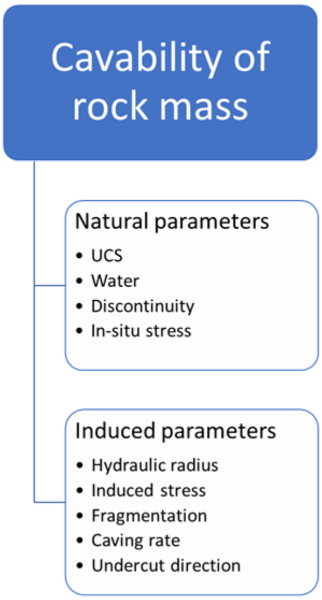


Fig. 2. Parameters effected on cavability of rock mass [41]

4.3. Fragmentation

The success of underground caving operations hinges on the effective fragmentation of the rock mass. Predicting fragmentation requires a deep understanding and identification of the natural discontinuities in the rock mass. The fragmentation process is influenced by several factors, including mine design, exploitation methods, the number and orientation of joint sets, their spacing, in-situ and induced stress, and the strength of the rock [41].

4.4. Caving Rate

The speed at which caving occurs is heavily influenced by the degree of fragmentation within the rock mass. This, in turn, has a notable impact on the integrity of the rock mass, the level of induced stress, and the rate at which fractures spread. The integration of the undercutting rate can exacerbate this factor, potentially leading to the formation of air gaps and air blasts within mining spaces. Hence, it is imperative to carefully consider the correlation between the caving rate and the undercutting rate, with a key focus on ensuring that the former consistently surpasses the latter [41].

4.5. Undercut Status

To efficiently extract ore through undercut excavation, it is crucial to consider the induced stress and its impact on the cavability of the rock mass. The selection of a suitable location for undercutting and the direction of its advancement is influenced by factors such as the shape of the ore body, distribution of ore grade, orientation and magnitude of induced stress, strength of the ore rock, and the presence and orientation of fractures [41].

Undercutting in the direction of the principal stresses can affect induced stress values. For optimal caving operation, it is advisable to excavate the undercut in the same direction as the maximum principal stress [52].

4.6. Discontinuities

The geometric and strength properties of rock mass discontinuities play a vital role in influencing the quality of the rock mass and its behavior during underground excavation. When it comes to the caving process and fragmentation in mines, the presence of discontinuities can result in rock mass failures. Therefore, it is crucial to accurately identify the characteristics of these discontinuities to gain a better understanding of the caving process and assess the quality of the rock mass [51].

5. DATA AND CHARACTERISTICS

Geological and tectonic studies of the Narigan IIX mine have revealed that the rock mass is categorized into three tectonic blocks due to the predominant faults in the area. The main section is delineated by two faults-oriented northwest-southeast, resulting in the division of the mine into three distinct parts: central (Bl2), eastern (Bl1), and western (Bl3), as depicted in Fig. 3.

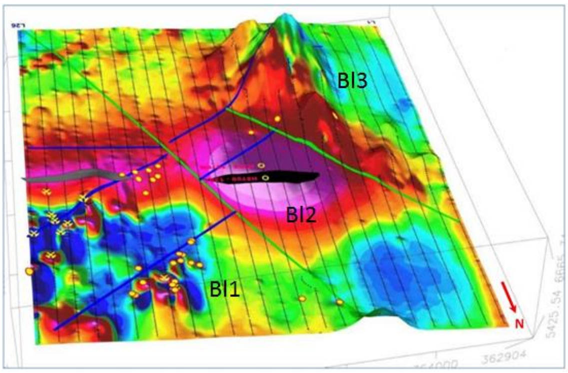


Fig. 3. The tectonic blocks of the Narigan IIX mine [50].

The research entails gathering information on the rock mass and its discontinuities, encompassing both geometrical and mechanical data. This data is acquired through on-site surveys of natural inclines and the analysis of core samples, using instruments like a compass, surveying gear, profilometer, and Schmidt hammer. Furthermore, tests are carried out to ascertain the properties of the intact rock through rock mechanics analysis.

5.1. Geometrical Data

Geometrical data from the Narigan IIX mine was classified into three blocks and organized to include joint set dip, dip direction, and spacing. These data were separately presented in Tables 1 to 3.

Table 1. Joint sets of tectonic Bl1 of Narigan IIX mine

Joint set	Parameter	Average value
Bl1-JS1	Dip (degree)	58.55
	Dip Direction (degree)	143.1
	Spacing (m)	2.884

Table 2. Joint sets of tectonic Bl2 of Narigan IIX mine

Joint set	Parameter	Average value
Bl2-JS1	Dip (degree)	58.55
	Dip Direction (degree)	143.1
	Spacing (m)	2.884
Bl2-JS2	Dip (degree)	69.00
	Dip Direction (degree)	282.9
	Spacing (m)	7.126
Bl2-JS3	Dip (degree)	70.08
	Dip Direction (degree)	111.2
	Spacing (m)	3.530
Bl2-JS4	Dip (degree)	67.36
	Dip Direction (degree)	175.0
	Spacing (m)	6.425
Bl2-JS5	Dip (degree)	35.79
	Dip Direction (degree)	63.0
	Spacing (m)	4.415

5.2. Mechanical data

The mechanical properties of the Narigan IIX mine were obtained by in-situ and laboratory tests. According to experimental and numerical modeling requirements, data was presented in the following tables separately.

Table 3. Joint sets of tectonic Bl3 of Narigan IIX mine

Joint set	Parameter	Average value
Bl3-JS1	Dip (degree)	66.37
	Dip Direction (degree)	134.2
	Spacing (m)	5.706
Bl3-JS2	Dip (degree)	45.61
	Dip Direction (degree)	87.2
	Spacing (m)	5.469
Bl3-JS3	Dip (degree)	67.31
	Dip Direction (degree)	202.5
	Spacing (m)	6.191
Bl3-JS4	Dip (degree)	66.82
	Dip Direction (degree)	313.0
	Spacing (m)	2.842
Bl3-JS5	Dip (degree)	69.49
	Dip Direction (degree)	0.75
	Spacing (m)	6.038
Bl3-JS6	Dip (degree)	70.77
	Dip Direction (degree)	261.8
	Spacing (m)	4.205

Table 4. Intact rock properties of Narigan IIX mine

Block No.	Density (gr/m3)		UCS (MPa)		Schmidt No.	
	Average	St. Div	Average	St. Div	Average	St. Div
1	2.79	0.144	26.17	0.501	31.67	19.93
2	2.78	0.105	18.84	0.88	35.04	16.27
3	2.76	0.129	25.90	0.71	30.96	20.33

Table 5. Intact rock shear strength factors of Narigan IIX mine

Block No.	Friction Angle (degree)		Cohesion (MPa)	
	Average	St. Div	Average	St. Div
1	25.70	4.31	0.117	0.0102
2	26.94	4.48	0.143	0.0135
3	26.00	4.54	0.127	0.0115

Table 6. Joint characteristics of Narigan IIX mine

Block No.	Cohesion (MPa)		Friction Angle (degree)		JRC	
	Average	St. Div	Average	St. Div	Average	St. Div
1	0.258	0.1027	19.16	5.63	6.98	2.82
2	0.312	0.1242	20.07	5.72	8.23	3.20
3	0.279	0.1118	19.24	5.74	7.51	3.00

5.3. Underground Water Condition

In the arid desert of the Narigan IIX mine, the dry conditions lead to an average temperature that regularly exceeds 20 degrees Celsius. Additionally, the annual evaporation rate in this environment has been measured at 138.2 mm. Given the presence of active tectonic conditions and the existence of faults and fractures within the rock mass, the permeability is likely to be high. This indicates that there is a high likelihood for the movement of fluids through the rock formations.

6. EMPIRICAL CAVABILITY PREDICTION

The assessment of rock mass characteristics involves using rock mass classification systems like RMR and Q-system, which are widely recognized in the field of rock engineering. Consequently, researchers and underground mining engineers employ these classification systems to analyze caving and predict the cavability of rock mass, making necessary adjustments as needed. The most important modifications used for this purpose are Laubscher's MRMR [5] and Mathew's stability graph [22] approaches. In this section, both of them are employed to predict the cavability of rock mass in the Narigan IIX mine. The cavability is compared by a variation to the required HR to start caving process.

6.1. Laubscher MRMR Approach

As noted in the literature, Laubscher [5, 18] used mining data and created a chart to predict the likelihood of rock mass caving in underground mines. The chart divided the conditions into three zones: stable, transitional, and caving. According to the chart, the HR for caving increased with the rock mass rating (MRMR) increase. In the following, the MRMR of tectonic blocks was calculated separately.

Consequently, to prevent rock mass stability and rock bursts in mine spans, the undercut must have an appropriate HR value. The table below presents the required HR based on the MRMR value and Lauscher's chart for each block.

Table 7. Calculating MRMR for all tectonic blocks of Narigan IIX mine

No.	Factor	Calculated Factor					
		Bl1		Bl2		Bl3	
		Value	Rate	Value	Rate	Value	Rate
1	Intact rock Strength (MPa)	26.17	4	18.84	2	25.9	4
2	RQD	25-50	6	25-50	6	25-50	6
3	Joint Spacing	2.884	25	5.36	25	5.08	25
4	Joint condition (JRC)	6.98	28	8.23	30	7.51	28
5	Weathering	100 %		100%		100%	
6	Joint orientation	90%		70%		70%	
7	Blasting effect	85%		85%		85%	
	MRMR	48		37		37	

Table 8. Assess minimum HR in Laubscher's chart for all tectonic blocks of Narigan IIX mine

Tectonic Block No.	MRMR	HR (m)
Bl1	48	27
Bl2	37	18
Bl3	37	18

6.2. Mathews Stability Graph Approach

To assess the cavability of rock mass by using Mathews [9, 22] approach, it is necessary to calculate the Stability Number (N), which is used in the caving prediction chart. The N is calculated using Q' and A, B, and C factors. Details of how to determine N can be found in the references [8, 21].

In the following, N is calculated for all tectonic blocks separately.

Table 9. Calculating N for all tectonic blocks of Narigan IIX mine

	Factor	Bl1	Bl2	Bl3
1	Q'	12.00	2.56	2.00
2	A	0.1	0.1	0.1
3	B	0.7	0.8	0.7
4	C	1.0	1.0	1.0
	N	0.97	0.20	0.14

After calculating N for all tectonic blocks using the modified stability graph [22], the minimum HR to start caving process is estimated.

Table 10. Assess minimum HR in Mathews graph for all tectonic blocks of Narigan IIX mine

Tectonic Block No.	N	HR (m)
Bl1	0.97	40
Bl2	0.20	19
Bl3	0.14	17

The comparison between the results of the Laubscher and Mathews approaches showed that the tectonic blocks generally produced similar outputs. However, there was a significant difference in Block 1, with the minimum Hydraulic Radius (HR) being 27 according to Laubscher, and 40 according to Mathews. It appears that improving the quality of the rock mass can lead to notable variations in the assessment of the minimum HR.

7. NUMERICAL MODELING

Numerical methods are essential for modeling rock masses, helping engineers simulate and analyze complex rock behaviors under different conditions. These methods include continuum approaches such as the Finite Element Method (FEM) and Finite Difference Method (FDM), as well as discontinuum approaches like the Discrete Element Method (DEM) and Discrete Fracture Network (DFN) modeling [53]. By considering factors such as pre-existing fractures, stress states, and material properties, numerical models aid in predicting how rock masses will respond to excavation, loading, and other engineering activities [54]. This predictive capability is crucial for designing safe and efficient mining operations, tunneling projects, and other geotechnical applications [55]

In numerous research studies, numerical methods have been used to investigate the ability of rock masses to cave and the caving process. It is crucial to assess the cavability of tectonic blocks in the Narigan IIX mine using empirical approaches and a model of the caving process. This numerical modeling assessment is essential for predicting the cavability of the rock mass and conducting feasibility studies for mining iron ore using an underground caving method. To accomplish this, the 3DEC Itasca software, based on DEM, was chosen to model the caving process and evaluate the capabilities of numerical methods and the conditions of the rock mass.

The study chose 3D modeling over 2D modeling because it provides results that are closer to reality. To understand the impact of high horizontal stress on the ability of rocks to cave and their behavior when caving, it is important to use 3D modeling of the rock mass. The mechanical model is employed to analyze the instability of the undercut, taking into account the physical and mechanical properties of the rock mass, using behavioral and strengthening relationships.

In cavability analysis, discontinuities such as layers, faults, and joint sets typically play a crucial role in controlling the stability of rock masses. The presence of numerous joint sets in a rock mass results in a blocky structure. In such cases, it is appropriate to investigate the caving potential by assuming the rock mass as a discontinuous area where blocks are together. Adjacent blocks are interconnected, leading to rotation and displacement. It is important to note that a significant amount of data is required to achieve an acceptable rock mass model. Therefore, all necessary data from the Narigan IIX mine were collected using in-situ and laboratory tests.

In this study, we conducted field investigations and examined the geotechnical aspects of tectonic Block 2 and its fragmentation rate concerning the overall block dimension. We assumed that the rock mass consists of discontinuous areas with several joint sets. Additionally, the main faults were defined as the block boundaries in the model. The main ore body was found in tectonic Block 2. In our numerical modeling, we focused only on investigating tectonic Block 2 to predict its cavability.

7.1. Model creation

Based on the capabilities of 3DEC Itasca, it can be used to investigate the cavability of rock masses. The model represents a jointed rock mass with five joint sets, as detailed in Table 11.

Table 11. Mechanical properties for numerical model input

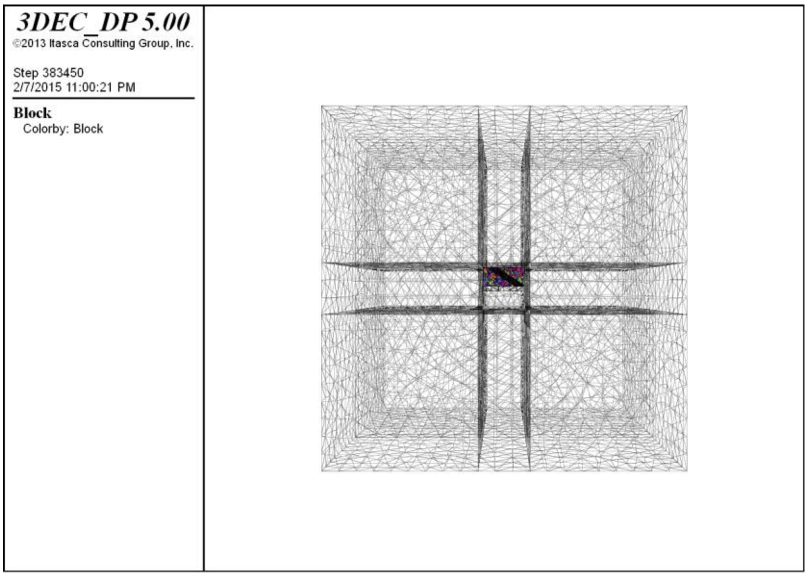
	Parameter	Value
1	Density (Kg/m3)	2800
2	Intact rock strength (MPa)	18.84
3	Cohesion (MPa)	30
4	Friction Angle (Degree)	40
5	Joint surface cohesion (MPa)	0.31
6	Joint surface friction angle (Degree)	20
7	Bulk Module (GPa)	14.84
8	Shear Module (GPa)	11.13
9	Normal Stiffness (GPa/m)	26.7
10	Shear Stiffness (GPa/m)	9.1

The ore body is situated at a depth of 700 m, so the block is formed as a cube with dimensions of 1400 m on each side. Once the undercut boundaries are identified, various parameters related to the joint sets are applied to the model. In-situ stress factors are then utilized to initiate the process and achieve the primary balance. The undercut is defined as a square span with an HR of 18 m based on the results of hydraulic radius in the empirical cavability prediction method in section 6.

As shown in Fig. 4, the model was created by following these data and the condition of the ore body and rock mass. The joint persistence is assumed unlimited. Also, Fig. 5 presents the main section of the model, which consists of fractures and joint sets.

After the model was meticulously generated, it was executed to simulate the behavior of the rock mass under caving conditions. It was essential for the model to achieve a state of equilibrium. This balancing process involved adjusting the forces within the model until the net unbalanced force was reduced to zero.

Once this state of stability was attained, the model was fully prepared to undergo the application of caving conditions, allowing for a detailed examination of how the rock mass would respond under those specific circumstances (Fig. 6). This involved excavating the undercut and representing failed blocks in the undercut space as shown in Fig. 7. Some blocks collapsed and were removed from the model, while the separation of other rock blocks became apparent.



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Block
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Fig. 4. Geometry of model and location of ore body and mining spans of Narigan IIX mine.

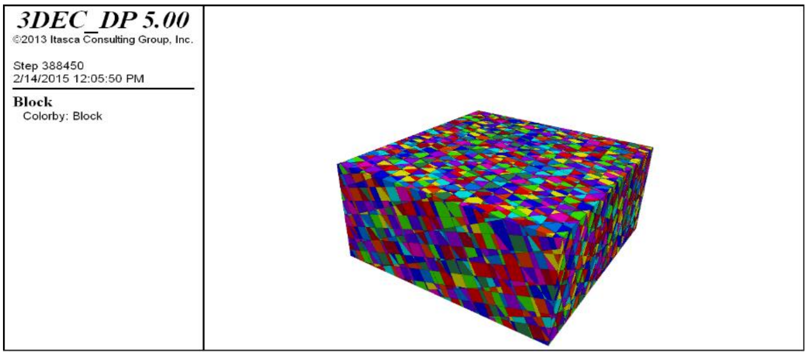

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Fig. 5. Fractured zone in the numerical model of Narigan IIX mine.

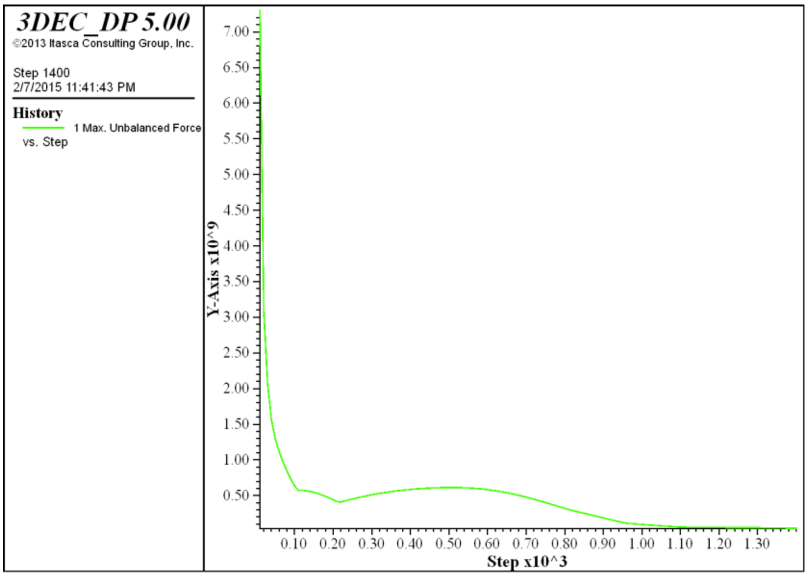


Fig. 6. Equilibrium conditions with the net unbalanced force were reduced to zero.

After generating the model, it was run to check the rock mass behavior under caving conditions by excavating the undercut and drawing failed blocks in the undercut space. Refer to Fig. 7. Some blocks were caved in and deleted from the model, and the separation of other rock blocks can be seen.

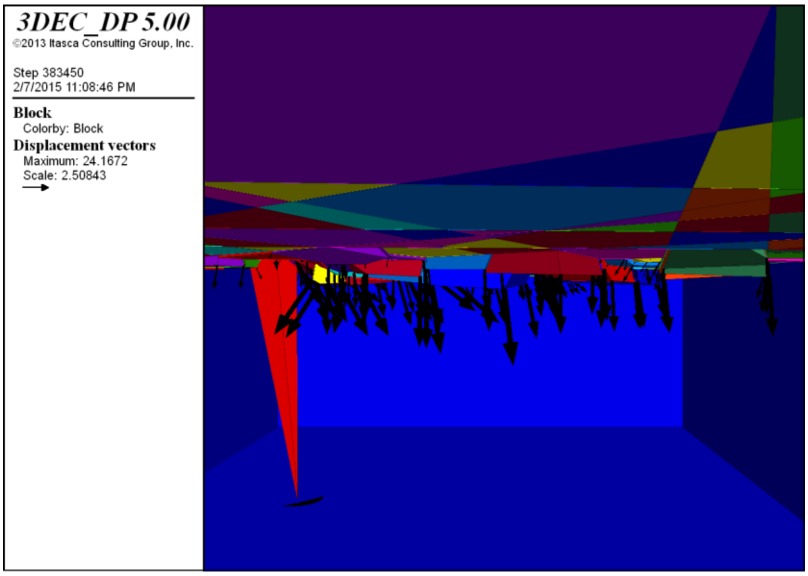
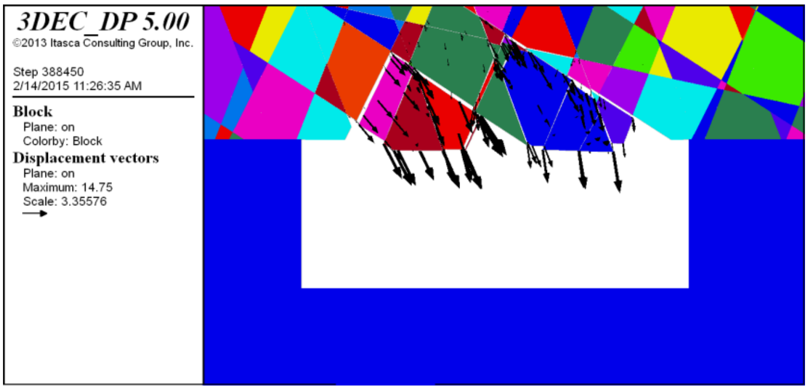


Fig. 7. Direction of displacement of caved block in the Narigan IIX mine.

Fig. 7 depicts the displacement direction of the caved blocks into the undercut span. This result suggests that the rock mass in the Narigan IIX mine is suitable for caving, as evidenced by the occurrence of caving under induced stress and mining design conditions.

To better understand rock block failure and the caving process, consider Fig. 8 and Fig. 9, which show sections of the caving model. Each block is separated from its neighbor blocks and falls into the undercut span. After that, the HR increases because the area of the exposed face increases, and caving occurs more easily.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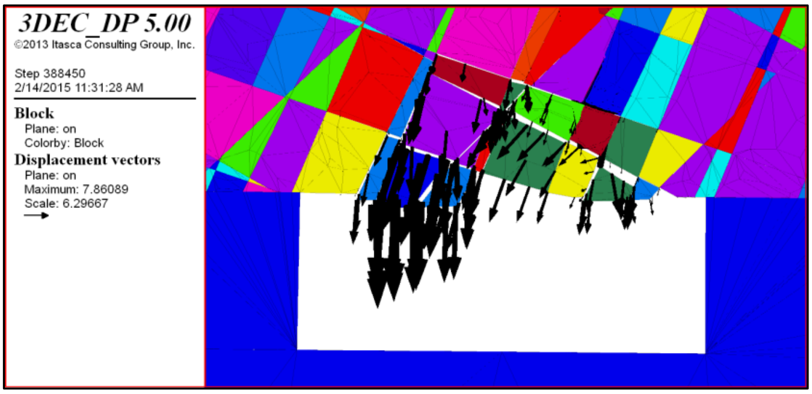
Block
Plane: on
Colorby: Block
Displacement vectors
Plane: on
Maximum: 14.75
Scale: 3.35576

Fig. 8. A 2D N-S section of caving model with displacement vectors in Narigan IIX mine.


3DEC_DP 5.00
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Block
Plane: on
Colorby: Block
Displacement vectors
Plane: on
Maximum: 7.86089
Scale: 6.29667

Fig. 9. A 2D W-E section of a caving model with displacement vectors in Narigan IIX mine.

The results of numerical modeling illustrate the available conditions and suitable situations to begin the caving process. Based on input parameters, it is possible to use an undercut with HR below 18 m and get a suitable caving operation. Also, by considering the model results and pattern of block displacements, it is observed that blocks were caved under a cave angle near 70 degrees, which led to the assessment subsidence of the surface due to cave mining operation.

5. CONCLUSIONS

The advancement of technology and the increasing global demand for minerals have led to a significant rise in surface mine ore extraction. As a result, the world is approaching the depletion of surface resources. To address this issue, underground mining methods, particularly caving underground mining, offer an economical and competitive solution. The cavability of the rock mass is crucial for ensuring a safe and effective operation when employing caving methods. Researchers like Laubscher and Mathews have proposed empirical approaches based on rock mass classification systems to predict the cavability of the rock mass for civil and mining applications. Additionally, recent developments in numerical methods have allowed many researchers to model rock mass behavior during the caving process.

The Narigan IIX mine, situated in the central block of Iran, contains a large, deep ore body of iron ore. This mine is divided into three main sections, which include faults. Given that the primary portion of the ore body lies between depths of 480 meters and 1000 meters, it is essential to investigate the cavability of the rock mass and the feasibility of using caving underground methods.

In this study, we assessed the cavability of the rock mass using both empirical and numerical methods to gain a reliable understanding of how the rock mass will behave under conditions related to the block caving method. First, we collected necessary data from the Narigan IIX mine through field and laboratory investigations. Next, by utilizing the Laubscher caving chart and Mathews stability graph, we predicted the cavability of the rock mass for each block individually. The results indicated that the minimum height of extraction (HR) in this mine is approximately 18 meters. Moreover, as the quality of the rock mass improved, the differences between the results from the Laubscher and Mathews approaches increased. Furthermore, using Itasca software, a numerical model was created to analyze the rock mass's responses to caving conditions. The modeling results revealed that the rock mass demonstrates suitable cavability at an HR of 18 meters, and caving is expected to occur at heights below this value. Additionally, the optimal cave angle of around 70 degrees, based on block displacements, could be beneficial for subsidence studies related to the surface. In conclusion, this study found that both empirical and numerical methods yielded similar results, which are valuable for studying cavability. The numerical model also provides further insights into the ground's response to caving operations and offers data for future research.

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