

# A DEMATEL-TOPSIS control model for enhancing rock mass rating reliability in weak rock conditions

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## Abstract

**Purpose.** This study aims to improve the reliability of the classical Rock Mass Rating system by introducing a control-based DEMATEL-TOPSIS framework that explicitly incorporates parameter interactions and reduces classification uncertainty near boundary conditions.

**Methods.** Parameter ratings were represented using triangular fuzzy numbers to model evaluation uncertainty, DEMATEL was applied to quantify interrelationships among classification criteria, and TOPSIS was used to determine the most representative rock mass class. The framework was validated using tunnel datasets obtained from two underground engineering projects under different geological conditions.

**Findings.** Results showed that incorporating parameter interactions improves classification consistency and reduces ambiguity for rock masses located near transition intervals, while maintaining strong agreement with conventional RMR evaluations (86%). A high Spearman's rank correlation coefficient ( $\rho = 0.872$ ) confirmed the statistical compatibility between classical and controlled classifications, supporting the reliability of the proposed framework. Influential criteria within the interaction structure were also identified systematically.

**Originality.** The study introduces a control-oriented extension of the RMR system that integrates parameter interdependencies into the classification process without modifying its original empirical structure. A graphical user interface enables transparent comparison between classical and controlled classification outcomes in engineering applications.

**Practical implications.** The proposed framework supports engineering decision-making by identifying potential misclassifications near class boundaries and providing a user-friendly tool for tunnel and mining projects involving weak rock masses. The developed interface facilitates consistent evaluation of parameter influence levels and improves transparency during support design assessments.

**Keywords:** rock mass rating; multi-criteria decision-making; DEMATEL; TOPSIS; weak rock

## 1. Introduction

Rock mass classification systems have long served as essential tools for engineering decision-making in underground excavations and other geotechnical applications. Since the early development of empirical classification approaches based on field observations, numerous methods have been proposed to translate geological characteristics into quantitative engineering indices. Among these systems, the Rock Mass Rating (RMR) method introduced by Bieniawski [1] and the Q classification system proposed by Barton et al. [2] remain the most widely adopted frameworks for evaluating rock mass quality in underground engineering practice.

Despite their widespread use, conventional rock mass classification systems have several limitations, including deterministic parameter weighting and sharp class boundaries. Because these systems use fixed rating intervals, small variations in parameter values can cause transitions between adjacent classes, leading to inconsistent classification outcomes. Furthermore, differences in expert interpretation may reduce the

reliability of classification results obtained using classical empirical approaches [3]-[5]. To address these limitations, fuzzy set theory has been increasingly applied to rock mass classification problems to represent uncertainty associated with geological variability and linguistic parameter descriptions. Early applications of fuzzy classification concepts in rock mechanics were reported by Nguyen [6], followed by developments from Juang et al. [7] and Habibagahi and Katebi [8], who demonstrated that membership-based evaluation schemes could better represent gradual transitions between rock mass quality classes. Later studies extended fuzzy approaches to classical classification systems. For example, Aydın [9] incorporated fuzzy membership functions into the RMR framework. At the same time, Khademi Hamidi et al. [10] demonstrated that uncertainty within rock mass classification procedures could be reduced using fuzzy evaluation methods. Similarly, Jalalifar et al. [11] developed adaptive neuro-fuzzy inference models to predict rock mass classes, and Daftari-besheli et al. [12] proposed the Fuzzy Slope Mass Rating (FSMR) approach, integrating fuzzy inference algorithms into slope stability classification.

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Because rock mass classification inherently involves multiple interacting parameters, multi-criteria decision-making (MCDM) methods have increasingly been applied to improve the reliability of classification procedures. Chen and Liu [13] integrated the Analytic Hierarchy Process (AHP) with the fuzzy Delphi technique to evaluate rock mass quality in tunnel engineering. Saeidi et al. [14] developed the Rock Mass Drillability Index using a fuzzy Delphi-AHP-based group decision-making approach; Jalalifar et al. [15] combined fuzzy inference systems with regression-based prediction models to estimate RMR values. Yardımcı and Karpuz [16] demonstrated that fuzzy logic-based classification schemes provide improved performance under weak rock conditions. Interval number-based evaluation approaches were applied by Song et al. [17] for engineering classification of jointed rock masses, while Wu et al. [18] proposed a TOPSIS-based model for evaluating rock mass stability. In addition, Bagloo and Ataee-Pour [19] introduced the Stone Quality Point classification model, using AHP-based weighting and triangular-fuzzy evaluation.

More recently, fuzzy logic-based multi-criteria decision-making approaches have also been applied to the Rock Mass Quality Rating (RMQR) system. In this context, Dönmez et al. [20] proposed a fuzzy AHP-TOPSIS framework for improving RMQR-based rock mass classification, demonstrating that uncertainty associated with linguistic parameter definitions can be effectively incorporated into classification procedures.

The objective of this study is to develop an integrated framework that addresses the inherent limitations of the classical Rock Mass Rating (RMR) system and establishes a reliable control mechanism for rock mass classification. In addition, the explicit incorporation of discontinuity orientation as an evaluation criterion is intended to reflect better its structural influence on the stability of underground excavations and to support decision-making in underground design applications.

In the classical RMR system, parameter ratings are directly summed, implicitly assuming equal importance and independence among the criteria. Such an assumption may lead to misleading representations of rock mass behavior, particularly under weak rock conditions where parameter interactions play a critical role. To overcome this limitation, the DEMATEL method is adopted to quantify the interrelationships among classification parameters and to derive their relative importance levels.

According to the available literature, the DEMATEL method has not been explicitly integrated into the RMR classification framework as a control-based weighting mechanism. In this context, a triangular fuzzy number (TFN)-based DEMATEL-TOPSIS model is proposed to reduce the sharpness of class boundaries, account for uncertainty in expert evaluations, and perform rock mass classification within a structured multi-criteria decision-making environment.

Rather than directly replacing the classical RMR system, the proposed approach is designed as a complementary verification tool to identify potential misclassifications, particularly those near class boundaries in weak rock masses. The framework is intended to facilitate engineering judgment and support RMR users' decision-making during underground excavation design. To ensure practical applicability, a graphical user interface (GUI) is developed to enable systematic implementation of the framework and direct comparison with classical RMR classification results.

## 2. Materials and methods

### 2.1. Rock mass rating

The Rock Mass Rating (RMR) or geomechanical classification system was first proposed by Bieniawski [1] at the Council for Scientific and Industrial Research (CSIR) in South Africa. Since its introduction, the system has undergone several significant modifications. In 1974, the number of classification parameters was reduced from eight to six; in 1975, the rating values were adjusted, and the recommended support requirements were reduced; in 1976, the class boundaries were revised to be multiples of twenty; and in 1979, the ISRM [21] definition of rock mass was adopted. Through these successive revisions, the system evolved into the version published in 1989 [22], which remains in use today.

In summary, the system is based on a rating principle in which the rock mass is evaluated according to the parameters of rock strength, rock quality designation, spacing of discontinuities, condition of discontinuities, and groundwater conditions, as presented in Table 1. The obtained rock mass score is referred to as the basic RMR value, and an adjustment is applied based on the orientation of discontinuities, as shown in Table 2. The system classifies rock masses based on the final RMR value, as shown in Table 3.

### 2.2. Case studies

The rock masses that require support and present greater difficulty in decision-making are generally those belonging to the last two classes of the RMR system. Therefore, the data used in this study were selected from these two RMR classes. Within this scope, the database was constructed using RMR data obtained from two tunnel projects: The Dim Highway Tunnel in Alanya [23] and the Kırık Highway Tunnel in Erzurum [24]. The dataset used in the analyses is presented in Table 4, and the location map of the case studies is shown in Figure 1.

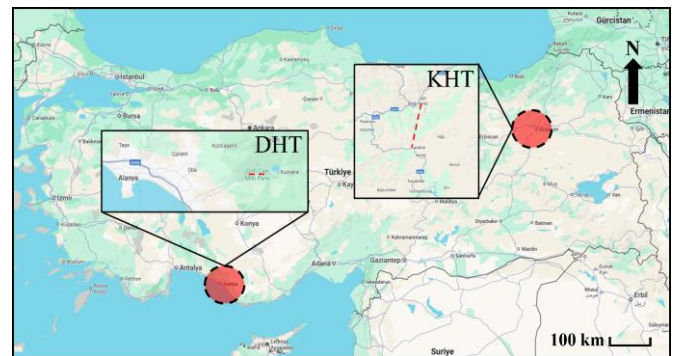


Figure 1. Location map of case studies

#### 2.2.1. The Dim highway tunnel (DHT)

The Dim Tunnel is located in southern Türkiye, along the Alanya-Gazipaşa 5<sup>th</sup> Regional Border Highway, between kilometers 6 + 050 and 7 + 400, approximately 6 km southeast of Alanya. The tunnel has a horseshoe-shaped cross-section with a diameter of 10 meters and a maximum overburden thickness of 70 meters. The rock types observed in the study area are dominated by schist, with occasional intercalations of recrystallized limestone, blocky limestone, conglomerate, and sandstone-shale alternations. The DHT dataset comprises 39 RMR values from 8 boreholes [23].

**Table 1. Rock mass rating system [22]**

| Parameter                        |                                              | Range of values       |                          |                         |                                |                                                                |     |     |
|----------------------------------|----------------------------------------------|-----------------------|--------------------------|-------------------------|--------------------------------|----------------------------------------------------------------|-----|-----|
| Strength of intact rock material | Point-load strength index (MPa)              | > 10                  | 4-10                     | 2-4                     | 1-2                            | For this low range, uniaxial compressive strength is preferred |     |     |
|                                  | Uniaxial compression strength (MPa)          | > 250                 | 100-250                  | 50-100                  | 25-50                          | 5-25                                                           | 1-5 | < 1 |
| Rating (R <sub>UCS</sub> )       |                                              | 15                    | 12                       | 7                       | 4                              | 2                                                              | 1   | 0   |
| Drill core quality (RQD) (%)     |                                              | 90-100                | 75-90                    | 50-75                   | 25-50                          | < 25                                                           |     |     |
| Rating (R <sub>RQD</sub> )       |                                              | 20                    | 17                       | 13                      | 8                              | 3                                                              |     |     |
| Spacing of discontinuities (m)   |                                              | > 2                   | 0.6-2.0                  | 0.2-0.6                 | 0.06-0.20                      | < 0.06                                                         |     |     |
| Rating (R <sub>DS</sub> )        |                                              | 20                    | 15                       | 10                      | 8                              | 5                                                              |     |     |
| Condition of discontinuities     |                                              | Very rough surfaces   | Slightly rough surfaces  | Slightly rough surfaces | Slickensided surfaces or Gouge | Soft gouge > 5 mm thick or                                     |     |     |
|                                  |                                              | Not continuous        | Separation < 1 mm        | Separation < 1 mm       | < 5 mm thick or                | Separation > 5 mm continuous                                   |     |     |
|                                  |                                              | Unweathered wall rock | Slightly weathered walls | Highly weathered walls  | Separation 1-5 mm continuous   |                                                                |     |     |
| Rating (R <sub>DC</sub> )        |                                              | 30                    | 25                       | 20                      | 10                             | 0                                                              |     |     |
| Ground water                     | Inflow per 10 m tunnel length, l/m           | None                  | < 10                     | 10-25                   | 25-125                         | > 125                                                          |     |     |
|                                  | Joint water press / major principal $\sigma$ | 0                     | < 0.1                    | 0.1-0.2                 | 0.2-0.5                        | > 0.5                                                          |     |     |
|                                  | General conditions                           | Completely dry        | Damp                     | Wet                     | Dripping                       | Flowing                                                        |     |     |
| Rating (R <sub>GC</sub> )        |                                              | 15                    | 10                       | 7                       | 4                              | 0                                                              |     |     |

**Table 2. Discontinuity orientation adjustment for tunnels and mines [22]**

| Discontinuity orientation                  |                   |             |                  | Adjustment (A <sub>Do</sub> ) |
|--------------------------------------------|-------------------|-------------|------------------|-------------------------------|
| I. Strike perpendicular to the tunnel axis | Drive with dip    | Dip 45°-90° | Very favorable   | 0                             |
|                                            |                   | Dip 20°-45° | Favorable        | -2                            |
|                                            | Drive against dip | Dip 45°-90° | Fair             | -5                            |
|                                            |                   | Dip 20°-45° | Unfavorable      | -10                           |
| II. Strike parallel to the tunnel axis     |                   | Dip 45°-90° | Very unfavorable | -12                           |
|                                            |                   | Dip 20°-45° | Fair             | -5                            |
| III. Irrespective of strike dip 0°-20°     |                   |             | Fair             | -5                            |

**Table 3. Rock mass classes [22]**

| Rock class               | I         | II       | III      | IV       | V         |
|--------------------------|-----------|----------|----------|----------|-----------|
| Description of rock mass | Very good | Good     | Fair     | Poor     | Very poor |
| RMR                      | [100, 80] | [80, 60] | [60, 40] | [40, 20] | [20, 0]   |

**Table 4. Used RMR data**

| Sample case | R <sub>UCS</sub> | R <sub>RQD</sub> | R <sub>DS</sub> | R <sub>DC</sub> | R <sub>GC</sub> | A <sub>DO</sub> | RMR |
|-------------|------------------|------------------|-----------------|-----------------|-----------------|-----------------|-----|
| DHT-1       | 1                | 3                | 5               | 15              | 7               | -5              | 26  |
| DHT-2       | 2                | 3                | 5               | 15              | 7               | -5              | 27  |
| DHT-3       | 3                | 3                | 5               | 15              | 7               | -5              | 28  |
| DHT-4       | 2                | 3                | 5               | 17              | 7               | -5              | 29  |
| DHT-5       | 2                | 3                | 5               | 17              | 7               | -5              | 29  |
| DHT-6       | 3                | 3                | 5               | 17              | 7               | -5              | 30  |
| DHT-7       | 3                | 5                | 5               | 15              | 7               | -5              | 30  |
| DHT-8       | 3                | 3                | 5               | 10              | 15              | -5              | 31  |
| DHT-9       | 4                | 3                | 5               | 17              | 7               | -5              | 31  |
| DHT-10      | 2                | 3                | 5               | 19              | 7               | -5              | 31  |
| DHT-11      | 7                | 2                | 3               | 17              | 7               | -5              | 31  |
| DHT-12      | 3                | 3                | 5               | 19              | 7               | -5              | 32  |
| DHT-13      | 4                | 4                | 5               | 17              | 7               | -5              | 32  |
| DHT-14      | 7                | 3                | 5               | 17              | 7               | -5              | 34  |
| DHT-15      | 2                | 3                | 5               | 15              | 15              | -5              | 35  |
| DHT-16      | 7                | 5                | 6               | 15              | 7               | -5              | 35  |
| DHT-17      | 3                | 7                | 5               | 19              | 7               | -5              | 36  |
| DHT-18      | 7                | 7                | 5               | 15              | 7               | -5              | 36  |
| DHT-19      | 6                | 3                | 6               | 19              | 7               | -5              | 36  |
| DHT-20      | 3                | 3                | 5               | 15              | 15              | -5              | 36  |
| DHT-21      | 3                | 4                | 5               | 15              | 15              | -5              | 37  |
| DHT-22      | 2                | 3                | 5               | 17              | 15              | -5              | 37  |
| DHT-23      | 5                | 7                | 6               | 17              | 7               | -5              | 37  |
| DHT-24      | 1                | 3                | 5               | 18              | 15              | -5              | 37  |
| DHT-25      | 5                | 3                | 5               | 14              | 15              | -5              | 37  |
| DHT-26      | 5                | 5                | 5               | 21              | 7               | -5              | 38  |
| DHT-27      | 3                | 3                | 5               | 17              | 15              | -5              | 38  |
| DHT-28      | 5                | 3                | 5               | 15              | 15              | -5              | 38  |
| DHT-29      | 6                | 9                | 5               | 17              | 7               | -5              | 39  |
| DHT-30      | 6                | 7                | 5               | 19              | 7               | -5              | 39  |
| DHT-31      | 3                | 4                | 5               | 17              | 15              | -5              | 39  |
| DHT-32      | 7                | 5                | 6               | 19              | 7               | -5              | 39  |
| DHT-33      | 7                | 8                | 5               | 17              | 7               | -5              | 39  |
| DHT-34      | 7                | 7                | 6               | 17              | 7               | -5              | 39  |
| DHT-35      | 5                | 3                | 6               | 15              | 15              | -5              | 39  |
| DHT-36      | 6                | 9                | 6               | 17              | 7               | -5              | 40  |
| DHT-37      | 5                | 10               | 6               | 17              | 7               | -5              | 40  |
| DHT-38      | 7                | 10               | 6               | 15              | 7               | -5              | 40  |
| DHT-39      | 5                | 3                | 5               | 17              | 15              | -5              | 40  |
| KHT-1       | 1                | 3                | 5               | 11              | 7               | -10             | 17  |
| KHT-2       | 2                | 3                | 5               | 14              | 4               | -10             | 18  |
| KHT-3       | 2                | 3                | 5               | 13              | 7               | -5              | 25  |
| KHT-4       | 2                | 3                | 5               | 14              | 7               | -5              | 26  |
| KHT-5       | 4                | 8                | 8               | 13              | 4               | -10             | 27  |
| KHT-6       | 2                | 8                | 5               | 13              | 7               | -5              | 30  |
| KHT-7       | 4                | 8                | 5               | 11              | 7               | -5              | 30  |
| KHT-8       | 2                | 8                | 8               | 18              | 4               | -5              | 35  |
| KHT-9       | 4                | 8                | 8               | 16              | 4               | -5              | 35  |
| KHT-10      | 2                | 8                | 8               | 19              | 4               | -5              | 36  |
| KHT-11      | 2                | 13               | 8               | 15              | 7               | -5              | 40  |

RUCS: Rating of strength of intact rock material, RRQD: Rating of drill core quality, RDS: Rating of Spacing of discontinuities, RDC: Rating of Condition of discontinuities, RGC: Rating of Groundwater, ADO: Rating of Adjustment

### 2.2.2. The Kırık highway tunnel (KHT)

The Kırık Tunnel is situated along the Erzurum-Pazaryolu-İspir Highway, between Erzurum and İspir, approximately 90 km away from the city of Erzurum. The tunnel has a horse-shoe-shaped cross-section with a diameter of 10 meters and a maximum overburden thickness of 900 meters. The rock types observed in the study area include limestone, marlstone, claystone, sandstone, and mudstone. The KHT dataset comprises 11 RMR values obtained from 7 boreholes [23][24].

### 2.3. Construction of the fuzzy decision matrix

In the proposed framework, the first stage transforms deterministic parameter ratings derived from field observations into a structured evaluation matrix suitable for multi-criteria analysis. In classical RMR applications, parameter values are assigned crisp numerical scores based on predefined rating intervals. However, such discrete representations may not adequately capture the uncertainties inherent in engineering judgment and geological variability.

To address this limitation, fuzzy set theory was employed to express parameter evaluations as gradual membership distributions rather than fixed numerical values. Fuzzy set theory, originally introduced by Zadeh [25], enables the representation of uncertain or linguistically defined variables using membership functions defined over the interval [0,1]. To represent this uncertainty explicitly, triangular fuzzy numbers (TFNs) were used to describe parameter ratings within the proposed framework. A TFN is defined by three characteristic values representing the lower bound, the most representative value, and the upper bound of a parameter rating interval. This structure enables gradual transitions between adjacent evaluation categories and provides a flexible mechanism for modeling uncertainty in expert-based classification procedures.

Using TFNs, each parameter score assigned in the classical RMR framework was transformed into a fuzzy evaluation interval that reflects possible variations in engineering interpretation. As a result, the constructed decision matrix incorporates both deterministic observations and the uncertainty associated with parameter boundaries, allowing for a more realistic representation of rock mass conditions than conventional crisp scoring approaches.

Based on these membership values, a decision matrix was constructed to represent the contribution of each classification parameter to rock mass quality. This matrix serves as the basis for subsequent weighting and ranking procedures conducted using the DEMATEL and TOPSIS methods (Fig. 2).

### 2.4. Determination of parameter weights using the DEMATEL method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is one of the multi-criteria decision-making (MCDM) approaches developed to analyze the mutual relationships among criteria in complex systems. Initially proposed by the Battelle Memorial Institute [26], this method expresses the direct effects among criteria in a numerical matrix form based on expert opinions. DEMATEL enables clearer modeling of a complex structure by revealing cause and effect relationships among factors [27]-[29].

The main objective of this method is to determine the direction (cause and effect) and degree of importance (prominence) of the factors involved in the decision-making process.

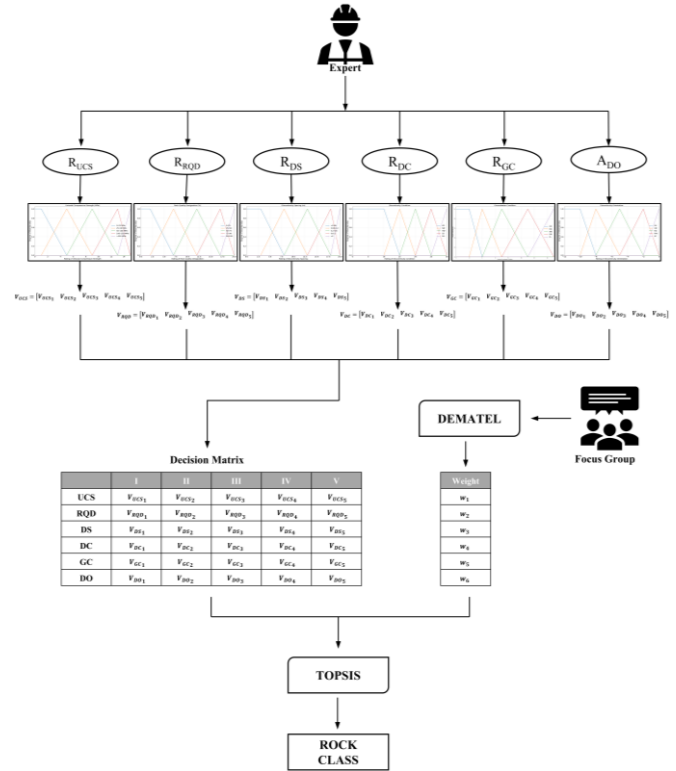


Figure 2. The methodological framework of the proposed model

Thus, not only the importance weights of variables within the system but also the extent to which they influence other factors can be analyzed [30], [31]. This characteristic distinguishes DEMATEL from conventional methods such as AHP or TOPSIS, making it a powerful tool, particularly for systems with multidimensional and interdependent relationships [32], [33].

The DEMATEL direct-relation matrix was developed using expert judgment to capture the interactions among rock mass classification parameters. To this end, an expert panel of six professionals with extensive experience in rock mechanics and underground engineering was convened. The panel comprised three academic researchers specializing in rock mass classification and geomechanics, and three senior field engineers with more than ten years of experience in tunnel design and construction. All experts were familiar with the RMR system and had previously applied rock mass classification methods in real-world tunnel projects.

To ensure consistency and reduce individual bias in expert evaluations, a modified Delphi approach was adopted. In the first round, the experts independently assessed the influence of each criterion on the others using a predefined scale ranging from 0 to 4. The initial evaluations were then aggregated and summarized, and the anonymous results were shared with the expert group. In the second round, experts were allowed to revise their judgments in light of the group feedback. The final direct-relation matrix was obtained by calculating the arithmetic mean of the revised evaluations, thereby providing a representative and consensus-based input for the DEMATEL analysis.

The DEMATEL computational procedure consists of the following stages.

Step 1. Establishment of the direct-relation matrix.

Experts are asked to evaluate the influence of each criterion on the others. The level of influence is usually determined on a scale from 0 to 4 (0 = no influence, 1 = very low influence, 2 = low influence, 3 = high influence, 4 = very strong

influence). Using the obtained values, an  $n \times n$  direct-relation matrix  $A = [a_{ij}]$  is constructed. The diagonal elements ( $a_{ii}$ ) are set to zero, as a criterion cannot influence itself:

$$A = (a_{ij})_{n \times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}. \quad (1)$$

Step 2. Computation of the normalized direct-relation matrix.

To make values on different scales comparable, the matrix is normalized. Normalization is performed by dividing each element by the maximum of the largest row or column sum:

$$X = (x_{ij})_{n \times n} = \frac{A}{\max \left( \max_{1 \leq i \leq n} \sum_{j=1}^n a_{ij}, \max_{1 \leq j \leq n} \sum_{i=1}^n a_{ij} \right)}. \quad (2)$$

Step 3. Derivation of the total-relation matrix.

Starting from the normalized matrix, both direct and indirect effects are considered, and the total relation matrix ( $T$ ) is computed:

$$T = X(I - X)^{-1}, \quad (3)$$

where:

$I$  – the identity matrix.

This step reveals the overall influence level of each criterion within the system.

Step 4. Calculation of row and column sums.

The values in each row and column of the total-relation matrix  $T$  are calculated. The vectors  $R$  and  $D$  are determined by summing up the rows and columns of  $T$ , respectively:

$$R = (R_i)_{n \times 1} = \left( \sum_{j=1}^n t_{ij} \right)_{n \times 1} \quad i = 1, 2, \dots, n; \quad (4)$$

$$D = (D_j)_{1 \times n} = \left( \sum_{i=1}^n t_{ij} \right)_{1 \times n} \quad i = 1, 2, \dots, n. \quad (5)$$

Step 5. Determination of weights.

Finally, the relative importance weights of the factors are obtained using the following Formula:

$$w_i = \frac{\sqrt{(R_j + D_j)^2 + (R_j - D_j)^2}}{\sum_{j=1}^n \sqrt{(R_j + D_j)^2 + (R_j - D_j)^2}}. \quad (6)$$

## 2.5. Determination of rock mass class using the TOPSIS method

After determining criterion weights using DEMATEL, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was applied to identify the most representative rock mass class. Developed by Hwang and Yoon [34], the method is based on the principle that the selected alternative should be the closest to the positive ideal solution and the farthest from the negative ideal solution. TOPSIS relies on a reasoning pattern that closely resembles human decision-making behavior. For these reasons, the TOPSIS method has been adopted in this study to evaluate rock mass classes. During the implementation of the method, the rock classification parameters have been defined as evaluation criteria, and the alternatives have been considered as the rock mass classes specified in the RMR system.

The TOPSIS procedure was implemented through the following stages.

Step 1. Construction of the Decision Matrix.

An evaluation matrix is created based on  $m$  alternatives and  $n$  criteria, represented as:

$$B_{ij} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m1} & \cdots & b_{mn} \end{bmatrix}. \quad (7)$$

Step 2. Normalized decision matrix.

The decision matrix is normalized using Equation (8):

$$r_{ij} = \frac{b_{ij}}{\sqrt{\sum_{k=1}^m b_{ik}^2}}. \quad (8)$$

Step 3. Weighted normalized matrix.

The normalized values are multiplied by the relative importance weights  $w_i$  of the criteria to obtain the weighted normalized matrix:

$$v_{ij} = w_i \times r_{ij}. \quad (9)$$

Step 4. Determination of positive and negative ideal solutions.

The positive ideal solution ( $A^+$ ) and the negative ideal solution ( $A^-$ ) are determined as follows:

$$A^+ = \left[ \left( \max_i v_{ij} \mid j \in J \right), \left( \min_i v_{ij} \mid j \in J' \right) \right] = \{v_1^+, v_2^+, \dots, v_n^+\}; \quad (10)$$

$$A^- = \left[ \left( \min_i v_{ij} \mid j \in J \right), \left( \max_i v_{ij} \mid j \in J' \right) \right] = \{v_1^-, v_2^-, \dots, v_n^-\}. \quad (11)$$

Step 5. Calculation of distances.

The distance of each alternative from  $A^+$  and  $A^-$  is calculated as:

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}; \quad (12)$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}. \quad (13)$$

Step 6. Calculation of the closeness coefficient.

The closeness coefficient ( $CC_i$ ) of each alternative is calculated using Equation (14):

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}. \quad (14)$$

## 2.6. Statistical validation of the model

To assess the level of agreement between the conventional RMR classification and the results obtained from the proposed control-based framework, Spearman's rank correlation coefficient was utilized. As a nonparametric statistical measure, Spearman's correlation is commonly used to assess monotonic relationships between ordinal variables without assuming normality [35]. The coefficient ranges from -1 to +1, where values near +1 indicate a strong positive correspondence, values near 0 suggest little or no monotonic association, and values near -1 reflect a strong negative relationship between the compared rankings [36]. Considering that rock mass classes represent ordinal categories rather than continuous measurements, Spearman's rank correlation coefficient was selected as an appropriate statistical tool to quantify the consistency between the classical RMR classifications and those produced by the proposed methodology.

### 3. Results and discussion

In this section, the full implementation of the proposed model is presented to explain the operation of the new approach. All procedures have been evaluated and demonstrated for the DHT-2 case given in Table 4. In addition, to demonstrate the statistical validity of the results obtained for all cases, the statistical relationship between the proposed model and the RMR system has been reported.

First, a decision matrix representing the rock mass was constructed. This matrix is unique for each rock mass, and during its construction, membership functions composed of TFNs, as shown in Figure 2, were utilized. For example, the determination of the UCS vector ( $v_{UCS}$ ) corresponding to the UCS rating ( $R_{UCS}$ ) for the DHT-2 case is illustrated in Figure 3.

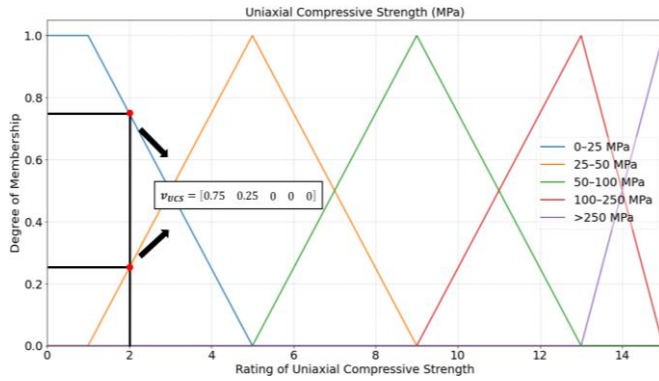


Figure 3. Illustration of TFN-based transformation for the UCS parameter

The same transformation procedure was applied to the remaining criteria, and the decision matrix B for DHT-2 is presented in Equation (15):

$$B_{DHT-2} = \begin{bmatrix} 0.75 & 0.25 & 0 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.6 & 0.4 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}. \quad (15)$$

The DEMATEL method was employed to determine the weights of the criteria. In this context, an expert focus group was convened, and the members reached a consensus on the final form of the Direct-Relation Matrix. The Direct-Relation Matrix, established from expert evaluations, is presented in Table 5.

Table 5. Direct-relation matrix of the criteria

|           | $R_{UCS}$ | $R_{RQD}$ | $R_{DS}$ | $R_{DC}$ | $R_{GC}$ | $A_{DO}$ |
|-----------|-----------|-----------|----------|----------|----------|----------|
| $R_{UCS}$ | 0         | 1         | 1        | 1        | 0        | 0        |
| $R_{RQD}$ | 0         | 0         | 1        | 1        | 0        | 0        |
| $R_{DS}$  | 3         | 4         | 0        | 3        | 2        | 0        |
| $R_{DC}$  | 4         | 4         | 3        | 0        | 2        | 0        |
| $R_{GC}$  | 1         | 1         | 0        | 3        | 0        | 1        |
| $A_{DO}$  | 1         | 1         | 0        | 2        | 2        | 0        |

The structure of the DEMATEL direct-relation matrix reflects the physical and mechanical interdependencies among the rock mass parameters rather than purely subjective judgments. In rock mechanics, the condition of discontinuities (DC) governs the mechanical behavior of the rock mass by directly controlling shear strength, block interlocking, and

deformation characteristics. Therefore, DC was evaluated as having a strong influence on both the intact rock strength (UCS) and the spacing of discontinuities (DS), since highly weathered or infilled discontinuities can significantly reduce the effective contribution of intact rock strength and amplify the adverse effects of closely spaced joints.

Similarly, the spacing of discontinuities (DS) was considered to exert a strong influence on UCS and DC. Closely spaced discontinuities reduce the intact rock strength and increase the likelihood of block instability, thereby intensifying the impact of discontinuity surface conditions. This physical relationship justifies the relatively high influence scores assigned from DS to UCS and DC in the DEMATEL matrix.

Groundwater conditions (GC) were modeled as an interacting parameter that affects multiple criteria rather than as an isolated factor. Elevated groundwater pressures reduce effective normal stress along discontinuities, weaken infilled joint materials, and accelerate weathering processes. Consequently, GC was assigned a moderate influence on DC and UCS, reflecting its indirect but significant role in degrading overall rock mass behavior.

Discontinuity orientation (DO) was explicitly incorporated as an independent criterion because of its critical role in governing kinematic feasibility and failure mechanisms in underground excavations. Although DO does not directly alter the intrinsic material properties of the rock mass, its geometric relationship with the excavation axis strongly governs stability. For this reason, DO was considered to influence parameters related to structural control, such as DS and DC, while exhibiting limited interaction with intact rock properties.

In contrast, the drill core quality parameter (RQD) primarily serves as a descriptive index of fracture frequency rather than an active controlling factor. As RQD is largely a derivative measure influenced by discontinuity spacing and condition, it was modeled as being predominantly affected by other parameters rather than exerting a strong influence on them. This assumption explains the relatively low outgoing influence values associated with RQD in the DEMATEL matrix.

Overall, the assigned interaction structure captures the hierarchical and coupled nature of rock mass behavior, ensuring that the DEMATEL-based weights are grounded in rock mechanics principles rather than arbitrary expert preference. The final criterion weights obtained using the DEMATEL method, which apply to all rock masses, are presented in Table 6.

Table 6. Criteria weights

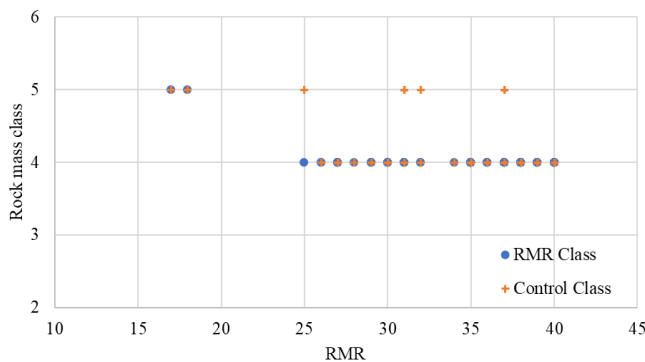
| Criteria | Weights |
|----------|---------|
| C1       | 0.15    |
| C2       | 0.18    |
| C3       | 0.20    |
| C4       | 0.24    |
| C5       | 0.13    |
| C6       | 0.10    |

Finally, the TOPSIS method was used to determine the rock mass classes. The decision matrix was multiplied by the obtained weights to form the weighted decision matrix, and the alternatives were ranked using the TOPSIS method based on their distance from the negative ideal solution and proximity to the positive ideal solution. As a result of the ranking, the alternative with the highest  $CC_j$  value was identified as the rock mass class. In this case, as shown in Table 7, the rock mass class of DHT-2 was determined as Class IV.

**Table 7. Determination of rock mass classes based on the TOPSIS method**

| Alternatives   | $d_i^+$ | $d_i^-$ | $CC_i$ | Ranking |
|----------------|---------|---------|--------|---------|
| Very poor (A1) | 0.2907  | 0.2186  | 0.4292 | 2       |
| Poor (A2)      | 0.1699  | 0.2891  | 0.6297 | 1       |
| Fair (A3)      | 0.3497  | 0.1     | 0.2223 | 3       |
| Good (A4)      | 0.3637  | 0       | 0      | 4       |
| Very good (A5) | 0.3637  | 0       | 0      | 5       |

The proposed model, which was applied to the DHT-2 case through all stages, was subsequently applied to all cases presented in Table 4, and the corresponding results are shown in Figure 4.

**Figure 4. Comparison of RMR and proposed control framework classifications for all cases**

As illustrated in Figure 4, the proposed control-based classification framework exhibits a high degree of agreement with the classical RMR system across most of the investigated cases. This overall consistency indicates that the developed model preserves the general classification trend of the classical RMR approach while providing an additional layer of verification. However, a limited number of discrepancies between the two classification methods are also observed in Figure 4, particularly in cases near the class boundaries.

In addition to the visual comparison shown in Figure 4, a quantitative assessment was conducted to evaluate the degree of agreement between the classical RMR system and the proposed control-based classification framework. The percentage agreement between the two approaches was calculated as 86%, indicating that most rock mass cases were assigned to the same class by both methods.

Furthermore, a Spearman rank correlation analysis was performed, taking into account the ordinal nature of the RMR classes. The analysis yielded a strong and statistically significant correlation with  $\rho = 0.872$  between the two classification approaches. This result confirms that the proposed control framework preserves the overall ranking behavior of the classical RMR system while providing increased sensitivity for borderline Class IV-V rock masses.

The cases for which inconsistent classifications were obtained are summarized in Table 8, in which nine samples were assigned to a lower rock mass quality class by the proposed control framework than by the classical RMR system. A detailed examination of these cases reveals that the mismatches are predominantly associated with marginal RMR values close to the transition between Class IV (Poor) and Class V (Very Poor). In the classical RMR system, the direct summation of parameter ratings may lead to optimistic class assignments in

such boundary regions, as the relative influence of critical parameters is not explicitly considered. In contrast, the proposed framework incorporates DEMATEL-based parameter weighting and triangular fuzzy number-based membership functions, allowing the cumulative effects of unfavorable parameters such as low UCS, reduced RQD, adverse groundwater conditions, and unfavorable discontinuity orientation to be more effectively reflected in the final classification. As a result, these borderline cases are identified more conservatively by the control framework, leading to their classification as Class V.

**Table 8. Samples with inconsistent classifications between RMR and the proposed control framework**

| Sample | UCS | RQD | DS | DC | GC | DO | RMR | RMR class | Control class |
|--------|-----|-----|----|----|----|----|-----|-----------|---------------|
| DHT-8  | 3   | 3   | 5  | 10 | 15 | -5 | 31  | IV        | V             |
| DHT-10 | 2   | 3   | 5  | 19 | 7  | -5 | 31  | IV        | V             |
| DHT-11 | 7   | 2   | 3  | 17 | 7  | -5 | 31  | IV        | V             |
| DHT-12 | 3   | 3   | 5  | 19 | 7  | -5 | 32  | IV        | V             |
| DHT-22 | 2   | 3   | 5  | 17 | 15 | -5 | 37  | IV        | V             |
| DHT-24 | 1   | 3   | 5  | 18 | 15 | -5 | 37  | IV        | V             |
| KHT-3  | 2   | 3   | 5  | 13 | 7  | -5 | 25  | IV        | V             |

It should be emphasized that the dataset used in this study was intentionally limited to rock masses classified as Class IV (Poor) or Class V (Very Poor) under the classical RMR system. This deliberate selection was made because uncertainties, subjectivity, and misclassification risks are most pronounced in weak rock masses, where small variations in parameter ratings may lead to significant changes in the assigned class. In such marginal conditions, the limitations of sharp class boundaries and fixed parameter weights inherent in the classical RMR system become more evident.

Accordingly, the proposed control-based framework was specifically designed and evaluated for weak rock mass conditions, where a more sensitive and conservative assessment is required for reliable engineering decision-making. The results presented in this section should therefore be interpreted within the context of Class IV-V rock masses, rather than as a generalized representation of all RMR classes.

Overall, the combined interpretation of Figure 4 and Table 8 demonstrates that the observed mismatches do not represent inconsistencies of the proposed method, but rather highlight its control and verification capability, particularly for borderline rock mass conditions. This confirms that the developed approach functions as a complementary tool to classical RMR, enhancing the robustness and reliability of rock mass classification for engineering decision-making.

To ensure the practical and efficient application of the proposed control-based classification framework, a graphical user interface (GUI) was designed and developed. Although the proposed DEMATEL-TOPSIS-based approach provides a systematic and robust verification mechanism for rock mass classification, its manual implementation may be time-consuming and impractical for routine engineering use. The developed GUI enables users to easily input rock mass parameters, automatically execute all stages of the proposed methodology, and obtain the corresponding control-based classification results.

The interface has been structured to allow direct comparison between the classical RMR classification and the results obtained from the proposed control framework, thereby simplifying the decision-making process for engineering practitioners. In

addition, the GUI supports evaluating multiple cases consistently and reproducibly without requiring detailed knowledge of the underlying mathematical procedures. The main screen of the developed application, which is presented in Figure 5, illustrates the layout of the interface, including parameter input fields, calculation controls, and result visualization components.

| # | SampleID | JCS,QD0,D5,DC,GC,DC | RMR | RMR Class | Control Class | Match? |
|---|----------|---------------------|-----|-----------|---------------|--------|
| 1 | DHT-1    | 1,3,5,15,7,-5       | 26  | IV (Poor) | IV (Poor)     | Yes    |
| 2 | DHT-2    | 2,3,5,15,7,-5       | 27  | IV (Poor) | IV (Poor)     | Yes    |
| 3 | DHT-3    | 2,3,5,15,7,-5       | 27  | IV (Poor) | IV (Poor)     | Yes    |
| 4 | DHT-4    | 2,3,5,15,7,-5       | 27  | IV (Poor) | IV (Poor)     | Yes    |
| 5 | DHT-5    | 2,3,5,15,7,-5       | 27  | IV (Poor) | IV (Poor)     | Yes    |

Figure 5. Graphical user interface developed for the proposed RMR control framework

Through this implementation, the proposed control framework is transformed into a practical decision-support tool suitable for real-world rock engineering applications.

#### 4. Conclusions

This study has presented a new integrated framework to address the inherent limitations of the classical Rock Mass Rating (RMR) rock classification system and to establish a reliable control mechanism for the original RMR approach. Within this scope, a triangular fuzzy number (TFN)-based DEMATEL-TOPSIS model has been successfully implemented for rock mass classification, with particular emphasis on weak rock masses characterized by poor and very poor-quality conditions. The proposed framework has effectively reduced the sharpness of class boundaries through TFN-based membership functions, determined parameter weights by considering their relative influence using the DEMATEL method, and minimized subjectivity in classification by applying the TOPSIS technique.

The results indicate that the proposed control-based framework preserves the fundamental classification behavior of the classical RMR system, as evidenced by a high percentage agreement (86%) and a strong, statistically significant Spearman rank correlation ( $\rho = 0.872$ ). At the same time, the framework provides a more sensitive and conservative assessment for borderline rock mass conditions, particularly near the transition between Class IV and Class V. The limited discrepancies observed between the two approaches are therefore interpreted not as inconsistencies, but as the outcome of explicitly considering parameter interactions, uncertainty, and weighting effects that are not captured in the classical RMR formulation.

It is important to emphasize that the proposed framework is not intended to replace the classical RMR system, but rather to function as a complementary verification and decision-support tool for weak rock mass conditions where misclassification risks are highest. The applicability of the proposed

approach to rock masses of higher quality (Class I-III) has not been investigated within the scope of this study and remains a subject for future research. To support practical implementation, a graphical user interface (GUI) has been developed to enable systematic application of the framework and facilitate direct comparison with classical RMR results.

Although this study proposes a new control mechanism for determining rock mass classes, several limitations warrant consideration in future research. The criterion weights used in this study were based on evaluations from the focus group established in the study; however, these weights could be re-evaluated by a larger group of experts in future work. In addition, alternative weighting techniques could be used, and the control-based approach could be extended to other rock mass classification systems and geological conditions.

#### Author contributions

Conceptualization: HOD, HT; Data curation: HOD; Formal analysis: HOD, ÖA; Investigation: HOD; Methodology: HOD, ÖA; Software: HOD; Supervision: HT; Validation: HOD, HT; Visualization: HOD; Writing – original draft: HOD; Writing – review & editing: HOD, HT, ÖA. All authors have read and agreed to the published version of the manuscript.

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#### Conflicts of interests

The authors declare no conflict of interest.

#### Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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## Контрольна модель DEMATEL-TOPSIS для підвищення надійності рейтингової оцінки гірського масиву в умовах слабких порід

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**Мета.** Дослідження спрямоване на підвищення надійності класичної системи рейтингової оцінки масиву гірських порід (Rock Mass Rating, RMR) шляхом упровадження контрольно-орієнтованої моделі DEMATEL-TOPSIS, яка безпосередньо враховує взаємодію між параметрами та зменшує невизначеність класифікації поблизу граничних значень.

**Методика.** Для моделювання невизначеності оцінювання рейтингові значення параметрів було представлено за допомогою трикутних нечітких чисел. Метод DEMATEL застосовано для кількісного визначення взаємозв'язків між критеріями класифікації, а метод TOPSIS – для встановлення найбільш репрезентативного класу масиву гірських порід. Модель перевірено з використанням даних двох підземних інженерних проєктів із будівництва виробок, реалізованих у різних геологічних умовах.

**Результати.** Встановлено, що врахування взаємодії між параметрами підвищує узгодженість класифікації та зменшує неоднорозумність оцінювання масивів гірських порід, розташованих поблизу перехідних інтервалів. Водночас зберігається високий рівень відповідності традиційним оцінкам RMR, що становить 86%. Високий коефіцієнт рангової кореляції Спірмена ( $\rho = 0.872$ ) підтвердив статистичну сумісність класичної та контрольованої класифікацій, засвідчуючи надійність запропонованої моделі. Також систематично визначено найбільш впливові критерії у структурі взаємодій.

**Наукова новизна.** Запропоновано орієнтовану на контроль розширення системи RMR, яке інтегрує взаємозалежності між параметрами у процес класифікації без зміни її початкової емпіричної структури. Розроблений графічний інтерфейс користувача забезпечує прозоре порівняння результатів класичної та контрольованої класифікацій під час розв'язання інженерних задач.

**Практична значимість.** Запропонована модель сприяє прийняттю обґрунтованих інженерних рішень завдяки виявленню можливих помилок класифікації поблизу меж класів масиву гірських порід. Розроблений інтерфейс може бути використаний під час проєктування гірничих виробок і виконання гірничих робіт у слабких породах. Він забезпечує послідовне оцінювання впливу окремих параметрів і підвищує прозорість вибору відповідних конструкцій кріплення.

**Ключові слова:** рейтингова оцінка масиву гірських порід; багатокритеріальне прийняття рішень; DEMATEL; TOPSIS; слабкі породи

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