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A New Approach for Drilling Method Selection in Open Pit Mines Using Rock Mass Drillability Index

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Abstract

Drilling operations play a pivotal role in open-pit mining, where drilling costs represent a significant portion of overall production expenses. Therefore, selecting an optimal drilling system is essential to enhance operational efficiency and cost-effectiveness. In this study, the rock mass drillability index (RDi) classification is employed to introduce a systematic approach for selecting the most appropriate drilling method. The proposed methodology adopts a stepwise framework that integrates mineralogical, mechanical, and physical properties of intact rock, along with the structural characteristics of the rock mass. By combining the cumulative scores of these parameters with the blasthole diameter, a comprehensive decision-making chart divided into eight distinct zones is developed. Each zone corresponds to the most suitable drilling technique among four alternatives: percussive, rotary, percussive-rotary, and down-the-hole (DTH) drilling. Results show that the proposed method successfully recommends the percussive drilling system for rocks characterized by high hardness (Mohs hardness of 6–7) and high uniaxial compressive strength (100–200 MPa). The practicality and effectiveness of the proposed approach are validated through its application to the Komshecheh barite mine in Iran, where the method successfully recommends the most efficient drilling options for site-specific geological conditions.

Keywords

rock mass drillability index, drilling method, blasthole diameter, intact rock properties, structural characteristics

1 Introduction

Drilling is the initial and foundational stage of open-pit mining operations, serving as a key determinant for the efficiency of subsequent extraction processes. It plays a crucial role not only in ensuring consistent production and operational continuity but also in influencing overall engineering performance and cost-effectiveness [1, 2]. As such, drilling is critical from both technical and economic perspectives, directly impacting the success of the entire mining workflow.

Given the substantial costs associated with drilling operations, selecting an appropriate drilling method is crucial for optimizing overall production in open-pit mines. An unsuitable choice can adversely affect blasting efficiency, leading to undesirable fragmentation, increased loading and hauling costs, accelerated wear, and reduced lifespan of drill bits, and ultimately a decrease in drilling rates [3–5]. For instance, poor drilling and blasting practices have been shown to cause inconsistencies in fragmentation and poor pit conditions, resulting in excessive downtime in loading, hauling, and crushing processes. Additionally, ineffective drilling and blasting can lead to increased costs for mine support to ensure safe working environments and more dilution of ore, reducing companies' profits [6, 7].

Optimizing drilling and blasting parameters has been identified as a key strategy for improving overall mining efficiency and reducing operational costs. Implementing best practices in drilling and blasting can enhance fragmentation quality, thereby improving downstream processes such as loading, hauling, and crushing, and ultimately leading to cost savings and increased productivity [8].

In open-pit mining, three primary drilling systems are commonly employed: percussive drilling, rotary drilling, and percussive-rotary drilling [9, 10]. Each system exhibits its unique operational characteristics and is selected based on rock conditions and production requirements. Within the percussive drilling method, two main techniques are distinguished: Top Hammer and Down-the-Hole (DTH) [4, 11].

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The key difference between them lies in the mechanism of energy transfer and the hammer's position, located at the top of the drill string in the top hammer system or directly behind the bit in the DTH system [12, 13]. In addition, several qualitative criteria guide the preliminary selection of an appropriate drilling method in surface mining. The most influential factors include penetration rate, hole straightness, hole depth, blasthole diameter, production capacity, fuel efficiency, economic service life of the drill string, investment cost, adaptability to demanding drilling conditions, operator convenience, and flushing flexibility [12, 14, 15].

The evaluation of drillability and the characterization of rock properties are well-established research topics in mining [16–18]. Rock drillability is defined as the relative ease with which a hole can be created within any type of rock mass [14]. This complex concept arises from the wide range of contributing factors, including the intrinsic properties of rock materials, structural features of the rock mass and operational parameters of the drilling machine [19, 20].

Numerous studies have investigated the influence of these factors on drillability, often considering parameters individually; however, there is general agreement that the first two factors have the greatest impact on drillability [21–24]. Key determinants of drilling performance in previous studies include the geological origin of the rock (igneous, sedimentary, or metamorphic) [9, 25–27], hardness [28–31], texture (grain shape and size) [23, 32], abrasiveness [33, 34], porosity [28], density [28, 35], uniaxial compressive strength (UCS) [36–39], tensile strength [28], rock quality designation (RQD) [17, 40], and rock mass characteristics such as discontinuities [41, 42], lithology identification using While-Drilling System [43], and estimating the drilling rate [44].

To date, no comprehensive approach has been developed for selecting the most appropriate drilling method in mining operations. This highlights the need for a systematic methodology that accounts for both intact rock and rock mass characteristics. In this study, a new method has been introduced for determining the optimal drilling system in open-pit mines, based on the rock mass drillability index (RDi), which integrates the key properties of rock material and rock mass. Given the critical role of drilling in the production cycle and its significant impact on extraction costs, the proposed method aims to improve decision-making in drilling system selection. The applicability of this approach is further demonstrated through a case study. The main innovation of this study lies in the development of a comprehensive and practical framework for drilling method selection in open-pit mines based on the rock mass drillability index (RDi). Unlike previous approaches that mainly focus on intact rock properties, the proposed methodology simultaneously incorporates both intact rock characteristics and rock mass structural parameters, including joint spacing, aperture, and orientation. Furthermore, the study introduces a new decision-making chart integrating RDi scores with blasthole diameter to systematically identify the most suitable drilling technique under different geological conditions. The applicability and reliability of the proposed approach are further demonstrated through a real case study in the Komshecheh barite mine, Iran.

2 Overview of drilling method selection techniques

The physical and mechanical properties of rocks are key factors in selecting the appropriate drilling method, as they determine drilling rates, machine requirements, and mine production capacity. To address this, Hoseinie et al. [19] proposed a systematic and comprehensive methodology that incorporates the mechanical, physical, and mineralogical characteristics of rocks to optimize drilling method selection in open-pit mines.

Previous drilling literature has introduced only a few approaches for selecting drilling methods [45, 46]. However, most of these methods focus on rock material properties while overlooking the structural parameters of the rock mass, which can lead to considerable uncertainty in practical applications. A brief overview of the most well-known approaches is provided below:

- Lopez Jimeno et al. [47]: this method considers the uniaxial compressive strength (UCS) of the rock and the borehole diameter. Based on these two parameters, one of four drilling systems, top hammer, rotary cutting, rotary crushing, or down-the-hole (DTH), is recommended (Fig. 1).
- Osanloo [48]: in this approach, the selection of a suitable drilling system depends on rock type (abrasiveness, hardness, and grain size). Rocks are classified into three main categories and eleven subcategories according to their origin and abrasiveness, and an appropriate drilling method is then suggested for each category based on blasthole diameter.
- Gokhale [13]: this method recommends drilling techniques according to formation type (ranging from very soft to extremely hard) and borehole diameter (Fig. 2). However, its major limitation is the exclusion of rock mass structural properties.

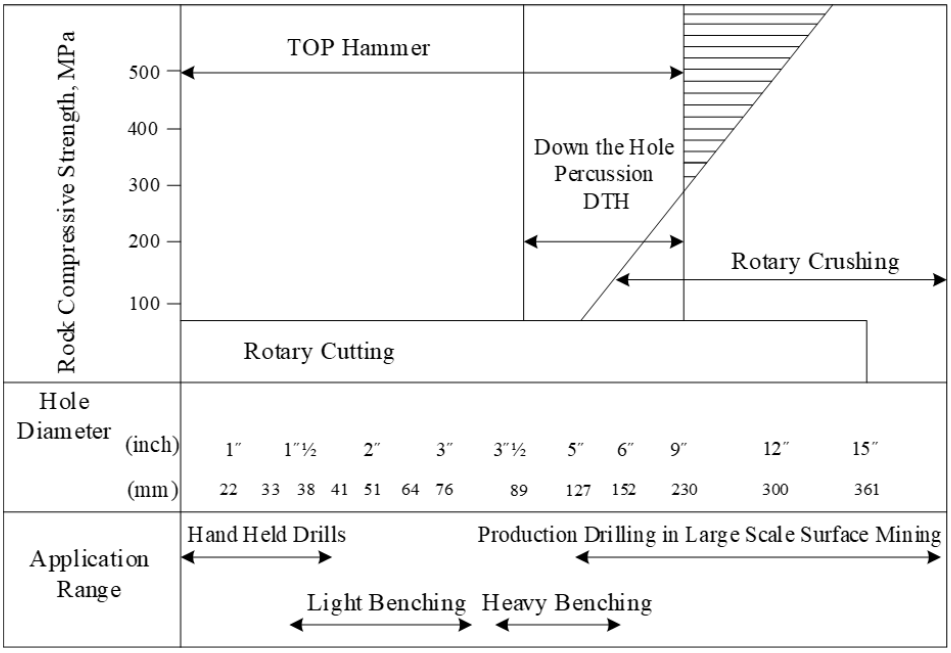

Fig. 1 Fields of application for drilling methods based on the UCS of the rocks and the diameters of the blastholes [47]

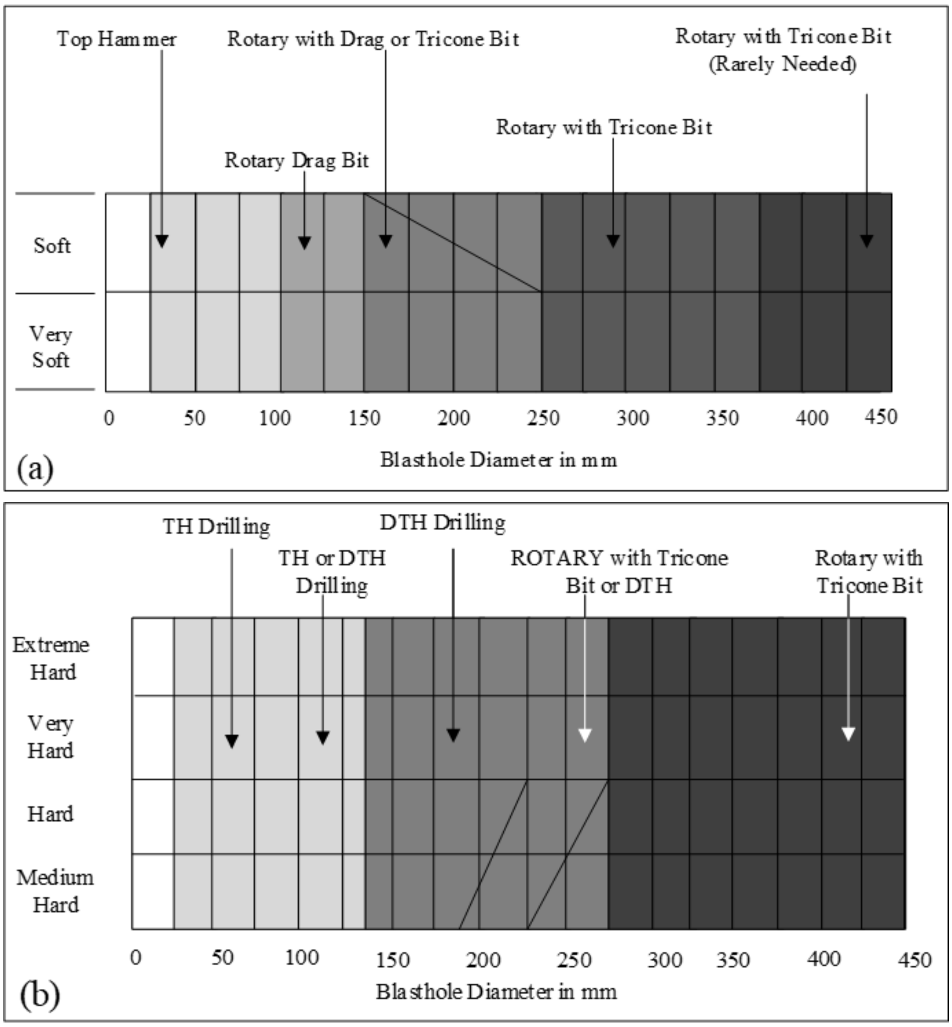

Fig. 2 Fields of application for drilling methods. Suitability of blasthole drilling method in: (a) Very soft and soft formations; (b) Medium to very hard formations [13]

- Zou [49]: this approach combines two drillability classification systems, NEU and NTNU/SINTEF (Fig. 3). The NEU system uses the indices "specific impact penetration work" and "abrasion width of the bit", while the NTNU/SINTEF system applies four indicators: brittleness value (S_{20}), Siewers' J-value (S_j), abrasion value (AV), and abrasion value cutter steel (AVS). Based on these indicators, a rock mass drillability index is determined, and the most appropriate drilling method is identified.

3 The RDi classification system

The progress of the drilling operation and its results are influenced by the various parameters of intact rock and rock mass. The effects of rock mass parameters on drilling operations are inevitable, as in many studies, the impact of these parameters has been emphasized. In the current paper, based on the rock mass drillability index presented by Hoseinie et al. [41], a comprehensive method for selecting a suitable drilling system in open-pit mines is presented.

In the RDi system (Table 1), three parameters of the rock material, including texture and grain size, Mohs hardness, uniaxial compressive strength (UCS), and three structural parameters of rock mass, including joint spacing, joint filling (aperture), and joint dipping, have been used to determine the rock mass drillability.

4 Development of a new approach

In this methodology, the total scores of the rock material and rock masses are quantified using the parameters defined in the RDi classification system. Based on the intersection of these two parameters along the horizontal and vertical axes (as illustrated in Fig. 4), the most appropriate drilling method is determined. The decision framework is systematically divided into eight distinct zones, each corresponding to specific combinations of rock material and rock mass characteristics. Additionally, the recommended drilling techniques for each zone, considering the relevant blasthole diameter, are summarized in Table 2.

As can be seen in Fig. 4, the selection of the drilling method varies depending on the rock material and rock mass scores, as well as the borehole diameter. In area I, where both rock material and rock mass scores are below 10, percussive-rotary drilling with high revolution and impact, DTH drilling with high revolution, and rotary drilling with button bits are recommended for borehole diameters of 3"–6", 6"–9", and 9"–17", respectively. In area II, for borehole diameters of 3"–4", 4"–9", and 9"–17", the recommended methods are percussive drilling, DTH drilling, and rotary drilling with button bits, respectively. In area III, where the rock mass score ranges from 20 to 45, percussive drilling, DTH drilling, and rotary drilling with low revolution and high thrust are suggested for borehole diameters of 3"–5", 5"–9", and 9"–17", respectively. In area IV (rock material score 20–40; rock mass <10) and area V (15 < rock material < 40; 10 < rock mass <20), percussive-rotary drilling and rotary drilling with fast revolution and moderate thrust are proposed for 3–6" in and 6–17" in boreholes, respectively. In areas VI and VII, where the rock mass score exceeds 15–20, percussive-rotary, DTH, and rotary

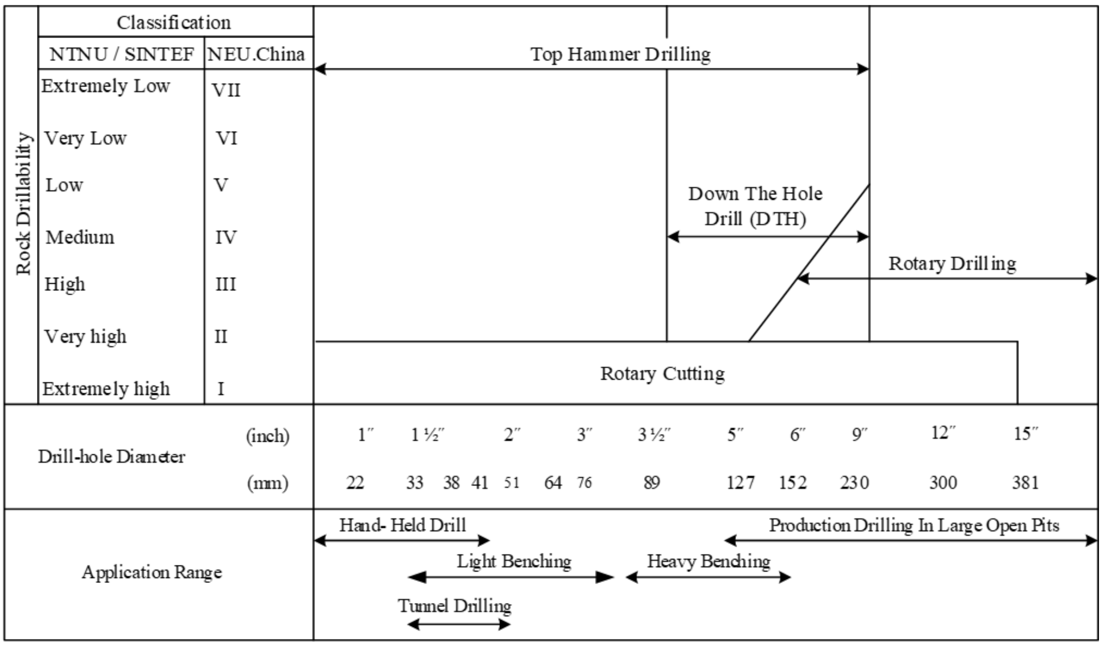

Fig. 3 Drillability classification systems based on abrasion indices [49]

Table 1 Rock mass drillability index (RDi) classification [41]

Texture	Porous	Fragmental	Granitoid	Porphyritic	Dense
Grain size	–	> 5 mm	2–5 mm	0.05–1 and 2–5 mm	0.05–1 mm
Rating	15	10	7	4	1
Mohs hardness	1–3	3–4.5	4.5–6	6–7	> 7
Description	Very soft – soft	Comparatively soft	Comparatively hard	Hard	Very hard
Rating	18	13	9	4	1
UCS (MPa)	1–25	25–50	50–100	100–200	> 200
Description	Very low strength	Low strength	Average strength	High strength	Very high strength
Rating	22	16	11	6	2
Joints spacing	> 2 m	1–2 m	0.5–1 m	0.15–0.5 m	0–0.15 m
Rating	18	13	9	5	1
Joint aperture and filling	Closed joint 0–2 mm	> 20 mm	12–20 mm	9–12 mm	2–9 mm
Rating	15	10	7	4	1
The angle between the joint and borehole axis	70°–90°	55°–70°	35°–55°	20°–35°	0°–20°
Rating	12	8	6	3	1

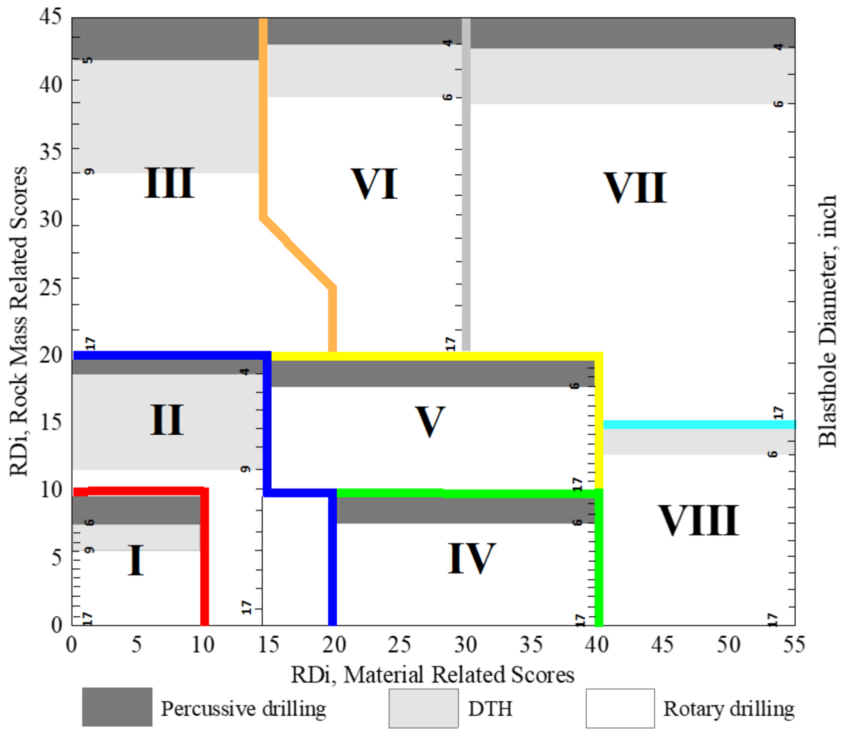

Fig. 4 A New method for the selection of a suitable drilling method

drilling are recommended for 3–4", 4–6", and 6–17" diameters. Finally, in area VIII (40 < rock material < 55; rock mass < 15), DTH and rotary drilling are suitable for 3–6" and 6–17" boreholes, respectively.

The boundaries of the eight zones presented in Fig. 4 were established based on the cumulative score ranges obtained from the RDi classification system and their engineering interpretation in terms of drillability. The total scores of rock material and rock mass parameters were first calculated from the corresponding rating intervals defined in Table 1. Subsequently, the score space was subdivided into eight zones representing different combinations of rock competence and structural conditions. The boundary values were selected to distinguish meaningful transitions in drilling behavior and to reflect the practical applicability limits of percussive, rotary, percussive-rotary, and DTH drilling systems reported in previous studies. The resulting framework therefore combines the quantitative basis of the RDi classification

Table 2 Proposed drilling method in eight areas

Area	Description
I	3"–6": percussive-rotary drilling with high revolution and impact
	6"–9": DTH with high revolution
	9"–17": rotary drilling with button bit
II	3"–4": percussive drilling
	4"–9": DTH
	9"–17": rotary drilling
III	3"–5": percussive-rotary drilling
	5"–9": DTH
	9"–17": rotary drilling with slow revolution and high thrust
IV	3"–6": percussive-rotary drilling
	6"–17": rotary drilling with fast revolution and mediocre thrust
V	3"-6": percussive-rotary drilling
	6"–17": Rotary drilling with fast revolution and mediocre thrust
VI	3"–4": percussive- rotary drilling
	4"–6": DTH
	6"–17": rotary drilling
VII	3"–4": percussive- rotary drilling
	4"–6": DTH
	6"–17": rotary drilling
VIII	3"–6": DTH
	6"–17": rotary drilling with fast revolution and high thrust

with established drilling practice and engineering experience to support systematic drilling method selection. Generally, the threshold values were selected according to the natural clustering of cumulative RDi scores and calibrated using documented drilling practices reported in the literature and field experience from several surface mining operations.

5 Implementation of the new proposed method, a case study

To validate the new approach, the Komshecheh barite mine was considered as the case study for this research. The mine is located in Ardestan, Isfahan Province, Iran, at geographic coordinates 33°13'27.65"N latitude and 51°59'19.43"E longitude. Its geographical location and access routes are illustrated in Fig. 5 [50]. The proven ore reserves of the deposit are estimated at approximately 1.6 million tons, with an average grade of 49% barite ($BaSO_4$) and 10% fluorite (CaF_2). Extending over an area of about 400 × 800 m, the Komshecheh deposit is recognized as the largest barite resource in Iran. An overview of the working environment of the mining operation is presented in Fig. 6.

It should be noted that the deposit is covered by a quartzite overburden with an average thickness of about 20 m. Quartzite is a granoblastic metamorphic rock consisting mainly of quartz (>90%) and formed by recrystallization of sandstone or chert by either regional or thermal metamorphism. In addition, accessory minerals include feldspar, micas, etc.

Due to the high strength and compact nature of quartzite, removing overburden requires the application of conventional drilling and blasting techniques. For this purpose, a drill wagon equipped with a percussive-rotary

Fig. 5 Geographical location of Komshecheh barite mine [50]

Fig. 6 Komshecheh barite mine environment

drilling system and a bit diameter of 3 inches was employed for blasthole drilling, and the quartzite is ultimately fragmented by charging and detonating ANFO (ammonium nitrate-fuel oil) explosive (Fig. 7). One of the main limitations of this machine is its inability to perform drilling operations at depths greater than 5 m.

As previously described, the RDi classification system was adopted to evaluate the drillability of the Komshecheh barite mine. Accordingly, two main categories of investigations were conducted: laboratory analyses and geological field surveys.

5.1 Laboratory tests

5.1.1 Uniaxial compressive strength

To evaluate the uniaxial compressive strength (UCS) and other tests including Mohs hardness (MH), and textural characteristics of rocks from the Komshecheh barite mine, representative block samples were carefully collected and transported to the Rock Mechanics Laboratory. The blocks were first cored to produce cylindrical specimens of size, with a diameter of 54 mm, and subsequently prepared to achieve a standardized length-to-diameter (L/D) ratio in the range of 2.0–2.5 [51].

Fig. 7 Drill wagon machine in the studied mine

Following the guidelines recommended by the International Society for Rock Mechanics (ISRM), UCS tests were performed on five core specimens (Fig. 8), and the test results have been tabulated in Table 3.

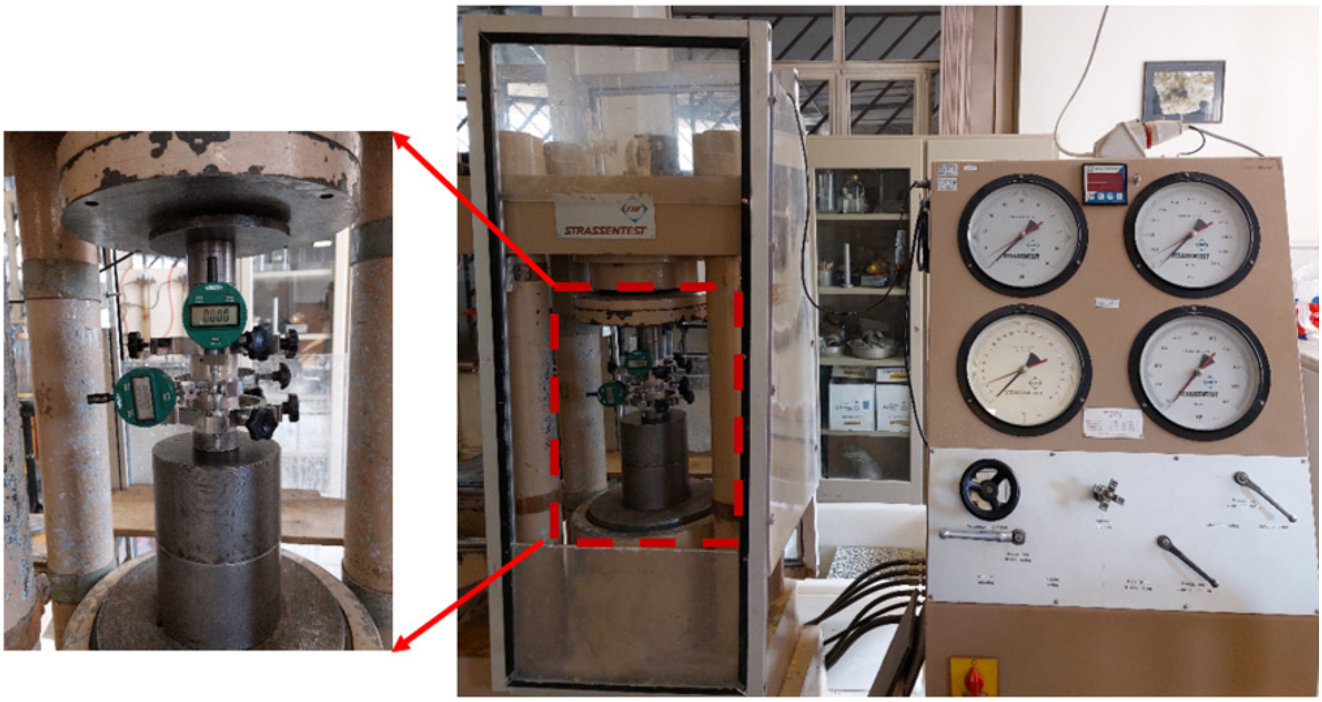

Fig. 8 The apparatus used in the present study for the determination of UCS

Table 3 UCS test results of the studied quartzite

Sample	UCS (MPa)
S_1	152
S_2	149
S_3	146
S_4	153
S_5	149

The experimental outcomes indicate that the quartzite samples exhibit an average UCS of 149.8 MPa within an accuracy of ±1.2 MPa. According to the Rock Drillability Index (RDi) classification framework, this strength value categorizes the rock within the high-strength domain.

5.1.2 Mohs hardness

The Mohs scale is one of the most widely used and practical methods for evaluating and classifying rock hardness, as it directly reflects the mineralogical characteristics of the rock [49]. Accordingly, it is often applied in drillability studies. In this work, two quartzite samples (10 × 10 × 10 cm) were prepared, from which thin sections in both vertical and horizontal orientations were produced and analyzed under a polarized microscope to determine mineral composition and mean Mohs hardness (MH). Fig. 9 shows the photomicrographs of vertical and horizontal orientations of the studied samples. As can be seen, quartz constitutes the major portion of this rock and appears in the thin section as granular crystals with gray, white, and black colors (due to extinction at different angles). Also, a small

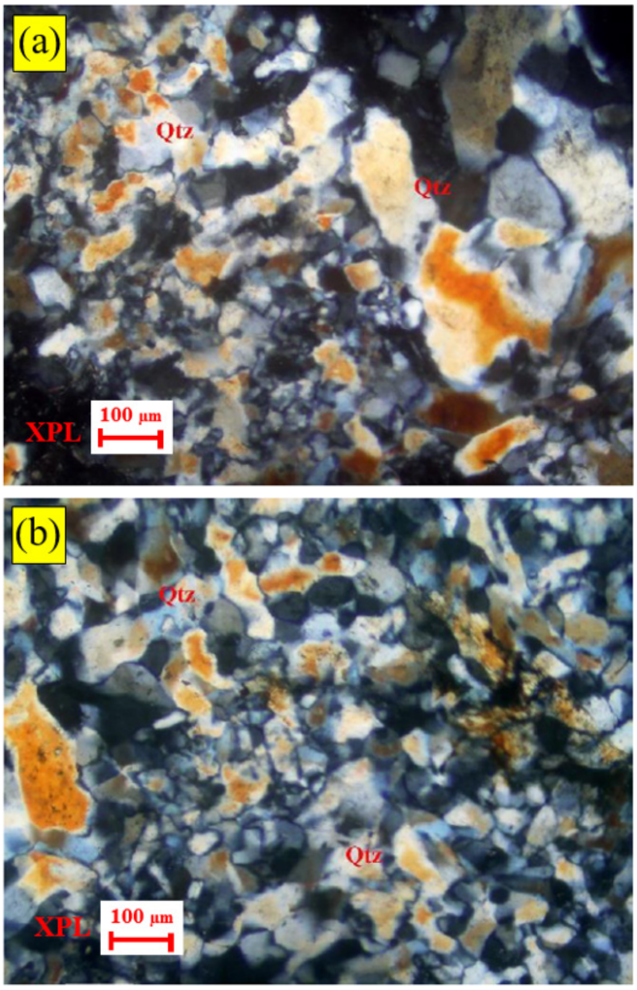

Fig. 9 Microphotographs of thin section: (a) Vertical direction; (b) Horizontal direction

amount of mica and feldspar with brown color is observed as an accessory mineral in it. The results of petrographic studies on quartzite samples, including type, content, and size of minerals, have been given in Table 4.

Based on the proportion of constituent minerals in the quartzite and the Mohs hardness of each mineral, the overall hardness of the studied rock was calculated using Eq. (1) [22, 52]:

$$\text{MH} = \sum_{i=1}^{n} A_i \times H_i , \quad (1)$$

where A_i is the percentage content of mineral present, and H_i is the Mohs number of every mineral. The obtained value of overall Mohs hardness has been given in Table 4.

5.2 Geological surveying

To determine the characteristics of the joint sets in the study area according to the RDi classification, such as dip, aperture, and spacing, the bench illustrated in Fig. 10 was examined. The length of the bench is 50 m, and the rock type is quartzite. In this bench, three dominant joint sets (J1, J2, and J3) are observed. The apertures of all three sets are less than 20 mm, while their average spacings are approximately 0.5 m, 0.75 m, and 0.9 m for J1, J2, and J3, respectively. Also, based on the dips of the joint sets, the average of these three dips of the joint sets can be introduced as the average dip of the joint sets of the study area. Therefore, the average dip of three joint sets J1, J2, and J3, which are 68°, 70°, and 65°, respectively, is equal to 67°. It should be noted that the average dip value was adopted to represent the overall structural condition of the rock mass within the framework of the RDi classification system. In the investigated bench, the three dominant joint sets exhibit relatively similar dip angles (65°, 68°, and 70°), resulting in limited variability among the discontinuity orientations. Therefore, the average dip of 67° was considered representative of the prevailing joint geometry affecting drilling performance. However, in rock masses characterized by highly heterogeneous discontinuity orientations, a weighted assessment considering the relative

Table 4 Overall Mohs hardness of the studied quartzite sample

Mineral	Mineral content (%)	Grain size (mm)	Mineral Mohs hardness	MH
Quartz	96	0.03–1	7.00	
Feldspar	2	0.03–0.07	6.00	6.89
Mica	2	0.02–0.04	2.75	

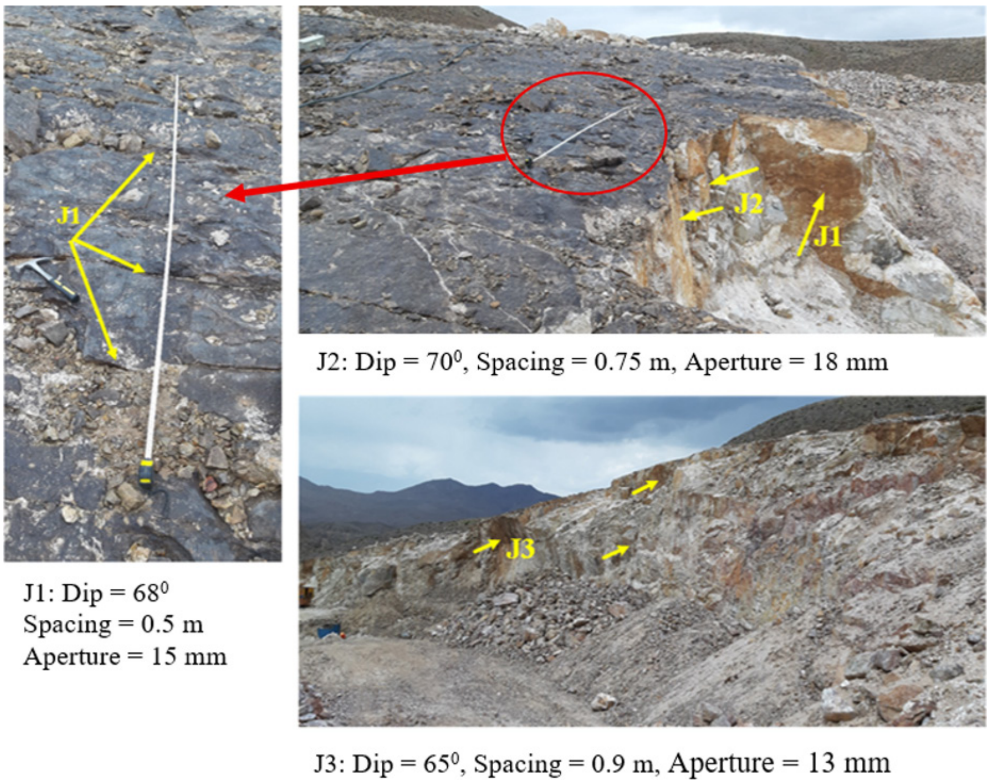

Fig. 10 Studied bench area and joint sets (J1, J2, and J3) at Komshecheh barite mine site

significance and persistence of individual joint sets may provide a more detailed characterization of drilling conditions and should be considered in future studies.

6 Choosing a suitable drilling method

To apply the proposed drilling method, the main production bench of the Komshecheh barite mine was selected as the study area. The corresponding values of the six parameters defined in the RDi classification system for this location are presented in Table 5. Based on these data, the total scores for the rock material and rock mass parameters were calculated as 11 and 19, respectively.

In the next step, the most suitable drilling system is proposed based on Fig. 11 and the score of rock material and rock mass, as well as the blasthole diameter (point A). Due to the high strength and hardness of the quartzite rock, the need for an impact mechanism in drilling is obvious. Accordingly, considering the 3" to 4" drilling diameters, high hardness and mechanical characteristics, the percussive drilling system is the top priority. For this, it has been recommended to use a RASOL drilling machine with a nominal diameter of 3-inch (Fig. 12). The proposed drilling technique was well received by the mine management and has since been adopted as the primary method for blast-hole drilling operations in the mine.

The advantages of employing the RASOL drilling system over the conventional drill wagon include enhanced mobility and operational flexibility resulting from its lightweight structure, the capability to perform drilling operations at greater depths (about 20 m) without limitation, and a reduction of overall drilling costs. It is evident that the overall drilling cost associated with the Top Hammer technique is higher than that of the percussive drilling method that was proposed by this study. This difference in cost can be attributed to factors such as greater energy losses along the drill string, higher wear rates of drilling tools, and more frequent maintenance requirements of the drilling equipment. Furthermore, the operational efficiency of the Top Hammer system tends to decrease with increasing hole depth, leading to higher unit drilling costs compared to the percussive method [4, 47, 53].

Compared with existing drilling method selection approaches [13, 47, 49], the proposed methodology offers several advantages. First, it simultaneously considers both intact rock properties and rock mass structural characteristics, whereas most conventional methods mainly focus on rock material parameters such as UCS, hardness, abrasivity, or borehole diameter. Second, the use of the rock mass drillability index (RDi) enables the integration of multiple geological and geomechanical factors within a unified quantitative framework. Third, the proposed decision chart provides a practical and easy-to-use tool for field engineers by combining rock material scores, rock mass scores, and blasthole diameter in a single selection procedure. Finally, because the required input parameters can be obtained through standard laboratory tests and routine geological mapping, the methodology can be readily applied in a wide range of mining and rock engineering projects.

Table 5 Result of rock mass drillability index (RDi) parameters in Komshecheh barite mine

Texture	Porous	Fragmental	Granitoid	Porphyritic	Dense
Grain size	–	> 5 mm	2–5 mm	0.05–1 and 2–5 mm	0.05–1 mm
Rating	15	10	7	4	1
Mohs hardness	1–3	3–4.5	4.5–6	6–7	> 7
Description	Very soft – soft	Comparatively soft	Comparatively hard	Hard	Very hard
Rating	18	13	9	4	1
UCS (MPa)	1–25	25–50	50–100	100–200	> 200
Description	Very low strength	Low strength	Average strength	High strength	Very high strength
Rating	22	16	11	6	2
Joints spacing	> 2 m	1–2 m	0.5–1 m	0.15–0.5 m	0–0.15 m
Rating	18	13	9	5	1
Joint aperture and filling	Closed joint 0–2 mm	> 20 mm	12–20 mm	9–12 mm	2–9 mm
Rating	15	10	7	4	1
The angle between the joint and borehole axis	70°–90°	55°–70°	35°–55°	20°–35°	0°–20°
Rating	12	8	6	3	1

Note: the colored columns in the table correspond to the scores attributed to the investigated mining zone.

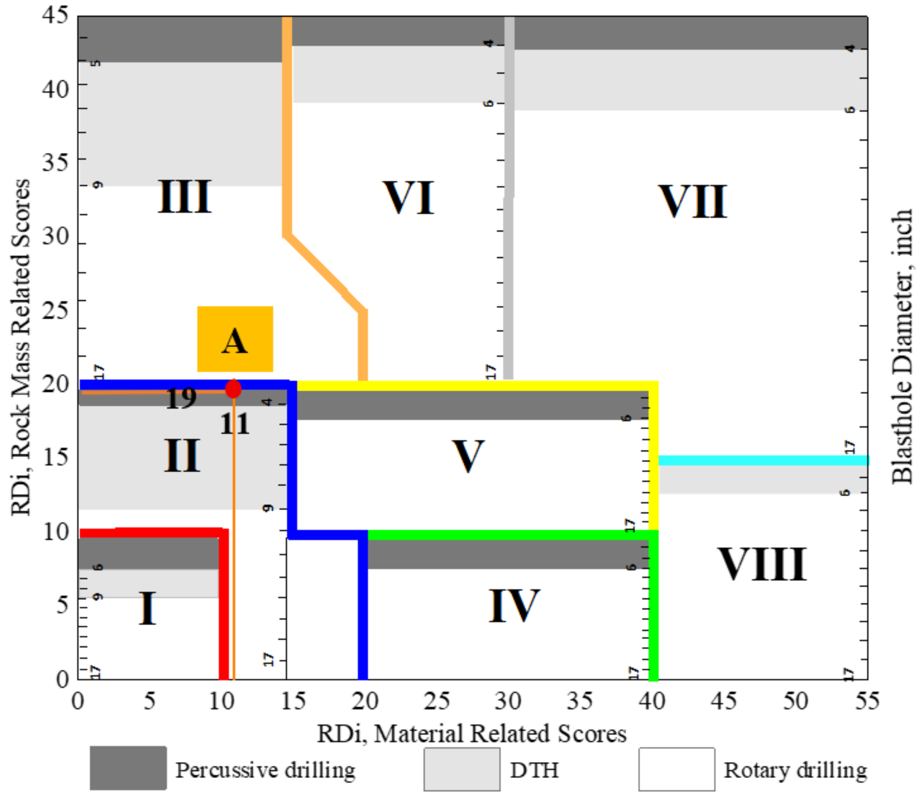

Fig. 11 Selection of the suitable drilling method in the Komshecheh barite mine

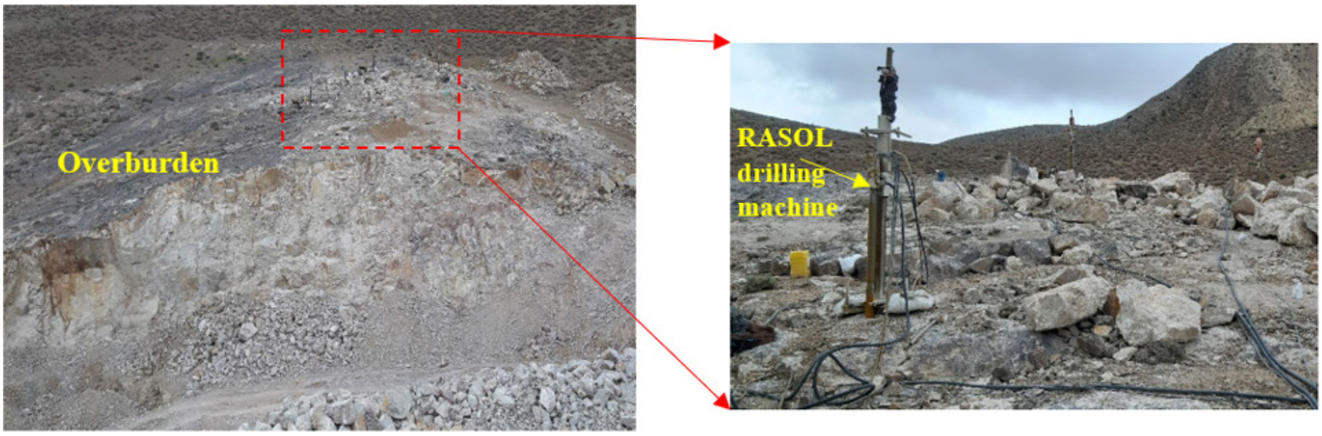

Fig. 12 Quartzite overburden and RASOL drilling machine in the studied mine

7 Conclusions

Choosing the correct drilling method for open-pit mines is one of the most critical operational decisions. The drilling method directly affects the production capacity of the mine, the depreciation of the machinery, and the production cost. This study presents a new methodology to select the appropriate drilling method in open-pit mines based on the RDi classification system. For this purpose, based on the total score of rock material parameters including Mohs hardness, UCS, and rock texture and the total score of structural parameters including joint spacing, joint filling (aperture), and joint dipping a new graph was proposed for selecting a suitable drilling method. Finally, the developed approach was applied in the Komshecheh barite mine, and the following key results were obtained:

- Percussive drilling (RASOL drilling machine) with 3-inch bit diameter has been recommended for rocks with high hardness and uniaxial compressive strength (UCS).
- Structural properties of joints are considered alongside rock hardness and strength, improving the accuracy of method selection.
- The proposed method provides a comprehensive understanding of rock mass properties, allowing informed selection of drilling techniques.

Therefore, the suggested method can greatly assist engineers in selecting the appropriate drilling method for open-pit mines, construction trenches, and other similar applications. Despite the promising results obtained in this study, several limitations should be acknowledged. First, the proposed methodology was validated using a single case study from the Komshecheh barite mine, and therefore the findings may not fully represent all geological and operational conditions encountered in surface mining projects. Second, the applicability of the proposed framework depends on the availability and reliability of the input parameters required by the RDi classification system, including both intact rock properties and rock mass structural characteristics. Furthermore, local operational factors such as drilling equipment specifications, operator experience, and site-specific production requirements may also influence drilling method selection.

Nevertheless, because the proposed approach is based on fundamental geological and geomechanical parameters, it is expected to be applicable to a wide range of open-pit mining operations and similar rock excavation projects. Further validation using different rock types, geological environments, and mining conditions is recommended to expand its applicability and enhance the robustness of the proposed decision-making framework.

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