A multi-option RES-based model (MORESM) for selecting optimum rock bolt system in underground coal mines

Abstract

The research presents a method entitled MORESM based on the rock engineering system (RES) for selecting the optimum rock bolt (RB) for underground coal mines. This method introduces a new application of RES that simultaneously provides the possibility of comparing various options in rock engineering and validating the model based on the relevant hazards. The model is intended to operate based on routinely collected field data in underground coal mines and does not require specialized or costly testing equipment. The model is based on two key components: the interaction matrix, which determines the weights of effective system parameters, and the rating matrix, which evaluates the response level of each RB under various system conditions. The rating matrix is used to evaluate each RB's relative efficiency by analyzing their responses compared to other RBs across different conditions, without considering the strength factors of each rock bolt, such as load-bearing capacity. This approach is applicable when outcome validation is supported by field data. Here, six RB types are involved as six options and the model is capable to determine the risk of applying (VI_{ap}) for each RB. In the following, a case study including 100 plus to 10 locations/cases of an underground coal mine was used to test and validate the MORESM. In this regard, the amounts of roof convergence (tell-tale displacement (TTD) at considered locations) are considered as the relevant hazard caused by increasing the VI_{ap} of applied (installed) RB. The results demonstrated that there is an acceptable correlation between the determined VI_{ap}s and corresponding TTDs with a coefficient determination (R^2) of 0.765, and also the measured and predicted TTDs with a R^2 of 0.803. The findings also indicated that when the applied RB, is far from the optimal RB, instability increases just as much. This could be considered as a criterion for evaluating the performance of MORESM. Finally, it is proved that the model could be helpful to estimate the substitution time of the applied RB with a useful option which is investigated for the case study.

Keywords: Rock bolt, Roof convergence, Rock engineering system (RES), Multi-option RES-based model, Underground coal mines.

List of symbols

C_i Cause of the ith parameter
E_i Effect of the ith parameter
a_i Weighting factor of ith parameter
VI Vulnerability index (refers to risk of applied/applying the rock bolt)
Q_i Value (rating) of the ith parameter
Qmax Maximum value assigned for ith parameter (normalization factor)
Nc Degree of squeezing
σ_{cm} Rock mass uniaxial compressive strength
Po In situ stress
γ Rock mass unit weight
H Tunnel depth below surface
CF Cost factor of rock bolt
c Costs of rock bolt including purchase and installation
D Discount rate
NE lifetime of considered location where the applied rock bolt is installed
BCF Bearing capacity factor of rock bolt
P Maximum bearing capacity of rock bolt
L Length of rock bolt
RB Rock bolt
TTD Recorded roof convergence from tell-tale extensometer
MORESM Multi-option RES-based model

1. Introduction

Underground coal mines have had the most use of rock bolt (RB) compared with other mining methods. The application of RBs has caused increase of productivity and decrease of support costs in these mines. In recent years, a significant number of RBs have been produced by companies (more than 35 types) for the support operation of underground excavations. Each of these products has various performances in various conditions of strata surrounding an underground space. Some of them are capable to cover a wide range of rock mass behaviors in support operation, and some just could be applied in a limited condition. Application of appropriate RB is a major challenge as the application of inappropriate options creates serious problems. So, it is necessary to present a comprehensive model for the selection of optimum RB.

The selection of RB type and their application conditions have been investigated by many researchers. Mark and Barczak (2000) stated that the strength of rock dependent on geology and the loads applied primarily by the in situ and mining-induced stresses are two major factors to determine the type and specifications of the support system. Mark et al. (2000) studied the performance of point-anchor tension and fully grouted resin RBs in different geological environments by field studies. Mark (2000), developed an approach to design the roof bolt systems. Based on the Mark's research, roof support mechanisms are determined by stress level and roof quality which are determinant factors in selecting the roof support system. Parker (2001) emphasizes time as an effective factor and recommends using the resin/bar bolt for long-term support. Van der Merwe and Madden (2002) discussed support system selection in underground coal mines and summarized their results in two tables as a very general guide. They involved the rock quality, horizontal stress, and time as the determinant factors to system selection in their charts. Yassien (2003) released some advice to apply the appropriate bolt type. In these recommendations, the rock quality, the horizontal stress, the mining method, and the time are emphasized as the major effective factors for RB selection. Canbulat et al. (2005) investigated the performance of four various RBs from different manufacturers in South Africa. They also studied the performance of the tensioned and un-tensioned bolts in different rock types. They explained Non-tensioned roof bolts achieved significantly greater bond strengths than the tensioned bolts in sandstone and shale roofs. They also concluded that the overall support stiffness of non-tensioned roof bolts was significantly greater than that of the tensioned roof bolts. Jalalifar et al. (2009) proposed an AHP-Entropy-TOPSIS method for the pick of the optimum RB. They considered 15 major effective parameters (see **Figure 2** of their paper) for choosing the best option from eight types of RB. They stated that selecting the suitable rock bolt is dependent upon the load transfer capacity, curing time, ease of installation, anchor length, cost, and distance from the heading face. Spearing et al. (2010) conducted experimental studies on corrosion of rock anchors in US underground coal mines. They explained that corrosion would only seem to be a potential issue for long-term applications in coal mines. Li et al. (2014) believe that the performance of an RB is dependent upon the loading conditions to which it is subjected. Scolari e al. (2017) tested a new RB in deep mining conditions and achieved better results compared with a simple frictional, inflatable bolt. The new RB is based on a frictional, inflatable bolt combined with an internal additional load-bearing element, called the Dynamic Omega-Bolt. Zhigang et al. (2017) proved the importance of using an energy-absorbing bolt for rock support in a high stressed rock mass. Li (2017) notified that the suitable types of RBs for a given rock mass are associated with the loading conditions in the rock mass. The rock mass behavior under the induced stresses is the main criterion for bolt selection. Li explained that the traditional principle of selecting strong RBs is valid only in conditions of low in situ stresses in the rock mass. Energy-absorbing RBs are preferred in the case of high in situ stresses. Song et al. (2017) discussed how smart sensor technologies can monitor rock bolt performance in real-time, enhancing the ability to select suitable bolts based on actual ground conditions and bolt health. Sun et al. (2018) demonstrated that applying the yielding bolts is an effective way to support the soft rock roadway under high stress. Wu et al. (2019) reached to experimental results highlighting how rock bolts perform under dynamic coal burst conditions, emphasizing bolt strength and ductility as critical parameters for optimal selection in burst-prone mines. Shaposhnik et al. (2021) demonstrated that friction-anchored rock bolts perform well in backfill environments, emphasizing the importance of frictional engagement in excavations with loose or unconsolidated fill. Tshitema & Kallon (2022) focused on the development of a specialized reinforcing rock bolt for hard rock mines, demonstrating that material properties and rock mass interaction significantly influence bolt selection. Frenelus et al. (2022) analyzed durability and long-term stability of rock bolts, highlighting environmental exposure and bolt design as crucial parameters for selecting bolts in deep rock tunnels. Chen et al. (2022) investigated modified cable anchor performance under varying joint openings, indicating that anchorage adaptability and joint characteristics guide the optimum anchor type choice. Li et al. (2022) evaluated the influence of pretension on cable bolts, showing that optimal pretension enhances bolt load-bearing capacity, a key factor in bolt design and selection for diverse geological conditions. Jiang et al. (2023) examined mechanical behavior of fully grouted rock bolts in soft rock, emphasizing grout quality and bolt stiffness as decisive factors for their suitability in weak ground. 9. Hansen et al. (2024) used machine learning to classify rock mass conditions from drilling data, aiding the selection of the most appropriate rock bolt types based on predictive ground characterization. Demin et al. (2024) presented a new technology combining support and friction anchors, suggesting that combining anchoring mechanisms can optimize bolt performance in ore mine workings. Mesutoglu & Ozkan (2024) compared rock bolting and steel arch supports in thick coal seams, finding that geological conditions and load requirements heavily influence the selection between these support types. Wang et al. (2025) investigated bolt support mechanisms for hard roof control, identifying bolt length, diameter, and installation parameters as key for optimizing rock bolt effectiveness. Isfahani et al. (2025) applied 3D numerical modeling to optimize rock bolt support for large underground structures, stressing bolt layout and mechanical properties as pivotal in support design. Zhou et al. (2025) introduced an anchoring approach grounded in pre-stress distribution within composite rock strata, emphasizing the role of pre-stress management in determining the optimal bolt anchoring method.

According to the literature review, understanding the rock mass behavior is very important for the selection of an appropriate RB type. Many parameters are involved in the rock mass behavior and loading conditions as each of them has different effects. Therefore, there is a system with three main components consisting of rock mass, loading conditions, and RB. These components have different factors. Interaction between rock mass and loading conditions determines the rock mass behavior. Also, the interaction between rock mass behavior and each RB has different responses. So, the performance of each RB in various rock mass behavior is different and the best response in support operation could be obtained by applying the most appropriate RB type. By using this theory, a model based upon the rock engineering system (RES) is presented for the selection of optimum RB in underground coal mines. The RES method is adopted because of its ability to evaluate the interaction between the effective parameters in rock mass that this process leads to simulating the rock mass behavior. MORESM provides the possibility of evaluating the risk of using various types of RB in various rock mass behaviors. A schematic of the adopted theory for the selection of an optimum option is shown in **Figure 1**. In this Figure, VI is the vulnerability index or risk of applying the RB. Interaction matrix and rating matrix are elements of MORESM which are introduced in the following.

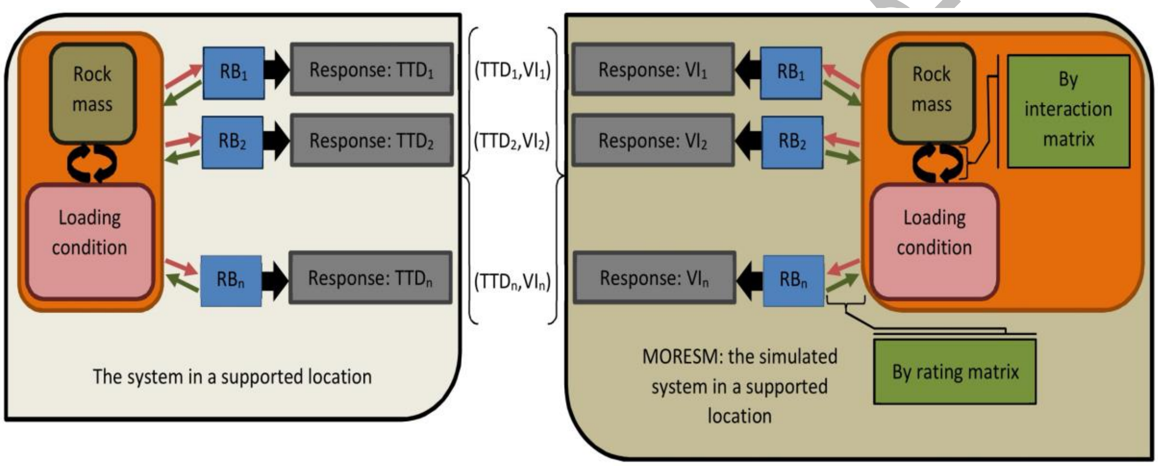

Figure 1: A schematic of adopted theory for selection of optimum RB

2. Applied method and presentation of MORESM

Hudson (1992) presented an approach named rock engineering system (RES) for analyzing the interaction between effective parameters and components involved in rock mass for evaluating and answering complex engineering issues. The RES determines and quantifies the interaction between parameters involved in a system. This process is conducted by an interaction matrix as a key element of RES (Figure 2). An n*n interaction matrix is created by n parameters affecting the system. The off-diagonal positions in the matrix are filled by values describing the degree of interaction between the parameters. This research has adopted the ‘‘expert semi-quantitative’’ (ESQ) method (Hudson 1992) for numerically coding the interaction matrix, in such a way that 0 for no interaction, 1 for weak, 2 for medium, 3 for strong, and 4 for critical interaction respectively. According to Figure 2, each particular parameter is denoted as coordinates (C, E). The interaction matrix helps in determining the weighting of each effective parameter within the system by Eq. (1).

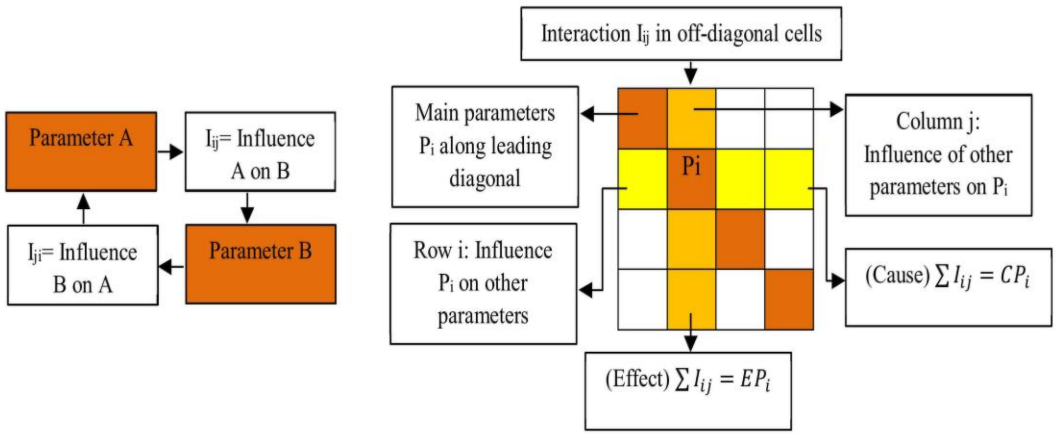

Figure 2: A general view of interaction matrix including principles of the interaction between parameters and the matrix coding (taken after Hudson (1992))

$$a_i = \frac{(C_i + E_i)}{(\sum_{i=1}^{n} C + \sum_{i=1}^{n} E)} \times 100 \quad (1)$$

Based on the adopted theory and theory of the RES, the following steps are applied to determine the VI of applying (VI_{ap}) for each RB type:

- Determination of effective parameters on RB selection to consider the various behaviors of rock mass and to select an optimum option.
- Determination of weighting factor of each effective parameter in the system by Eq. (1).
- Determining the VI_{ap} by Eq. (2). When the VI_{ap} value is approaching 0 the risk level of the applying is lower, while its value approaching 100 shows that the risk level of the applying is higher.
- Testing and validating MORESM by field data. RBs with higher VI_{ap} have a lower performance in considered cases which increases roof convergence, instability, and operation costs.
- Comparison of determined VI_{ap}s of different RB types and selecting an optimum option with help of auxiliary criteria.

$$VI = 100 - \sum_{i=1} a_i \frac{Q_i}{Q_{max}} \quad (2)$$

In this paper, six types of RB were taken into account based on the most application in underground coal mines. The selection of these bolts, it is tried to cover the whole various strata behaviors in underground coal mines from hard rocks in low-stress conditions to soft rocks in high-stress conditions. However, the selected RBs may not be a comprehensive representatives, emphasizing this note that the main purpose of the paper is how to applying a method to choose the optimum RB. The six RBs are included such as mechanical expansion shell rock bolt (ES.RB), swellex rock bolt (S.RB), swellex-hybrid rock bolt (SH.RB), full-column slow/fast resin rock bolt (FCR.RB), point anchored resin rock bolt (PR.RB), and resin-grouted cone bolt (RG. CB). In this section, more than 30 RBs were investigated and the selection were conducted based on parameters like type of point anchor part, genus, active or passive status, stiffness, needed time for pre-tensioning, delivery time of maximum load, lifetime, etc. Table 1 presents the investigated RBs with some of their characteristics.

2.1 Selection of the effective parameters and performing the interaction matrix

The interaction matrix was created by taking into account eight major parameters, which included the following: P1: coal mine roof rating (CMRR), P2: discontinuities formation (according to Figure 3), P3: induced-mining stress conditions (stress concentration factor), P4: the largest dimension of excavation, P5: conditions and location of the strong bed in the roof (distance from the roofline of excavation), P6: the ratio of bolt spacing to joint spacing, P7: the lifetime of excavation and P8: stress condition (degree of squeezing by Eq. (3) (Jethwa et al. 1984)). The six discontinuities formations include bedding without inclination and discontinuities (B1), inclined bedding without discontinuities (B2), jointed bedding by one joint set and without inclination (B1J1), inclined and jointed bedding by one joint set (B2J1), jointed bedding by two joint sets with no inclination (B1J2), and inclined and jointed bedding by two joint sets (B2J2).

These parameters were chosen to tackle a wide range of rock behavior and geotechnical conditions, including soft rock to hard rock, non-squeezing to squeezing, low to high-stress concentration, short to long time life for excavation, short to wide RB spacing, and shorter to wider excavation dimension and good to very bad conditions of discontinuities. The inclusion of excavation lifetime (P7) in the model allows the system to account for time-dependent deformation and fatigue in rock bolt performance, providing insight into temporal degradation effects across different excavation geometries and support durations.

For the purpose of this study, only the influence and interaction of rock mass and loading conditions on the reaction mechanism of RBs was considered and parameters such as the bearing capacity and elongation of RBs could be used as auxiliary criteria for final selection. As shown in Table 2 the interaction matrix was constructed to determine the contribution of each parameter in selecting the optimal RB. The interaction matrix values were derived through a structured expert elicitation process akin to the Delphi method, involving multiple rounds of feedback from six domain experts combined with comprehensive literature review, to ensure consensus and robustness. The ai values for these parameters is illustrated in Figure 4.

Table 1: List of RBs (The six selected rock bolts are highlighted in green.)

No.	Rockbolt/Anchor name	Class	Type of point anchor part	Genus	Active/ Passive
1	Point anchored rock bolt (slot & wedge)	Mechanical	Slot & wedge	Steel	Active
2	Point anchored rock bolt (expansion shell)	Mechanical	expansion shell	Steel	Active
3	Roof truss	Mechanical/frictional/grouted	expansion shell/pint grouted	Steel	Active
4	Worley bolt	Frictional (deformable tube)	-	Steel	Passive
5	Split set/split-tube/friction stabilizer/swellex	Frictional	-	Steel	Passive
6	Power set self-drilling friction (expendable) bolts	Frictional	-	Steel	Passive
7	Swellex hybrid	Expendable set (frictional + mechanical)	-	Steel	Passive
8	Wooden dowels	Frictional	-	Wood	Passive
9	Fiber glass dowels/rockbolts	Frictional or grouted	-	GRP	Passive
10	Full-column concrete rockbolts (conventional bar or threadbar)	Cement grouted	-	Steel	Passive
11	Full-column concrete and fully threaded solid GRP bar	Cement grouted	-	GRP	Passive
12	Pre-tensioned cement fully-grouted rockbolts (conventional bar or threadbar)	Cement grouted +pre-tensioned	Cement grout	Steel	Active
13	Pre-tensioned cement semi-grouted rockbolts (conventional bar or threadbar)	Point + grouted	Cement grout	Steel	Active
14	Cement grouted expansion shell rockbolts (conventional bar or threadbar)	Mechanical + cement grouted	expansion shell	Steel	Active
15	Fully cement grouted and fully threaded self-drilling hollow GRP bar	Cement grouted	-	GRP	Passive
16	Perfo rocbolts	Grouted + frictional	-	Steel	Passive
17	Resin injected rockbolts (conventional bar or threadbar)	Resin grouted	-	Steel	Passive
18	Pre-tensioned resin fully-injected rockbolts: full-column slow/fast-resin combination bolts (conventional bar or threadbar)	Resin grouted + pre-tensioned	resin grout	Steel	Active
19	Point anchored resin-assisted mechanism anchor bolt (semi-injected) or pre-tensioned resin semi-injected anchor bolt (conventional bar or threadbar)	Mechanical + resin	resin grout	Steel	Active
20	Resin Grouted expansion shell rockbolts (conventional bar or threadbar)	Mechanical + resin	expansion shell	Steel	Active
21	Full-column resin and fully threaded solid GRP bar	Resin grouted	-	GRP	Passive
22	Full-column resin and fully threaded self-drilling hollow GRP bar	Resin grouted	-	GRP	Passive

23	Innovative constant resistance large deformation anchor bolt	Mechanical + frictional-energy absorption	Resin grout	Steel	Active
24	Cable bolts	Grouted (cement or resin)	-	Steel cable	Passive
25	Cable bolts	Cement or resin	Cement/resin anchor	Steel cable	Active
26	Resin capsulate cable bolts	Resin grouted	resin grout	Steel cable	Active
27	Yielding grouting rockbolt	Mechanical-grouted + yielding	Twist anchor head	Steel	Passive
28	Energy-absorbing rock bolts (such as con bolt)	Energy absorption	Mechanical (cone + deformable sleeve)	Steel	Passive
29	Dynamic omega-bolt (dynamic inflatable, friction rockbolt)	Energy absorption-inflatble	-	Steel	Passive
30	Spin to stall resin bolt	Resin grouted (self-spinning)	Resin cartridge	Steel	Passive

*GRP refers to glass reinforced plastic. The type of point anchor parts mentions RBs that anchored and pre-tensioned at the end part of RB by mechanical, frictional or grouted mechanism.

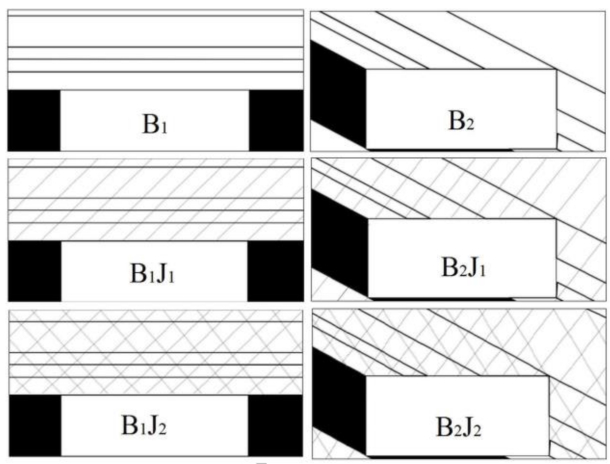

Figure 3: Six considered categories of discontinuities formation around an underground coal mine gate for rating ranges of P_2

$$N_c = \frac{\sigma_{cm}}{P_o} = \frac{\sigma_{cm}}{\gamma H} \tag{3}$$

Table 2: Interaction matrix for the parameters affecting the selection of optimum RB in underground coal mines

P_1	3	0	2	0	3	1	1
3	**P_2**	0	2	0	3	1	1
0	0	**p_3**	1	0	2	1	0
0	0	3	**P_4**	0	2	2	2
3	0	0	1	**P_5**	1	0	1
1	1	0	1	0	**P_6**	0	1
0	0	0	2	3	1	**P_7**	0
1	2	2	0	0	3	1	**P_8**

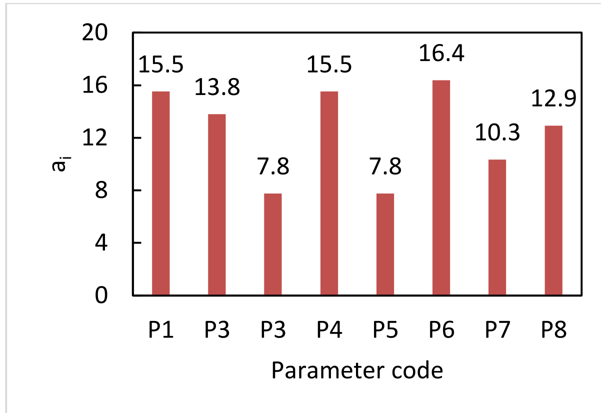

Figure 4: Weighing of the principal parameters affecting the selection of optimum RB

2.2 Presenting a new rating method for MORESM

In previous related research, the Q_i/Q_{max} in Eq. (2), was calculated by using a conventional rating method. In this method, one option or hazard was evaluated to calculate its associated risk. Several related studies are discussed here, including assessing the geotechnical hazards of TBM tunneling by Benardos and Kaliampakos (2004), prediction of rock fragmentation by blasting by Faramarzi et al. (2013), risk analysis and prediction of out-of-seam dilution in longwall mining by Bahri et al. (2014), risk analysis of floor failure mechanisms by Aghababaei et al. (2015), and prediction of face advance rate in retreat longwall mining panel by Aghababaei et al. (2019). In these research, the rating of parameters' values has been carried out based on their effect on the considered hazard (for example, calculation of the out-of-seam dilution by Bahri et al. (2014)) or single option or factor (for example, face advance rate by Aghababaei et al. (2019)) to calculate the Qi/Qmax in Eq. (2).

In cases where there are several options/hazards to asses and multiple parameters (Pi) affect each option differently, the conventional RES rating method is not adequate, as it does not allow for the bidirectional prioritization needed for multi-hazard assessments. In this regard, MORESM should satisfy two purposes; first, the possibility of determining the VI_{ap} of various RBs in various conditions, and second, finding the relationship between VI_{ap}s and displacements in the roof. So, a new rating method was developed named Hazard-Dependent Priority-Option Setting Rating (HPSR). The HPSR method introduces a two-dimensional rating approach that allows consistent prioritization of rock bolt options across varying parameter value ranges. This structure enhances adaptability in multi-hazard/options conditions, reduces subjectivity, and supports validation using routinely collected field data. This method was based on an m*n rating matrix formed by m value ranges of P_i and n options to achieve both of the above purposes (Figure 5). HPSR introduces a structured two-dimensional rating process:

- **Horizontally**, it ranks the relative suitability of value ranges of each Pi for each option.
- **Vertically**, it ranks all options under each specific value range of Pi.

The maximum value in each rating matrix is considered as Qmax for corresponding Pi which is considered to calculate Qi/Qmax. This dual-axis rating allows for greater consistency in the prioritization process, prevents subjective inconsistencies by using a unified baseline (Qmax), and ensures adaptability across varying hazard/options conditions. Additionally, this structure enables validation through field data and avoids potential misjudgments that arise from using fixed or isolated scoring systems.

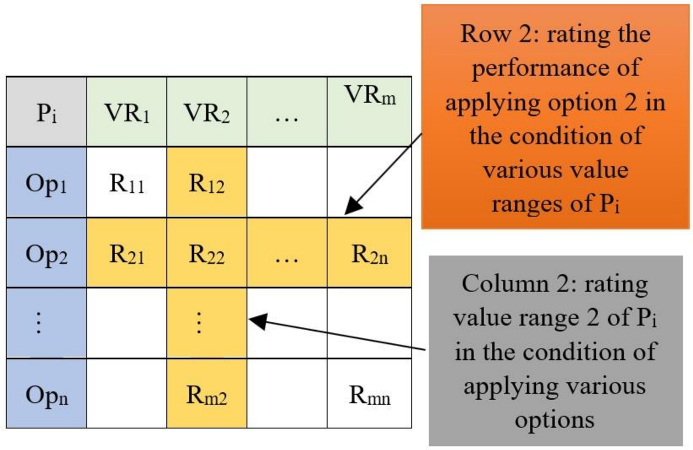

Figure 5: Rating matrix for a MORESM; VR and Op are the value range and option, respectively

In this research, eight rating matrices were formed based on the selected parameters and six considered for RBs. According to the investigations, experiences, and extensive literature review, the ratings of these matrices were carried out and results are illustrated in Table 3 and Figure 6. In this figure, the legend for all graphs (a to f) is the same as the considered legend for graph (c). For P_2, categorical discontinuity types were converted to numerical ratings through expert experience and literature-informed evaluation of their relative effects on RB performance under various geological conditions, ensuring consistency and practical applicability across different mining sites.

Table 3: Assigning the values to rating matrix of P_1 (CMRR)

P_1: CMRR	**$P_1<25$ (very Weak)**	**$25 \leq P_1<45$ (Weak)**	**$45\leq P_1<65$ (Moderate)**	**$65\leq P_1$ (Strong)**
ES.RB	0	2	9	10
S.RB	2	4	8	9
SH.RB	3	6	7	8
FCR.RB	4	6	7	8
PR.RB	1	3	8	9
RG.CB	4	5	6	7

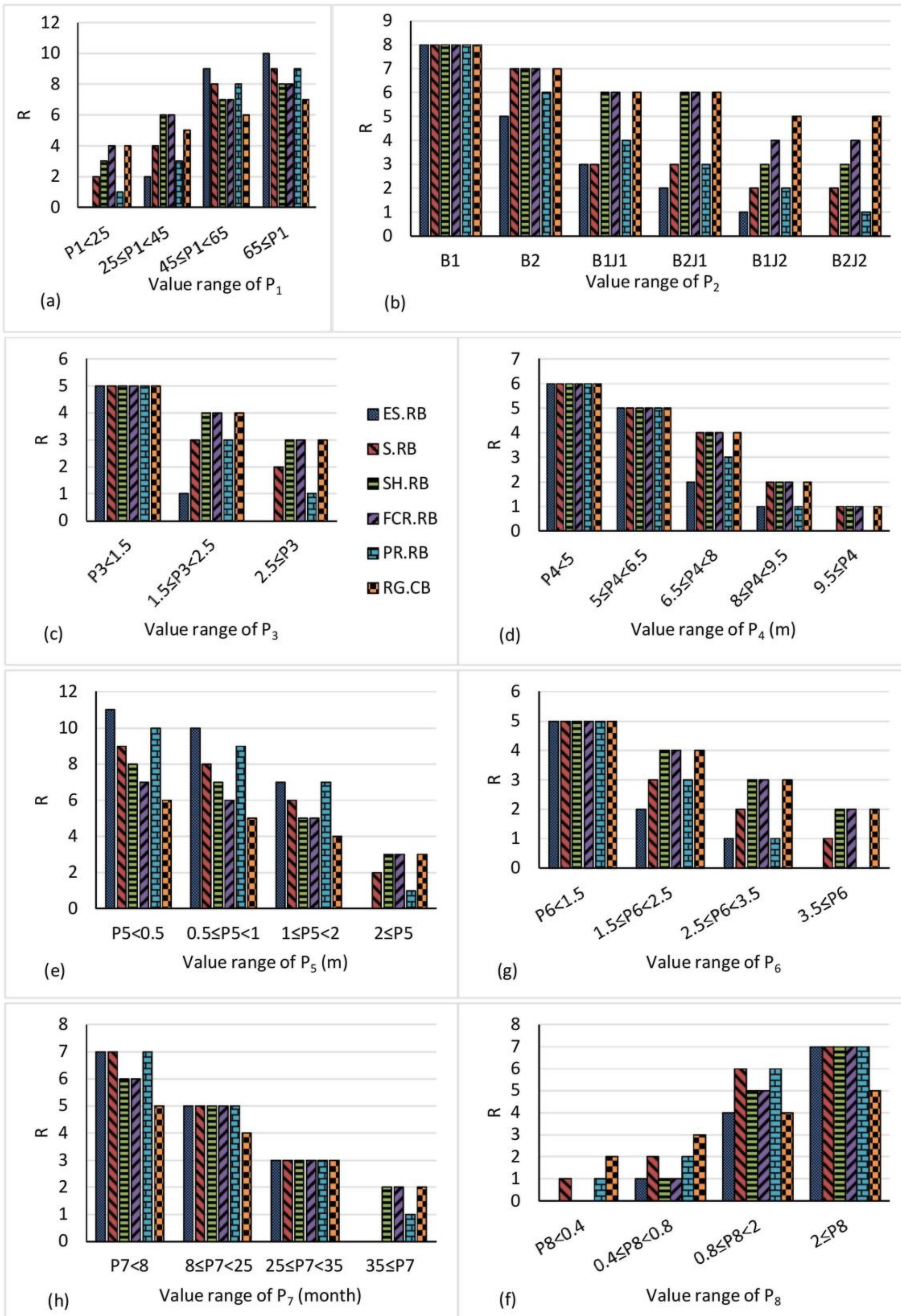

Figure 6: Ratings of the P_1 to P_8 effect in VI_{ap} of RB in underground coal mines (a to f), obtained results from rating matrixes of the P_3 to P_8

In the following, a summary of adopted principles for rating and division of the parameters is presented. Ratings and divisions were carried out based on the experiences of experts and the literature review. In the presented graphs (Figure 6), there is an ascending-descending trend in the all results. This trend indicates that worsening conditions for the parameters generally increase instability in the roof and applying extra load on the support system. Also, the best and worst options were specified for each considered range value of the parameters. In some value ranges, there is no priority for the options, which refers to the specified almost identical performance of the RBs in the considered class.

P1: Increasing the quality of roof strata causes increasing the self-supporting capability that creates minimum pressure on the support system. FCR.RB and RG. CB are the best options for soft rocks. The division of P1 was carried out in four value ranges based on the presented classification by Mark (1994) which was divided into two classes, 0 to 25 and 25-45 for interval of 0 to 45, referring to very weak, and weak strata, respectively.

P2: Discontinuities formation has high effect on the mechanism of roof falls and required supporting systems. The stability of the roof decreases with increasing the number of discontinuities and inclination of strata which creates a hard condition for the support system, so that RG. CB and FCR.RB are the best options in a weak rock mass. P_2 was divided into six classes according to strata inclination and number of discontinuities sets in the roof.

P3: Increasing the induced stresses due to intense mining operation causes more failures and displacements in strata, so, it creates a hard condition for applying some RBs. Longwall mining with a roughly concentration factor of 2.5 around the operation area was considered as a scale for the division of P_3. ES.RB and PR.RB are appeared to have the worst performance in high induced stress conditions.

P4: A large dimension of excavation (width for roadways in coal mines) causes an increase in the height of the damaged zone in roof and changes the required support mechanism that generally provides a worse situation for applying RBs and so the worst options are ES.RB and PR.RB. These conditions lead to more and intense instabilities in the roof. The widest widths applied for the roadways, reached 9 to 10 m, and minimum widths are generally equal to 4 m. So, the division was adopted in the five classes.

P5: The existence of a strong bed near the roofline increases the loading capacity of the immediate roof. The presence of a strong bed beyond the first 2 m of roof makes a hard or impossible situation for applying the mechanical RBs to implement the suspension supporting mechanism. Based on these points, rating and value ranges of P_5 were determined.

P6: Generally, the large number of joints make a hard condition for the RBs, if it is the only component in the support system. Decreasing the bolt spacing to less than 1.5 times the joint spacing provides suitable conditions for applying the RBs. Resin bolts are the best options for an intensely jointed rock.

P7: The lifetime of the excavation is one of the determinant factors for support design and bolt selection (based on the literature review). According to the lifetime of different excavations in underground coal mines and imposed situations by their application, four value ranges were considered for this parameter. Generally, increasing the lifetime makes a hard situation for applying the RBs. ES.RB and S. RB are not suitable options for longtime support.

P8: Increasing the degree of squeezing provides a hard condition for any support system. The division was carried out based on the present classification for the degree of squeezing based on Jethwa (1984). Energy-absorbing RBs are suitable options for highly squeezing rock conditions.

2.3 Application Procedure for MORESM in New Mines

To apply MORESM in a new mining environment, field engineers should:

- Collect comprehensive field data on rock mass properties, excavation characteristics (like geometry), installation conditions, and stress environments.
- Apply parameters calculable from the field data (both previously introduced and potentially new parameters) that represent rock mass properties, rock mass behavior, interactions created by excavation, and the hazard considered for model validation and optimization. These parameters should accurately simulate the relevant processes influencing the selection of the optimum option.
- Preprocess and organize the data according to MORESM input requirements and develop the model accordingly.
- Validate the model outputs against field observations to ensure accuracy and reliability.
- Use the validated model to select the optimum rock bolt options under varying site conditions.
- Successful implementation requires geomechanical knowledge, training on the MORESM methodology, and a time commitment for initial data collection and model calibration. Once established, MORESM provides a valuable decision-support tool for optimizing rock bolt selection.

3. Case study

To test and validate the presented MORESM, a case study consists of 100 locations/cases of six panel gates (E0 TG, E_0 MG, E_2 TG, E_2 MG, E_3 TG, and E_3 MG) and two set-up rooms (E_0 Face and E_3 Face) were taken into account from longwall panels in Parvadeh-I coal mine (Figure 7). These locations are the installation points of tell-tale extensometers in panel gates and set-up rooms. The required information of these cases was collected and values of the effective parameters were determined for them. These cases have an approximately equal interval from together and cover various geological and geotechnical conditions. Information of 12 cases is presented in Tables 4 and 5. Table 6 provides a statistical description of the case study. The recorded convergence from tell-tales (TTD) consists of recorded values of part A and part B. Parts A and B indicate movement above and within bolted height, respectively. Three statuses of stress concentration factor ranged less than 1.5, 1.5 to 2.5, and more than 2.5 were taken for considering various conditions of P_3 (induced-mining stress conditions). The corresponding lifetime (P_8) and the corresponding TTD were also determined for these three statuses. Lifetime refers to the life of the excavation from the time of creation to the time of recording the relevant TTD. Therefore, with these three statuses, 197 cases/dataset were prepared to calculate VI_{ap}. It should be noted that in 197 cases the recorded TTDs were available for 100 locations. To calculate the corresponding distance between longwall face and tell-tale for each range of stress concentration factor, information and presented results of longwall numerical modeling in Basic Design report of Parvadeh-I (IRASCO et al. 2005) were used.

Using measured and recorded field data collected along excavated spaces provides more reliable information and helps reduce uncertainties, while also capturing anisotropy better than other data collection methods. This approach compensates for spatial variability in rock mass conditions, such as anisotropy and fault proximity, by using parameter values averaged over short, well-defined roadway segments (straps) rather than individual points. These averages are based on frequent, systematic field measurements taken during routine operations, capturing localized geological variations. This method balances practical data collection constraints with the need to reflect spatial heterogeneity, providing robust and representative input for the model despite inherent variability.

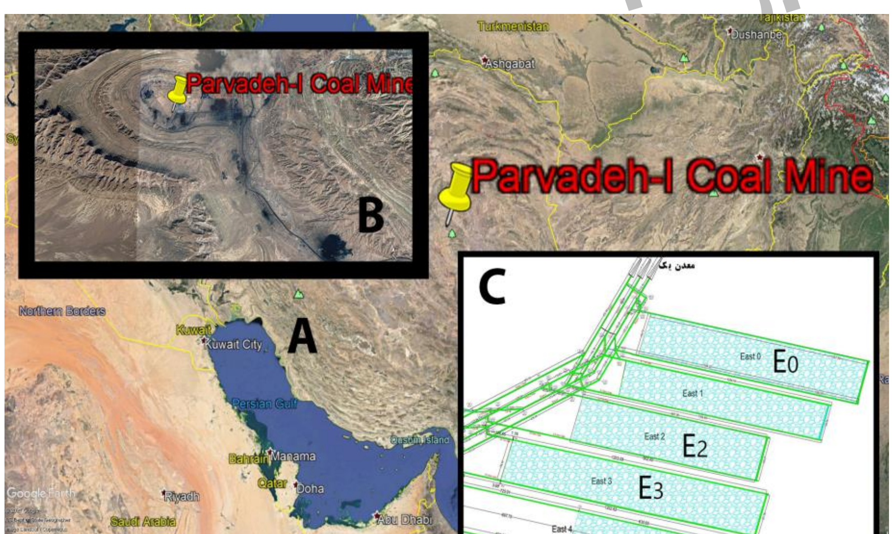

Figure 7: A plan view of layout of the first longwall panels in Parvadeh-I coal mine, A and B show the location of Parvadeh-I, and C show the plan of considered longwall panels

Table 4: Information of 12 locations from considered case study

Panel	Exc. type	Strap No.	Tell-tale No.	Depth (m)	P_1: CMRR	P_2	P_4	P_5	P_6	P_8
E_0	TG	900	77	55.00	40.1	B2	4.5	No Present	No joint	3.26
E_0	TG	170	15	90.00	22.4	B2J1	4.5	No Present	0.40	2.56
E_0	MG	1150	72	160.00	31.8	B2J1	5.0	No Present	1.82	0.89
E_0	MG	900	54	135.00	40.1	B2	5.0	No Present	No joint	1.33
E_2	TG	1010	59	230.00	23.5	B2J2	4.5	No present	6.29	0.43
E_2	TG	368	27	200.00	16.4	B2	4.5	No present	No joint	0.81
E_2	MG	1079	68	300.00	1.5	B2J1	5.0	No Present	15.38	0.54
E_2	MG	833	46	270.00	34.3	B2J1	5.0	No Present	0.75	0.76
E_3	TG	1300	93	365.00	28.7	B2J1	4.5	No present	2.50	0.28
E_3	TG	918	64	330.00	40.1	B2J1	4.5	No Present	0.41	0.63
E_3	MG	1590	113	440.00	18.9	B2J1	5.0	No present	0.96	0.53
E_3	MG	1168	80	390.00	28.7	B2J1	5.0	No present	2.56	0.37

Table 5: Information of 12 locations from considered case study (Continuation of **Table 4**)

Panel	Exc. type	Strap No.	P_3 Status 1	P_7 Status 1	related TTD (mm) Status 1	P_3 Status 2	P_7 Status 2	related TTD (mm) Status 2	P_3 Status 3	P_7 Status 3	related TTD (mm) Status 3
E_0	TG	900	<1.5	12.5	0	1.5-2.5	12.8	0	2.5≤	12.9	0
E_0	TG	170	<1.5	23.9	1	1.5-2.5	24.1	1	2.5≤	24.3	1
E_0	MG	1150	<1.5	3.6	0	1.5-2.5	3.7	9	2.5≤	4.0	14
E_0	MG	900	<1.5	4.2	0	1.5-2.5	4.5	0	2.5≤	5.0	2
E_2	TG	1010	<1.5	28.6	81	1.5-2.5	34.3	110	2.5≤	35.0	132
E_2	TG	368	<1.5	57.8	21	1.5-2.5	58.8	30	2.5≤	58.9	42
E_2	MG	1079	<1.5	33.4	190	1.5-2.5	36.6	457	2.5≤	37.1	556
E_2	MG	833	<1.5	46.5	60	1.5-2.5	48.1	83	2.5≤	48.2	94
E_3	TG	1300	<1.5	9.3	15	1.5-2.5	10.6	84	2.5≤	10.7	100
E_3	TG	918	<1.5	22.6	28	1.5-2.5	24.1	28	2.5≤	24.2	52
E_3	MG	1590	<1.5	4.7	11	1.5-2.5	6.2	14	2.5≤	6.2	25
E_3	MG	1168	<1.5	16.4	40	1.5-2.5	17.2	82	2.5≤	17.5	140

Table 6: Statistical description of the case study

Parameters name/code	Ave.	Min	Max	St. Dev.
P_1	32.16	1.5	40.1	8.67
P_2	Nominal	-	-	-
P_4 (m)	4.99	4.5	7	0.71
P_5 (m)	2<	2<	2<	-
P_6	1.88	0.20	15.38	2.55
P_7 in condition of P_3<1.5 (month)	21.97	0.55	61.59	16.37
P_7 in condition of P_3=1.5-2.5 (month)	26.28	3.70	63.20	18.60
P_7 in condition of 2.5≤P_3 (month)	30.50	4.00	63.55	18.79
P_8	0.99	0.28	3.26	0.76
TTD (mm) in condition of P_3<1.5	25.36	0	216	38.16
TTD (mm) in condition of P_3= 1.5-2.5	52.03	0	457	77.55
TTD (mm) in condition of 2.5≤P_3	80.94	0	556	107.24

4. MORESM validation

To evaluate MORESM's performance and capability, the model was considered in the case study. In this regard, VI_{ap} of each RB type was determined for all the locations of the case study in Parvadeh-I mine, and results are illustrated in Table 7 and Figure 8. As it can be seen, FCR.RB, SH.RB and RG. CB are the best options for the considered case study, respectively. These results are affected by the geomechanical conditions of the considered site as soft rocks under stresses increasing with the depth. According to the outputs, RG. CB is the optimum selection in E_2 MG, E_3 TG, E_3 MG, and E_3 Face which is resulted by variation of low-stress condition to high -stress condition in soft rocks due to increasing the depth. In these conditions, energy-absorbing of RBs displayed better performance to control the roof strata. Although, the difference between VI_{ap}s of FCR.RB, SH. RB, and RG. CB is low. On the other side of these investigations, mechanical RBs have the lowest performance for all considered locations.

According to the reults of Table 7, the uncertainty bounds for VI_{ap} values were quantified using 95% confidence intervals, with margin of errors ranging from ±0.75 to ±1.63 units across the six RBs. These translate to relative errors of approximately 2.3% to 3.8%, indicating that the MORESM model predicts optimum support systems with an estimated error margin of about ±3%, demonstrating high confidence in the model's accuracy and reliability.

Table 7: Description of all calculated VI_{ap} for the RBs in Parvadeh-I coal mine

RB code	Ave. VI_{ap}	Min VI_{ap}	Max VI_{ap}	St. Dev.	Margin of Error	CI lower bound	CI upper bound	Relative Error %
ES.RB	51.78	28.3	81.77	11.64	1.64	50.15	53.42	3.16
S.RB	40.08	20.34	67.31	10.78	1.51	38.56	41.59	3.78
SH.RB	32.83	16.53	53.94	8.31	1.17	31.66	34.00	3.56
FCR.RB	32.37	16.53	52.39	7.99	1.12	31.25	33.49	3.47
PAR.RB	43.39	24.32	72.92	10.88	1.53	41.86	44.92	3.52

RG.CB	32.86	23.25	48.7	5.31	0.75	32.11	33.61	2.27

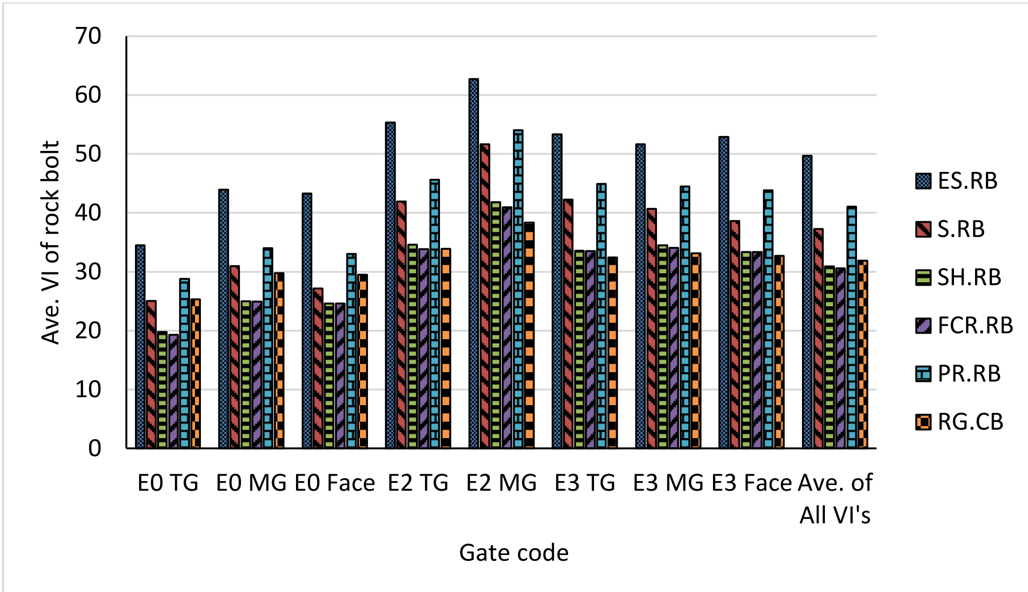

Figure 8: Average VI_{ap} for each RB type in the panel gates in Parvadeh-I coal mine

For validation and identification of the model performance, the relationship between the determined VI_{ap}s of applied RB in Parvadeh-I mine and the corresponding recorded TTDs were investigated and results are presented in Figure 9. In the following, a dataset including 14 locations/cases (see 10 locations on Table 8) located in all three desired panels is involved to test the ability of the model to predict the TTD for new locations. Figures 10 and 11 depict the comparison of predicted TTDs with the measured TTDs in the site. In this step, root mean squared error (RMSE) and mean absolte error (MAE) were used to assess the accuracy of fitted models and outcomes, which were formulated in Eqs 6 and 7. The obtained values of 0.803, 54.8, and 13.8 for R^2 , RMSE, and MAE, respectively, which are acceptable and consistent with the scale of the data.

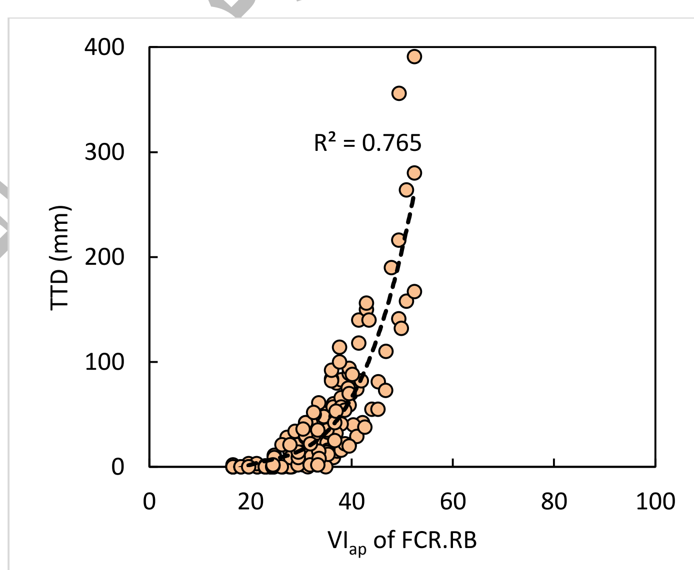

Figure 9: Relationship between the VI_{ap}s of applied RB and corresponding recorded TTDs, polynomial and linear regression analyses

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - y_i^*)^2} \quad (6)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(y_i - y_i^*)| \quad (7)$$

Table 8: Information of the 10 considered cases/locations to test the ability of MORESM for TTD prediction

Case No.	P_1	P_2	P_4	P_5	P_6	P_8	P_7 Status 1	TTD Status 1	P_7 Status 2	TTD Status 2	P_7 Status 3	TTD Status 3
1	40.1	B2	4.5	No present	NJ	NJ	22.3	3	22.9	3	MD	MD
2	40.1	B2	5.	No present	NJ	NJ	3.6	0	3.84	4	MD	MD
3	40.1	B2	5.0	No present	NJ	NJ	9.27	0	MD	MD	MD	MD
4	40.1	B2	7.0	No present	NJ	NJ	5.5	2	MD	MD	MD	MD
5	25.6	B2J1	4.5	No present	0.32	0.60	33.17	18	37.11	38	37.77	57
6	16.4	B2	4.5	No present	NJ	NJ	55.59	35	56.5	45	56.77	105
7	32.1	B2J1	5.0	No present	1.88	0.76	44.7	42	46.19	54	46.6	77
8	40.1	B2J1	4.5	No present	0.55	0.63	24	18	25.9	24	MD	MD
9	36.3	B2J1	5.0	No present	0.77	0.43	10.12	14	10.84	14	MD	MD
10	40.1	B2J1	5.0	No present	0.21	0.51	21.9	2	MD	MD	MD	MD

MD means that information of TTD corresponding to the considered status was not measured or was not found in the reports. NJ means No joint. P3 values for three statues are similar to those considered in Table 5. According to MD data, 20 VIs were determined for the related process.

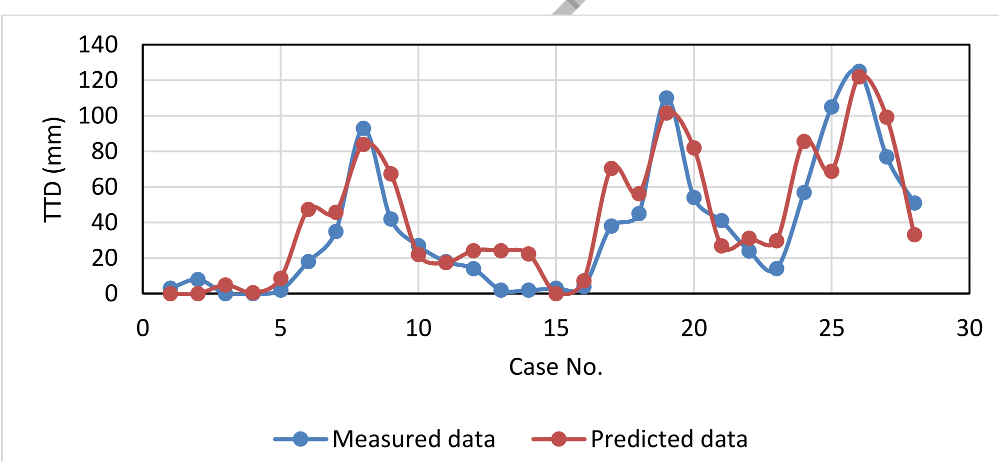

Figure 10: Relationship between the measured and predicted TTD

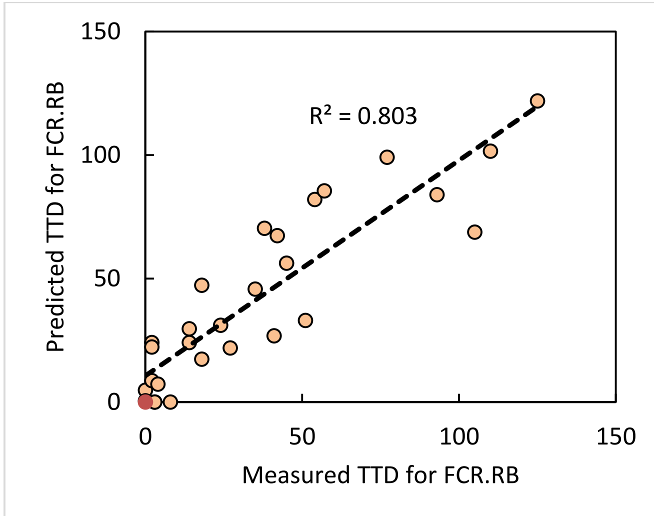

Figure 11: Relationship between the measured and predicted TTD

Increasing the difference between the VI_{ap} of applied RB and VI_{ap} of optimum RB (VI_{op}) leads to the lower performance of selected RB, which causes more instability and convergence in the roof. According to this concept, the relationship of the difference between the VI_{ap} of applied RB and VIop with the corresponding TTD was obtained and outcomes are shown in Figure 12. The graph shows a non-linear ascending trend that indicates increasing the TTD because of applying a non-optimal option. The highest difference between the applied RB and optimum RB was determined for E2 MG with very weak rocks under vertical stress of 6.62 to 7.85 MPa. In return, E0 TG, E0 MG, and E0 face showed the least difference (zero) in weak rocks under vertical stresses of 1.35 to 4.17 MPa.

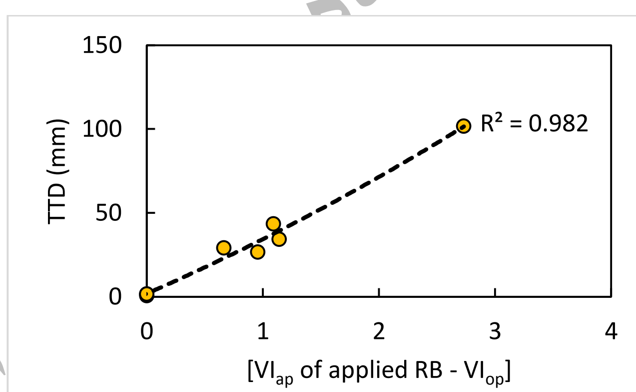

Figure 12: Relationship of the difference between VI_{ap} of applied RB and VI_{op} with the corresponding TTD for each considered gate, average amount for each gate, a polynomial regression analysis

Considering the substitution time of the support system type (in this study, the type of rock bolt) has been one of the challenges that engineers encounter in mines with various geological and geotechnical conditions. One of the abilities of MORESM is estimating the substitution time (depth) of RBs according to the new requirements due to changing geological conditions versus depth. This challenge is investigated in the current study by the defined model and the results are illustrated in Figure 13. For this aim, the relationship of the difference between VI_{ap} of applied RB (FCR.RB) and VI_{ap} of RG. CB with the corresponding TTD was investigated (Figure 13). RG. CB was selected due to its capability for supporting the soft rock strata under high-stress conditions. The results in the graph indicated that there is an ascending trend between the increase of the difference and the depth. Displacement in the roof is increased with the difference between the applied RB and the target bolt. It demonstrates that the trend is going towards the substituting

FCR.RB with RG.CB. Estimating the corresponding depth of substitution time could be determined by following the trends of results where the VI_{ap} of applied RB (FCR.RB) is more than VI_{ap} of RG.CB.

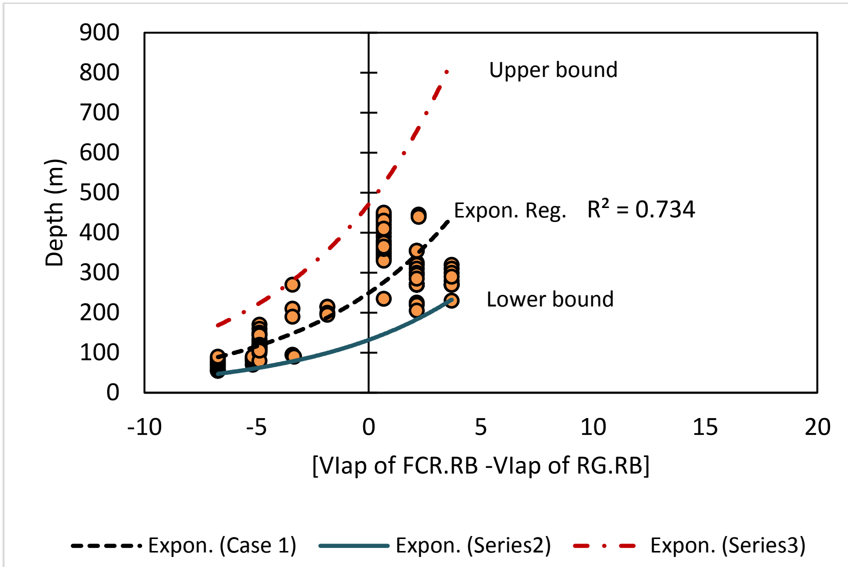

Figure 13: Relationship of the difference between VI_{ap} of applied RB (FCR.RB) and VI_{ap} of RG. CB with the corresponding TTD, an exponential regression analysis with upper and lower bounds (confidence factor 95%)

5. Discussion

Analyzing the results of the interaction matrix determine priorities for the selection of the optimum RB. There are other effective parameters in selecting optimum RB that could be involved and examined. Therefore, the obtained results indicated the importance of each parameter among the eight considered parameters based on the several expert surveys in completing the interaction matrix. MORESM only includes geological and geotechnical parameters. The influence of other effective parameters, such as the loading capacity of RB, the accessibility of related products of RBs, etc., should be applied using the auxiliary criteria. This research has prioritized the performance of RB in rock mass for selecting an optimum option (see sections 1 and 2). The authors have believed that involving the economic parameters and some operational parameters can produce unanalyzable results and cause deviation from the research priority.

The obtained results of MORESM validation showed that the presented rating method to calculate the VI_{ap} is well recognized to achieve the desired purposes, including determining the VI_{ap} of various options in various conditions and finding the relationship between the VI_{ap} and the instability in the roof. There are a lot of issues and uncertainties in rock engineering that is necessary to compare the various options or hazards with each other to solve and understand the problem. This rating method could increase the capability of RES to solve such complicated problems and issues. However, the conventional rating method only allows the researcher to study one hazard or option. This method could be further explored and supplemented.

Based on the average VI_{ap} of FCR.RB, SH.RB and RG. CB, considering an auxiliary criterion for the final decision is helpful. Generally, the simplicity of accessibility to products of the selected RB is an important factor that is considered by mining companies. Although when they are encountered with a long-life project, investing to buy or produce the best option has a lot of benefits against the related operational costs of a non-optimal RB. In connection with selecting optimum RB, the main purpose is the investigation of more types of RB involving all possible effective parameters. In this regard, the results of this study indicated that reaching the aim is feasible.

By considering positive functions of the model based on the results in Figures 9 to 12, the provided new application of RES could be applied for various cases and sites, under more investigations. The amounts of R^2 between the VI_{ap}s of applied RB and the corresponding recorded TTDs demonstrated that MORESM has shown acceptable performance. However, the ability of prediction of TTD is one of the major criteria for validation of MOREM, but it should be noted that the main purpose is determining an optimum RB with expected high performance. Investigating the relationship of the difference between the VI_{ap} of applied RB and the VI_{ap} with the corresponding TTD could be also one of the applicable criteria for validating the performance of an optimizer model. Results from Figure 12 specified that the instability in the roof is increased with increasing the distance of the applied option from the optimum one. The difference is high for locations with weak to very weak rocks under relatively low to high-stress conditions. It refers to the locations with a degree of squeezing lower than 0.7. This finding provides a tool to investigate the capabilities of the other RBs to substitute with the current system. In this regard, as is mentioned before, rock mass behavior is going to the soft rock under high-stress conditions with increasing the depth of mining in Parvadeh-I mine. The upper bound in Figure 13 can be introduced as the latest time to substitute the applied RB with the optimal RB which indicates a depth of about 500 m as the substitution depth. RG. CB, as the optimal RB for the case study, has better performance than FCR.RB, as the applied RB, in rock mass with soft rocks under high stresses. Latest reports indicate that there is a very large pressure on support arches and floor heave in some roadways in depths of more than 500 meters in Parvadeh-I. The depth of 500 m in Parvadeh-I is where the degree of squeezing is approximately lower than 0.53. This technique could be used in other support systems and even other sections in mines however it needs to be more investigated. Lack of timely assessment and substitution of the current support system with a more suitable one can lead to operational issues such as increased roof convergence, floor heave, higher operational costs, and reduced advancement rates.

The issue of RB selection has not been studied in this way in any of the previous studies (based on the literature review). Other researchers have often focused on examining the influence of technical parameters on the performance of different types of RBs, the parameters influencing the selection of RBs, and the performance of RBs in the field and laboratory conditions. Although, each of these researches has provided valuable results. The present article showed that it is possible to apply all the worthwhile results of these researches to propose a comprehensive model.

While MORESM presently operates deterministically, future versions could incorporate probabilistic methods, such as Monte Carlo simulations or Bayesian RES, to better capture uncertainty in input parameters like rock mass characteristics, stress conditions, and more. This enhancement would improve the robustness and reliability of the model in complex geomechanical settings.

In addition to the core mechanical factors modeled by MORESM, practical considerations such as installation ease and grout curing properties play a crucial role in field applications. These factors are best treated as auxiliary criteria to support final decision-making. Corrosion, given its influence on rock bolt durability, represents an important aspect that could be integrated into future versions of the model to enhance its predictive capability.

6. Conclusions

This research introduces a novel application of the Rock Engineering System (RES) for selecting the optimum rock bolt (RB) among various types. The main results and conclusions are summarized as follows:

- The proposed model relies on two fundamental components: an interaction matrix assigning weights to influential system parameters, and a rating matrix assessing each RB's performance under varying system conditions. The rating matrix enables comparative evaluation of RB effectiveness by examining relative responses without directly incorporating strength characteristics such as load-bearing capacity. This approach is particularly effective when validated against empirical field data.
- The training model was developed using data collected from 114 locations (197 cases under three stress conditions). The fitted model demonstrates an expected, stable trend without fluctuations or oscillations and with an R^2 of 0.765. Validation across 14 additional locations (28 cases) further confirmed MORESM's effectiveness for comparing RB options. Validation metrics include: correlation between VI_{ap} of applied RBs and recorded total tunnel displacements (TTD) ($R^2 = 0.765$); correlation between measured and predicted TTDs ($R^2 = 0.803$, RMSE = 54.8, MAE = 13.8); and a novel metric correlating the difference between VI_{ap} of applied and VI_{ap} of optimum RBs with corresponding TTDs ($R^2 = 0.982$), offering a new scale for optimizer model assessment.
- MORESM's ability to be validated with field data is a significant advantage. The model can determine the optimal RB, evaluate performance of different RBs at a site, analyze installed RB conditions, and estimate substitution timing for more suitable support systems.
- A new feature leverages the relationship between differences in VI_{ap} values of applied and optimum RBs and their corresponding TTDs to estimate substitution time for replacing the current support system with a more suitable option under evolving rockmass and stress conditions. For the case study, an approximate substitution depth of 500 m was identified, coinciding with hazards such as floor heave and severe roof convergence around this depth.
- While theoretical support for a causal relationship is provided by this study and prior work (Aghababaei et al., 2020), further experimental studies and long-term monitoring are needed to conclusively confirm the causality between the difference in VI_{ap} of applied and optimum options (e.g., rock bolt, as examined in the current research) and its potential use as a predictor of hazards such as roof convergence.
- The model's repeatability has been validated to ensure robustness against varying expert inputs and site data, recognizing that legitimate geological changes—especially at greater depths—may lead to different optimum RB selections.
- Given that mining challenges often involve hazards and ground response measurable by advanced tools, the method is adaptable to other issues and environments, provided validation against measured data. Though

developed for coal mines and specific RB types, MORESM can be calibrated for metalliferous mines or civil tunneling projects using site-specific data.

- MORESM incorporates induced mining stress conditions related to advancing longwall faces, but its real-time adaptability to rapidly evolving stress environments (e.g., sudden face advances or longwall retreats) requires further validation.
- Although sensitivity analysis of input parameter weights is acknowledged as important, this study primarily introduces and validates the RES-based framework for rock bolt selection.
- The core of this research focuses on the interaction mechanisms between RBs and surrounding strata under varying rock mass and stress conditions. In cases with similar model results for different RBs, auxiliary criteria such as cost, bearing capacity, or operational factors may guide the final selection.
- Finally, MORESM is presented as a promising model for further investigation and application rather than a fully validated, finalized method.

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