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Integration of empirical and systems engineering frameworks in tunnel support design: a comprehensive study of 38 tunnels in Iran

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ABSTRACT

Reliable assessment methods are required for designing initial support for tunnels in complex geological conditions. This study provides a thorough comparison of the Rock Mass Rating (RMR) and Rock Engineering System (RES) frameworks, examining a substantial dataset comprising 38 tunnels situated in various lithological and tectonic zones across Iran. While the RMR framework offers empirical simplicity, the RES framework provides a systems-based approach that quantifies parameter interdependencies. Analysis of field data, including shotcrete thickness and bolt density, revealed that the RES framework captures hydro-mechanical coupling more effectively, particularly in intermediate rock masses. To reconcile discrepancies between the two systems, we explored an integrated statistical formulation combining normalized RMR ratings with RES stability indices. This approach demonstrated a significantly higher correlation with field performance ($R^2 \approx 0.99$) than the individual methods. The results emphasise the importance of integrating empirical and systems-based approaches to improve the reliability of predictions in tunnel support design and provide a solid foundation for engineering decisions in heterogeneous rock masses.

Introduction

Ensuring the mechanical stability of underground openings, such as transportation tunnels, water conveyance tunnels, and railway drifts, remains a key challenge in the field of engineering geology and rock mechanics. This complexity arises from the non-linear interplay of multiple factors, including lithology, intact rock strength, joint geometry, groundwater pressure, and in-situ stress orientation.

These variables often interact in an interdependent manner, making integrated approaches necessary for accurately predicting deformations and designing suitable support systems. To address these challenges, the present study examines a comprehensive dataset comprising 38 tunnels excavated through various lithological and tectonic settings in Iran. The total length of the sections studied amounts to 23,359 metres, covering a wide range of geotechnical conditions. Figure 1 illustrates the spatial distribution of these case studies across different structural zones, while Figure 2 depicts representative geological settings. Detailed specifications, including tunnel type, location, length, and dominant lithology, are summarized in Table 1.

All tunnels were excavated using controlled blasting techniques, with detailed geological mapping conducted concurrently. Although geological conditions varied significantly, the tunnels were categorised into six main groups based on their lithological and structural characteristics, in order to facilitate meaningful comparisons of their engineering behaviour (see Table 2). Additionally, most tunnels are classified as deep to semi-deep excavations with similar cross-sectional areas, which mitigates the

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impact of surface weathering on their overall stability.

Table 1. Specifications of the Studied Tunnels

No	Tunnel Type	Province	Structural Zone	Tunnel Length (m)	Dominant Lithology
1	Highway	Tehran	Central Alborz	123	Tuff
2	Highway	Tehran	Central Alborz	155	Tuff and Shale
3	Highway	Tehran	Central Alborz	120	Tuff and Shale
4	Highway	Tehran	Central Alborz	645	Andesite, Tuff ,Shale
5	Highway	Tehran	Central Alborz	542	Andesite, Tuff ,Shale
6	Highway	Tehran	Central Alborz	455	Agglomerate ,Tuff
7	Highway	Tehran	Central Alborz	3000	Limestone ,Shale, Gypsum, Andesite
8	Road	Shahrekord	Folded Zagros	235	Limestone
9	Railway	Ardabil	Western Alborz	305	Rhyolite
10	Railway	Ardabil	Western Alborz	517	Andesitic Basalt
11	Railway	Ardabil	Western Alborz	355	Andesitic Basalt
12	Railway	Ardabil	Western Alborz	190	Weathered Andesite
13	Railway	Ardabil	Western Alborz	360	Limestone ,Shale, Andesite
14	Railway	Ardabil	Western Alborz	549	Limestone ,Shale, Andesite
15	Railway	Ardabil	Western Alborz	502	Basalt ,Rhyolite
16	Railway	Ardabil	Western Alborz	93	Andesite
17	Railway	Ardabil	Western Alborz	640	Andesite
18	Railway	Ardabil	Western Alborz	65	Rhyolite
19	Water Transfer	Urmia	Azerbaijan	110	Granite
20	Water Transfer	Hormozgan	Crushed Zagros	1570	Limestone ,Flysch
21	Highway	Lorestan	Crushed Zagros	3700	Limestone ,Congl.,Shale
22	Railway	Lorestan	Crushed Zagros	2200	Limestone ,Shale
23	Railway	Lorestan	Crushed Zagros	210	Limestone ,Andesite
24	Railway	Lorestan	Crushed Zagros	230	Conglomerate
25	Railway	Lorestan	Crushed Zagros	1700	Shale, Marl ,Marlstone
26	Railway	Lorestan	Crushed Zagros	800	Marlstone ,Conglomerate
27	Railway	Lorestan	Crushed Zagros	650	Conglomerate ,Limestone
28	Railway	Lorestan	Crushed Zagros	300	Limestone, Marl
29	Railway	Lorestan	Crushed Zagros	600	Limestone
30	Railway	Lorestan	Crushed Zagros	650	Marl, Limestone
31	Railway	Isfahan	Central Iran	430	Limestone
32	Road	Mazandaran	Central Alborz	170	Limestone
33	Road	Mazandaran	Central Alborz	182	Siltstone ,Limestone
34	Railway	Kermanshah	Folded Zagros	230	Marl, Shale
35	Water Transfer	Shahrekord	Folded Zagros	180	Limestone
36	Road	Mazandaran	Central Alborz	155	Limestone
37	Road	Mazandaran	Central Alborz	91	Sandstone
38	Road	Fars	Folded Zagros	350	Limestone and Marl

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Table 2. Engineering and geological characteristics of the studied tunnels.

Dominant Lithology	Length(m)	Tunnel Categories
Limestone	4752	Limestone
Shale	4260	Shale
Conglomerate	4730	Conglomerate
Serpentine -Flysch	1800	Serpentine -Flysch
Tuff	1585	Tuff
Andezite	6232	Andezite

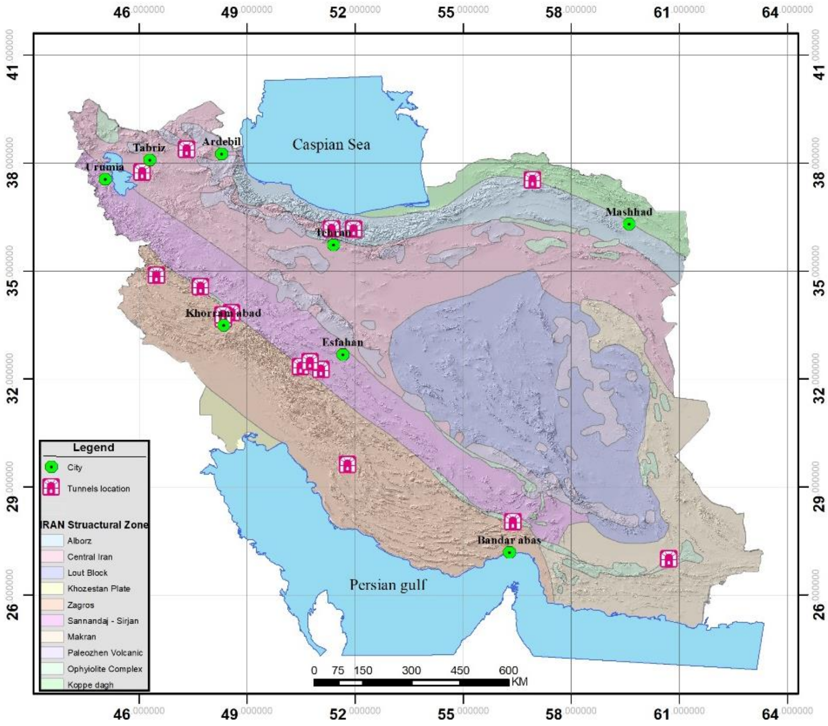

Fig. 1. Location of the studied tunnels on the structural zone map of Iran (Stöcklin,1968)

Rock-mass classification systems most notably the Rock Mass Rating (RMR) have long served as practical tools for assessing the stability of underground structures (Hudson, 1991). Computational approaches typically assume that each variable affecting stability operates within a fixed range, yet such simplification overlooks the inherent uncertainty caused by incomplete or ambiguous field data (Hudson et al., 1989). In reality, rock-engineering problems involve highly nonlinear and interdependent mechanisms. Since Terzaghi's pioneering investigation of rock-load factors in tunnel design (Yan-jun et al., 2017), numerous classification frameworks have been proposed. Among these, the Rock Mass Rating (RMR) and Tunnel Quality Index (Q) systems have become globally accepted standards for empirical design (Barton and Bieniawski, 2008; Barton and Grimstad, 2014; Pells et al., 2017). Originally proposed in 1973 and revised in 1989 and 2014 (Bieniawski, 1973; Bieniawski, 1989; Celada et al., 2014), the RMR method remains the most widely used rock-mass classification scheme. Over the past decade, systems-based methodologies have increasingly been applied in rock mechanics, enabling simultaneous analysis of multiple interacting parameters. The Rock Engineering System (RES), introduced by Hudson (Hudson, 1992), extends conventional classifications by quantifying the degree of parameter coupling through an interaction matrix an approach particularly relevant to underground excavations where subsurface

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stress fields and fracture networks are strongly interrelated (Hudson and Feng, 2015).

Fig. 2. Images of some of the studied tunnels (the number of each image corresponds to the tunnel number in Table 1).

The Systems Engineering concept treats every rock-engineering classification as a function of these coupled relationships, expressed mathematically through the interaction matrix that governs factor weighting. Within this framework, the characterization of the rock mass remains the foundation of empirical design (Palmstrom et al., 2001; Stille and Palmström, 2003). Recent advances in tunnel-support design aim to reduce subjective judgment by linking classification outcomes to measurable support parameters such as shotcrete thickness and rock-

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bolt density (Lowson and Bieniawski, 2013). However, as the number of influential parameters increases, traditional deterministic models struggle to represent their combined effects, underscoring the need for more advanced analytical systems capable of handling complex geological interactions. Accordingly, this study conducts a comparative evaluation of the RMR and RES methods, analyzing their respective strengths and limitations. Despite decades of refinement, the RMR framework still excludes critical factors such as bedding-plane thickness, anisotropic (tectonic) stress, and lithologic variability and lacks the ability to represent the mutual interactions among geological, hydrogeological, and stress-related parameters. In contrast, the Rock Engineering System (RES) introduced by Hudson (1992) provides a systems-engineering perspective that explicitly quantifies such interdependencies through a structured interaction matrix, enabling a more physically realistic assessment of rock-mass behaviour. Recent research has shown that combining empirical and system-based classifications can further enhance predictive reliability. Palmström (Palmstrom and Broch, 2006) demonstrated the advantages of merging RMR, Q, and RMi systems, while Gao et al. (Gao et al., 2020) and Noorian-Bidgoli & Golmohammadi (Noorian-Bidgoli and Golmohammadi, 2023) successfully integrated RES with regression and fuzzy models to improve the accuracy of stability assessments. Preliminary findings on a smaller dataset (6 tunnels) were reported by Talkhablou et al. (2022), which laid the groundwork for this expanded analysis. Accordingly, this study not only compares the RMR and RES methods but also introduces a hybrid RMR–RES stability index calibrated against observed support performance. The main contributions of this study are threefold: (i) a systematic comparison of RMR and RES for 37 tunnels excavated in contrasting lithological and tectonic settings in Iran, (ii) derivation of RES-based empirical equations that quantify the relative influence of ten interacting parameters on tunnel stability, and (iii) development and field calibration of a Hybrid RMR–RES Stability Index (HSI) that reconciles discrepancies between the two systems and improves robustness to parameter uncertainty.

Materials and Methods

Rock Mass Rating (RMR) Method

This study employed the Rock Mass Rating (RMR) classification system to quantify the quality of the rock mass across the 38 selected tunnels. The overall rating was derived from the weighted summation of six key parameters: (1) the uniaxial compressive strength (UCS) of intact rock; (2) the Rock Quality Designation (RQD); (3) discontinuity spacing; (4) joint condition; (5) groundwater inflow; and (6) the orientation of discontinuities relative to the tunnel axis. Field data were collected directly from the tunnel faces after excavation, in accordance with standard mapping protocols (Bieniawski, 1989). Laboratory tests provided UCS values, while scanline surveys were used to determine RQD, joint spacing, and surface conditions. Groundwater conditions were documented based on inflow rates, and adjustment factors were applied for joint orientation. The final RMR score guided the selection of preliminary support measures, including shotcrete thickness and rock bolt density, in accordance with established guidelines. Statistical evaluation of the collected data revealed specific trends within the 38-tunnel dataset. Plotting RMR scores against UCS revealed a non-proportional trend (Figure 3). Beyond a threshold of 40 MPa, additional strength contributed minimally to the overall rating; most data points clustered between RMR values of 40 and 60 despite higher UCS measurements. This indicates that once intact rock strength exceeds a certain limit, its marginal utility in improving the classification, and consequently the support design, diminishes significantly.

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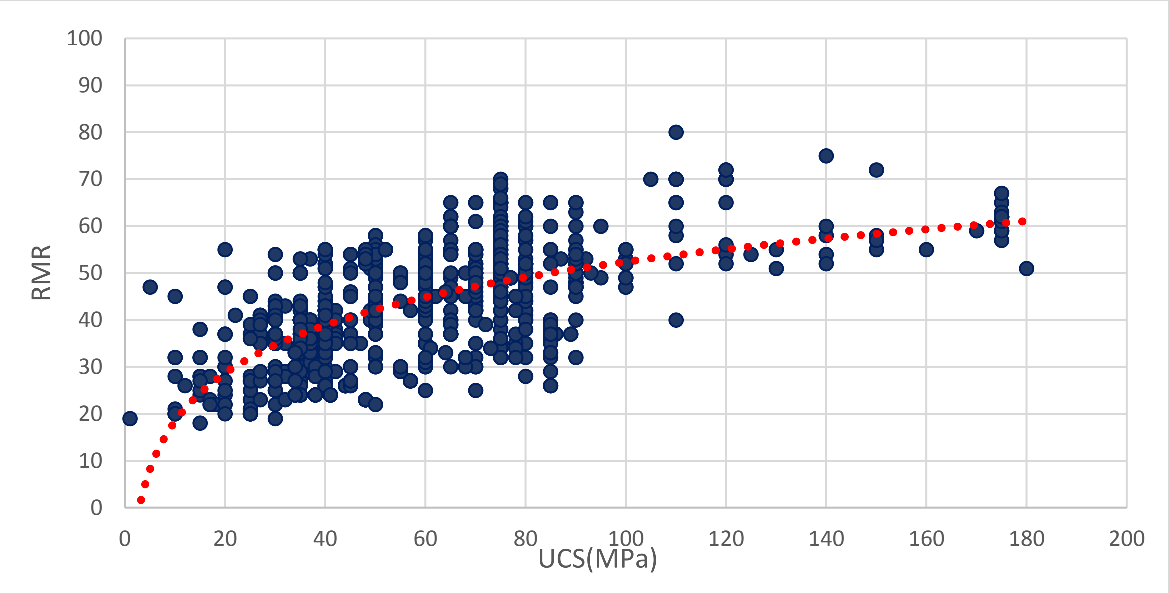

Fig. 3.The relationship between RMR value and uniaxial compressive strength (UCS)

Conversely, RQD demonstrated a more direct linear relationship with the final classification (Figure 4). Samples with RQD values exceeding 90% consistently corresponded to RMR ratings above 60, falling within the moderate support category. In contrast, RQD values below 20% resulted in RMR indices under 30, necessitating heavy reinforcement. Intermediate RQD ranges (40%–60%) aligned with RMR scores between 40 and 60, reflecting a consistent need for intermediate support strategies.

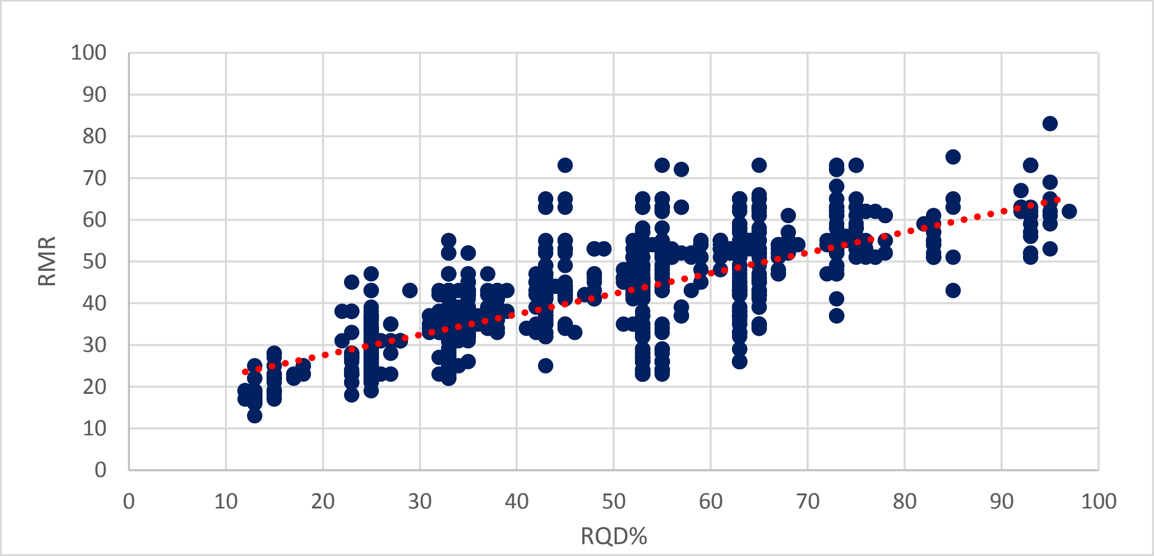

Fig. 4. The relationship between RMR value and Rock Quality Designation (RQD) index

Fracture frequency, represented by joint set counts, exhibited a comparable limiting effect (Figure 5). When the number of joint sets surpassed five (approximating eight in highly fractured zones), RMR values consistently declined below 40. This reduction was observed even in rock masses with high UCS, highlighting the compounded negative influence of weathering, joint surface conditions, and groundwater. Thus, a high density of joint sets can substantially degrade the rock mass classification regardless of intact strength.

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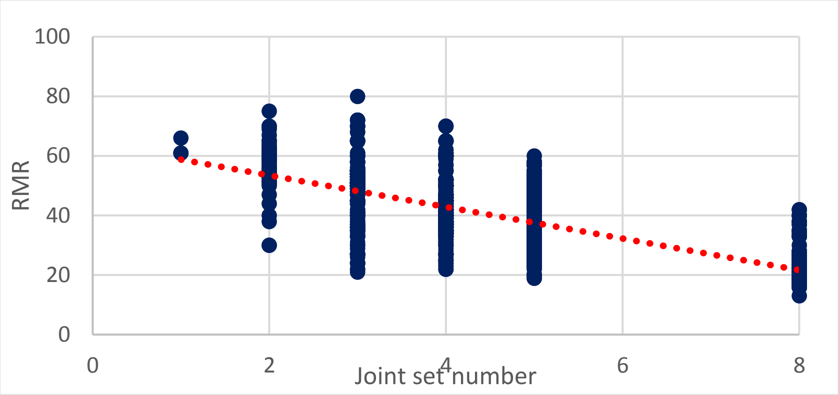

Fig. 5. The correlation between RMR and the number of joint sets, particularly in highly fractured rocks (with more than five sets)

Regarding discontinuity spacing, the data indicated a plateau effect similar to UCS (Figure 6). Spacing values greater than 40 cm did not yield significant improvements in the RMR class, with scores remaining predominantly between 40 and 60. This suggests that increased spacing alone does not guarantee a higher quality rating, particularly when adverse factors such as joint infill or water inflow are present. Consequently, the RMR system appears to reach a saturation point concerning joint spacing beyond a specific threshold.

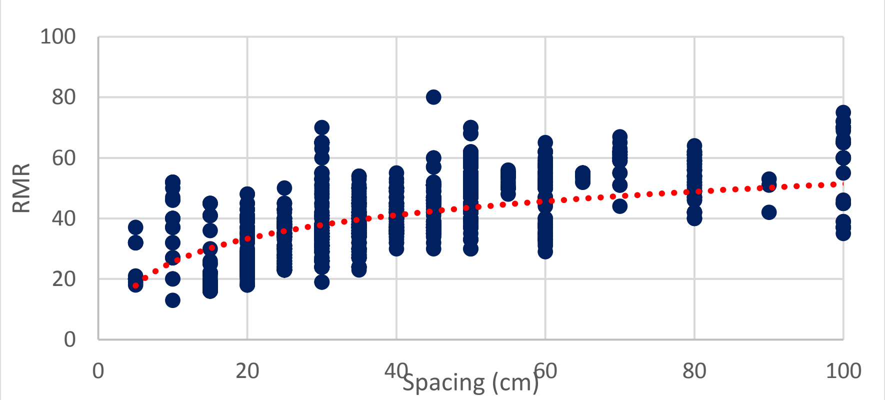

Fig. 6. The Relationship Between RMR Values and Joint Spacing

Collectively, these observations underscore that while RMR is a robust empirical tool, its sensitivity to individual parameters may diminish beyond critical limits. Enhancements in isolated parameters, such as UCS or spacing, should not be assumed to automatically elevate the final classification. Instead, a holistic assessment incorporating parameter interdependencies remains essential for accurate characterization and support design.

Rock Engineering System (RES) Method

The Rock Engineering System (RES) framework models rock-mass behavior through a systems-engineering approach that quantifies the degree of interaction among controlling parameters. In this method, the rock mass is described by an interaction matrix in which each element Iij represents the causal influence of parameter i on parameter j. Ten key parameters were considered in the RES analysis, including joint spacing, orientation, surface roughness, weathering, filling, groundwater condition, in-situ stress, overburden thickness, lithology, and uniaxial compressive strength. The grading criteria for these parameters follow the engineering experience-based classification presented in Table 3. The degree of mutual influence between each pair of parameters was coded from 0 (no interaction) to 4 (critical interaction) using the Expert Semi-Quantitative (ESQ) scheme (Hudson and Feng, 2015). The operating principles and physical meaning of this interaction matrix are illustrated in Figure 7. The resulting 10 × 10 matrix yields a Cumulative Influence Index (CII), calculated as the sum of both active (Cause) and passive (Effect) interactions for each parameter. Parameters with higher CII values exert greater control over tunnel stability. This approach captures the interdependence of geological, hydrogeological, and stress-related variables that are often neglected in empirical methods. Based on the RES data, the tunnel stability index is classified into five categories ranging from "Very Poor" to "Very Good," as defined in Table 4. Model validation was achieved by comparing RES-predicted support classes with field-implemented measures such as shotcrete thickness and bolt density recorded during construction.

Comparative Evaluation and Validation

To facilitate a direct comparison, both RMR and RES outcomes were normalized to a common stability scale ranging from 0 (poor) to 100 (excellent). Comparative plots were generated to illustrate the correlation between RMR ratings and RES indices for each of the 38 tunnels. A sensitivity analysis was performed by varying key parameters (e.g., groundwater condition, joint weathering, and overburden) by ±10% to ±30% to assess the robustness of each method to parameter uncertainty. This comparison allowed for the identification of dominant controlling factors and an assessment of each system's predictive capability. The RES model's ability to incorporate parameter coupling was further evaluated by comparing predicted stability indices with field-observed support performance, ensuring that the theoretical classifications align with practical engineering requirements.

Hybrid RMR–RES Stability Index

Several recent studies have emphasized the need for a unified rock-mass evaluation scheme to integrate the strengths of both RMR and RES (Gao et al., 2020; Palmstrom and Broch, 2006). Because the RES-derived stability index (SI) is already scaled between 0 and 100, the first step consisted of normalizing the RMR ratings to the same range. For each tunnel i, the normalized RMR value ($RMR*$) was computed based on the minimum and maximum observed RMR values in the dataset. The relative weight of RMR and RES in the hybrid index was then defined from the calibrated coefficients, leading to the following expression for the Hybrid Stability Index (HSI):

$$\mathrm{HSI_i} = \alpha\ \mathrm{RMR^*_i} + (1 - \alpha)\ \mathrm{SI_i} \qquad (1)$$

Calibration against the observed support measures (shotcrete thickness and rock-bolt density) showed that the optimal weighting coefficient slightly deviates from the conventional [0–1] range. For the present dataset, $\alpha \approx -0.1$ provided the best fit, indicating that the $RMR*$ term acts as a minor compensatory adjustment to the dominant RES-based component. Such a negative weight is consistent with the different scaling sensitivities of the two systems and ensures that their combined response closely matches field performance. For practical design purposes, the HSI values were mapped onto the five stability classes of Table 4 (0–20: very poor; 20–40: poor; 40–60: fair; 60–80: good; 80–100: very good), maintaining full compatibility with the existing RMR and RES frameworks. The performance of the hybrid index was evaluated against field support records for all 38 tunnels, and the corresponding results are presented in Section 3.2.

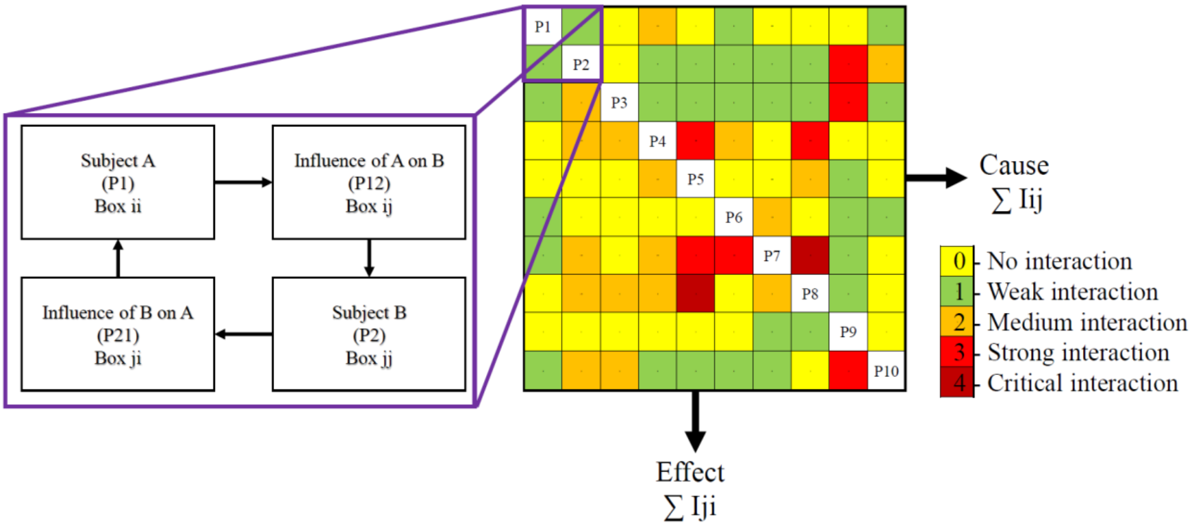

Fig. 7. Operating principles and physical meaning of the interaction matrix.

Table 3. Classification of parameters affecting tunnel stability based on engineering experiences

1. Strength of Intact Rock	**Grade**	**6. Joint surface Roughness**	**Grade**
Extremely weak (<1 MPa)	0	Slicken sided	0
Very weak (1-5 MPa)	1	Smooth	1
weak (5-20 MPa)	2	Slightly rough	2
Medium strong (20-50 MPa)	3	Rough	3
Strong (>50 MPa)	4	Very rough	4
2. Jointing Pattern	**Grade**	**7. Joint Filling**	**Grade**
Crushed	0	Swelling clay materials	0
4 joint sets	1	Soft, cohesive materials	1
3 joint sets	2	Hard, cohesive materials	2
1 joint set	3	Friction materials	3
Massive	4	No filling	4
3. Joint spacing	**Grade**	**8. Groundwater Condition**	**Grade**
Very small spacing (<5 cm)	0	Flowing	0
Small spacing (5-20 cm)	1	Dripping	1
Moderate spacing (20-50 cm)	2	Wet	2
Large spacing (50-100 cm)	3	Damp	3
Very large spacing (>100 cm)	4	Completely dry	4
4. Joint surface weathering	**Grade**	**9. In-situ Stress Condition**	**Grade**
Decomposed	0	Very High	0
Highly weathered	1	High	1
Moderately weathered	2	Medium	2
Slightly Weathered	3	Low	3
Uneathered	4	Very Low	4
5. Joint Separation	**Grade**	**10. Joint Orientation**	**Grade**
Separated (>5 mm)	0	Angle between J & D <30 , 75>dip>60	0

Separated (1-5 mm)	1	Angle between J & D <30 , 60>dip>30	1
Mostly Separated (Width<1 mm)	2	Other Condition	2
Partly Separated (Width<1 mm)	3	Angle between J & D >60 ,80 >dip>60	3
No Separation	4	Angle between J & D >60 , dip>80	4

Table 4. Classification of tunnel stability index based on RES data

Class	Adjusted RES	Stability Index
1	0-20	Very poor
2	20-40	Poor
3	40-60	Fair
4	60-80	Good
5	80-100	Very good

Results

The calculated parameter values obtained from field mapping and laboratory data were subsequently processed using the RMR and RES formulations described in Section 2. RMR-based ratings for each tunnel were derived from field observations (Table 5) and subsequently used to classify rock-mass quality and assign preliminary support categories.

The colour-coded distribution of indices follows the same convention as in Figure 7, and Figure 8 illustrates the spatial representation of all ten parameters. The cause–effect diagrams (Figures 8–10) show that parameters with stronger bidirectional coupling cluster near the C = E line. Dominant cause-type variables plot to the right and subordinate effect-type variables plot to the left. This is consistent with the patterns described by Hudson and Feng (2015).To further quantify the interaction intensity, average values for each parameter were computed and plotted in Figure 9. Based on the graphical and numerical analyses, the following findings were established:

- The system displayed a high degree of interactivity, as more than 50 % of the parameters lay on or above the interaction line, indicating substantial cross-coupling between variables.
- Parameters 4, 7, 8, and 10 representing surface alteration, joint filling, joint orientation, and groundwater conditions are the most dominant, positioned to the right of the C > E line (Cause > Effect).
- Parameters 2, 3, 5, and 9 joint pattern, spacing, aperture, and residual stress constitute the less dominant (effect-type) group, plotted to the left of the line.
- Parameters 1 and 6 uniaxial compressive strength of intact rock and joint-surface roughness are identified as globally influential, controlling both the cause and effect domains.

Based on the interaction matrices and the parameter classifications, the following empirical relationships were derived for the ten parameters across all tunnels. This relationship can be regarded as a suggestion for a new rock mass classification(NRMC), incorporating revised scoring for the parameters influencing rock mass classification.

$$NRMCS=(1.4P1+2.5P2+2.4P3+3.3P4+2.8P5+1.9P6+2.6P7+3.3P8+2.5P9+2.2P10) \quad (2)$$

To statistically evaluate the reliability of these empirical equations, regression analyses were performed between the RES-derived stability indices and the corresponding RMR values. The obtained coefficients of determination (R^2 = 0.87) and root-mean-square error (RMSE = 3.2) indicate a strong linear consistency and limited dispersion, confirming that the proposed SI equations accurately capture the interaction behavior among the ten parameters (Table 6). The regression was performed on N = 42 data points representing tunnel segments where both RES stability indices and corresponding RMR values were available. The RMR values were calculated based on the classification scheme of Bieniawski (1989). Each parameter rating was assigned according to field measurements of intact rock strength (UCS), Rock Quality Designation (RQD), joint spacing, joint condition, groundwater inflow, and orientation of discontinuities. Final RMR values correspond to the sum of all parameter ratings including orientation adjustments. These normalized ratings were subsequently used to derive the hybrid RMR values presented in Table 9.

Table 5. Rock Mass Rating (RMR) parameter ratings and total scores for the 38 investigated tunnels based on Bieniawski (1989).

Parameter	T 1	T 2	T 3	T 4	T 5	T 6
UCS (MPa)	7	4	5	6	7	8
RQD (%)	10	5	12	8	10	11
Joint Spacing (m)	10	8	10	10	8	9
Condition of Joints	18	11	20	11	11	18
Groundwater Condition	10	10	10	10	10	10
Adjustment for Discontinuity Orientation	−10	−5	−12	−10	−10	−12
Total RMR Rating	45	33	45	35	36	44

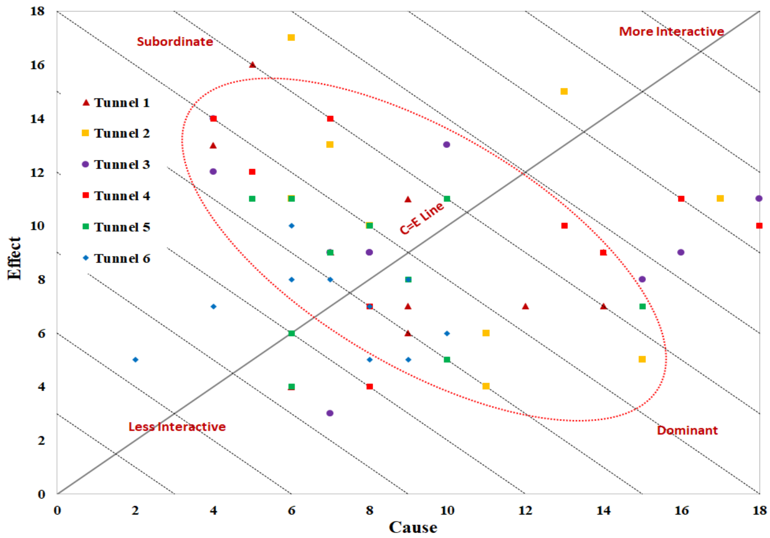

Fig. 8. The Cause-Effect plot using the coordinates established from the ESQ coding method

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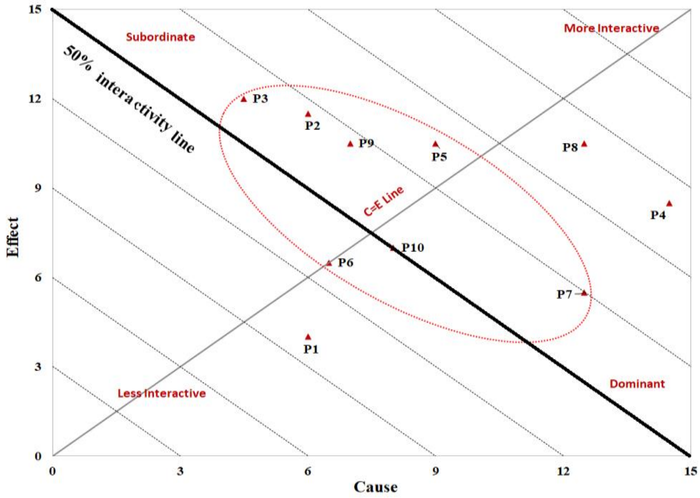

Fig. 9. The Cause-Effect plot using the coordinates established from the ESQ coding method for the main value of 6 tunnel types.

Table 6. Coefficients of RES empirical equation for tunnel stability index

Parameter	Equations Coefficients						
	EQ 01	EQ 02	EQ 03	EQ 04	EQ 05	EQ 06	EQ-Mean
P 1	1.4	3.3	1.3	1.5	1.5	1.3	1.4
P 2	2.9	2.1	2.3	2.3	2.4	2.7	2.5
P 3	2.4	2	2.1	2.1	2.4	2	2.4
P 4	2.9	3.3	3.2	3.4	3.4	2.9	3.3
P 5	2.8	2.3	3	2.9	2.7	2.5	2.8
P 6	2.1	1.8	2.2	2	1.8	2.4	1.9
P 7	2.7	2.3	3	2.9	2.3	2.5	2.6
P 8	3.2	3.3	3.7	3.5	3.2	3.1	3.3
P 9	2.2	2.7	2.1	2.6	2.6	2.9	2.5
P 10	2.2	2	2.2	1.9	2.6	2.7	2.2

Statistical Analysis of Parameter Interactions

In addition, probability-based (C–E) plots enable evaluation of whether all parameters are essential for defining the system or if certain parameters exert negligible influence. To achieve this, the expected interaction intensities (C+E) for each parameter were computed and plotted as shown in Figure 10. Error bars represent the uncertainty associated with each estimate, quantified by the standard deviation of their probability distributions. These statistical descriptors were derived from the calculated probability distributions of C+E values, including their means and standard deviations. Similarly, Figure 11 also illustrates the expected superiority or compliance of each parameter, expressed as (C−E) values. The associated uncertainties represented as standard deviations of the (C−E) distributions are likewise displayed through error bars. The combined interpretation of Figures 10 and 11 demonstrates that all ten “input” parameters exhibit a high level of interactivity and exert a measurable effect on the “output” parameter, i.e., the required initial reinforcement. Consequently, all parameters should be considered in the engineering design and decision-making process. Furthermore, Figure 11 provides the expected values and uncertainties (in terms of standard deviations) for the “mastery criterion” of each parameter,

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represented by its (C−E) value. These diagrams visualize the balance between cause- and effect-type influences, enabling identification of controlling and subordinate variables within the system. Based on the collective evaluation of the cause–effect diagrams for all ten parameters (Figures 8–11), the following conclusions can be drawn:

- All analyzed parameters are relatively interactive, as most data points lie along or near the diameter of the C–E diagram, confirming mutual dependence.
- Parameters with higher interaction intensity include P4 (joint surface weathering) and P5 (joint separation/aperture), indicating their strong mutual influence on tunnel stability.
- Parameters with weaker interaction, such as P1 (uniaxial compressive strength of intact rock), exhibit a more independent role, primarily acting as input rather than reactive factors.
- Parameters P4 (joint surface weathering) and P7 (joint filling) demonstrate the highest dominance (cause-type behavior), whereas P2 (jointing pattern) and P3 (joint spacing) display more compliant, effect-type characteristics controlled by the system.

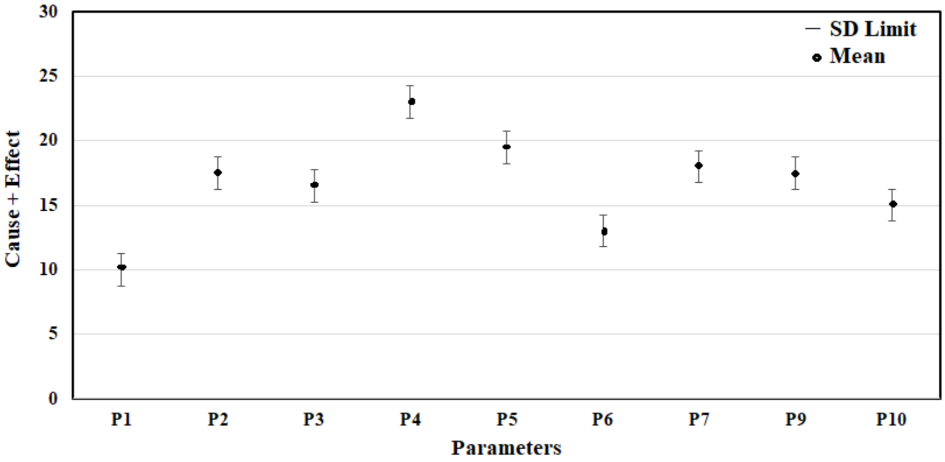

Fig. 10. Mean values and standard deviation limits for interactivity of 10 parameters affecting the initial support

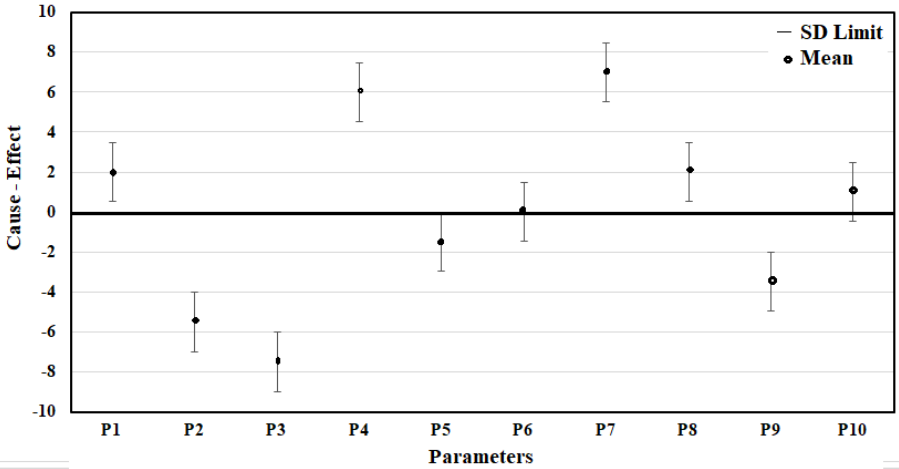

Fig. 11. Mean values and standard deviation limits for subordinance of 10 parameters affecting the initial support

Performance of the Hybrid Stability Index

Using the regression procedure described in Section 2.4, the coefficients (b_1) and (b_2)

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were calibrated against the observed support measures (shotcrete thickness and bolt density) listed in Table 6, ensuring that the Hybrid Stability Index is directly tied to field performance. The resulting weights yielded a value of α that assigns comparable, but not identical, influence to the normalised RMR ratings and the RES stability index. This confirms that both systems contain non-redundant information on rock mass behaviour and support demand. For each tunnel, the Hybrid Stability Index (HSI) was then calculated from the calibrated α and classified into stability classes using the thresholds in Table 4. The resulting HSI values and classes are summarised in Table 7, together with the corresponding RMR and RES indices and the field-based support intensity. Overall, the resulting HSI values show a weighted bias toward the RES-based stability indices, reflecting their stronger empirical correlation with the observed support requirements. Rather than being strictly confined between RMR* and SI, the HSI acts as a calibrated hybrid estimator in which the RMR* term provides a small corrective contribution ($\alpha \approx -0.1$) to compensate for the scale compression inherent in the RMR system.

Table 7. Summary of normalized RMR, RES stability index (SI), and Hybrid Stability Index (HSI) values for the 38 tunnels.

Tunnel Categories	RMR (raw)	RMR* (normalized 0–100)	Mean RES Index (SI)	HSI ($\alpha \approx -0.1$)	Dominant Lithology	Support Observation (cm)
T1	45	100	61.5	57.6	Limestone	≈ 5
T2	33	0	32	35.2	Shale	≈ 6
T3	45	100	40.5	34.5	Congl., Sst.	≈ 5
T4	35	16.7	30	31.3	Flysch	≈ 7
T5	36	25	44.5	46.5	Tuff	≈ 5
T6	43	83.3	61	58.8	andesite	≈ 4

The Hybrid Stability Index (HSI) closely reproduced observed field performance, yielding smaller residuals than either RMR or RES alone. In particular, for Tunnels 1 and 6 where RMR assigns lower stability classes than those inferred from field observations, whereas RES indicates better stability the HSI provides intermediate stability values that align more closely with the actually applied shotcrete thickness of 5 cm. The HSI successfully reconciled the discrepancies between RMR- and RES-based stability estimates, aligning closely with actual shotcrete thickness. For Tunnels 2–5, where both RMR and RES indicate similar stability classes, the HSI essentially confirms the joint response of the two classifiers without introducing artificial divergence. Scatter plots of support intensity versus RMR, RES, and HSI (Figure 12) show that the hybrid index markedly reduces data dispersion and produces the tightest correlation with observed shotcrete thickness. These results suggest that the hybrid RMR–RES index can serve as a practical, low-complexity enhancement of conventional rock mass classification. By combining the empirically calibrated RMR scale with the interaction-based RES framework, the HSI provides a more balanced representation of both rock mass quality and parameter interdependencies, particularly in intermediate rock-mass conditions where the two systems may diverge. As illustrated in Figure 12, the hybrid index exhibits the tightest clustering with respect to the measured support thickness, reflecting its

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improved predictive capability compared with the individual RMR and RES indices.

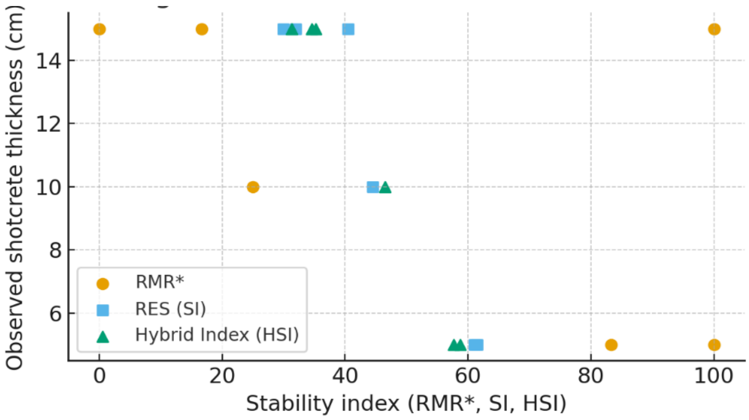

Fig. 12. Scatter plots of observed shotcrete thickness versus normalised RMR (RMR), mean RES stability index (SI), and Hybrid Stability Index (HSI).

Discussion

This discussion synthesizes the comparative performance of the Rock Mass Rating (RMR) and Rock Engineering System (RES) frameworks across the 38 investigated tunnels. While both methodologies converge on similar stability trends for extreme rock mass conditions, divergences become apparent in intermediate quality zones where hydro-mechanical coupling is significant. The RES approach distinguishes itself by incorporating the interdependencies between geological variables through an interaction matrix, whereas RMR treats parameters as independent additive components. This structural difference allows RES to capture non-linear behaviors, such as the amplification of groundwater inflow effects in highly fractured zones, which empirical schemes often oversimplify. Consequently, RES-derived stability indices tend to align more closely with field-obs support requirements, particularly where stress-fracture interactions dominate the deformation mechanism. The comparative data delineated in Table 8 highlight specific instances where the two systems yield different support recommendations. For tunnels excavated in medium-quality rock masses (e.g., Tunnels 1 and 6), RES assigned higher stability classes (60–80 range) compared to RMR (20–40 range), corresponding to thinner shotcrete layers (≈5 cm) that were successfully implemented in the field. In contrast, RMR suggested thicker support (5–10 cm) due to penalizing factors like groundwater presence, without accounting for the mitigating influence of favorable joint orientations. These findings corroborate earlier studies by Benardos and Kaliampakos (2004) and Naghadehi et al. (2011), who noted that empirical classifications may fail to represent complex hydro-mechanical interactions during underground excavation. The present dataset of 38 tunnels extends those observations, confirming that RES provides a more realistic depiction of rock mass behavior in heterogeneous geological settings.

Table 8. Comparison between RMR- and RES-derived stability ratings and corresponding shotcrete requirements.

Tunnel Categories	RES		RMR	Shotcrete (cm)		
	A	B		RMR	RES	Carried out
T1	61	62	45	5-10	5	5
T2	31	33	33	10-15	10-15	15
T3	40	41	45	5-10	5-10	15
T4	30	30	35	10-15	10-15	15
T5	44	45	36	10-15	5-10	10
T6	60	62	43	5-10	5	5

Hence, the RES-based formulation can be regarded as a robust, interaction-driven framework particularly suited for tunnels excavated in medium-quality rock masses where coupled mechanical–hydrological effects dominate. Nevertheless, operational decisions during tunnelling should ensure that initial reinforcement remains proportional to real-time ground conditions rather than rigidly following empirical classification charts. An additional insight concerns the influence of Rock Quality Designation (RQD) and in-situ stress within the two classification frameworks. Although RQD is not explicitly included in RES, its contribution is implicitly captured through parameters that represent fracture frequency, persistence, and continuity, thereby preserving an equivalent measure of structural integrity. Conversely, in-situ stress, one of the dominant controls on tunnel deformation governed by both lithological and tectonic factors, is absent from the RMR formulation. In RES, this parameter interacts with the remaining nine variables, refining the overall stability rating and yielding a more realistic depiction of mechanical behavior. Taken together, these comparisons confirm that RES provides a more physically realistic and dynamically coupled representation of rock-mass behavior than traditional RMR-based systems. The method effectively captures cross-parameter interactions, particularly between stress and hydrogeological conditions, while maintaining practical applicability for engineering design. Beyond the comparative assessment, this study introduces a Hybrid RMR–RES Stability Index (HSI) that statistically combines the empirical robustness of RMR with the systemic interdependence captured by RES. The regression analysis revealed that the optimal calibration yields $\alpha \approx -0.1$, implying a predominantly RES-driven hybrid formulation where the RMR* term slightly offsets the scaling differences between the two systems. This adjustment enhances the consistency between predicted and observed support requirements, particularly for tunnels exhibiting intermediate rock-mass quality. Consequently, the hybrid framework reconciles discrepancies between RMR- and RES-based stability estimates, offering a balanced tool for preliminary design.

Sensitivity Analysis

To evaluate the robustness of both classification frameworks under parameter uncertainty, a sensitivity analysis was conducted by perturbing key variables by ±10 %, ±20 %, and ±30 % from their measured field values. The selected parameters groundwater condition, joint surface weathering, joint spacing, and in-situ stress represent those exhibiting the highest interaction indices in the RES framework. The resulting percentage changes in stability indices (ΔRMR and ΔRES) are summarized in Table 9. This procedure allows for a quantitative assessment of how errors in field data propagation affect the final stability classification in each system.

Table 9. Comparison of RMR and RES response sensitivity under parameter perturbation (±10–30 %).

Parameter	Maximum parameter perturbation (± %)	ΔRMR (%)	ΔRES (%)	Behavioural role in RES Cause–Effect analysis	Interpretation / Comment
Groundwater Condition	±30	±18	±7	Cause-type	Strongest control on system variability
Joint Spacing	±20	±12	±6	Effect-type	Moderate interaction
Joint Surface Weathering	±25	±14	±8	Cause-type	Major influence on RES index
In-situ Stress	±15	±9	±5	Cause-type	Sensitive to tectonic regime
Lithology	±10	±5	±3	Neutral	Weak direct effect, strong indirect impact

As illustrated in Figure 13, variations in groundwater and joint-spacing conditions exert the strongest influence on the RMR index, leading to deviations of up to 18 % in the final rating when the groundwater condition changes from dry to wet. In contrast, the RES-derived stability index shows a maximum deviation of only about 8 %, reflecting the enhanced damping capacity of the RES model that arises from its explicit consideration of parameter interdependence. Across all perturbation levels, the RES curves display smoother and more consistent responses compared with RMR, confirming that interaction-based modelling inherently mitigates abrupt fluctuations. This damping effect suggests that RES is less sensitive to localized anomalies in data collection, providing a more stable basis for design decisions. The relative robustness ratio (ΔRMR / ΔRES), presented in Figure 14, generally exceeds two for the dominant parameters, indicating that RES predictions remain roughly twice as stable as those derived from RMR under equivalent uncertainty. Overall, the sensitivity analysis demonstrates that the RES framework is substantially less vulnerable to error propagation originating from uncertain or variable input data. The non-linear damping trend visualized in Figure 14 further confirms that RES distributes the influence of uncertain parameters throughout the interaction matrix, preventing any single factor from disproportionately controlling the outcome. This property is particularly valuable in practical tunnelling environments, where input data are often incomplete or spatially variable, ensuring that the resulting support recommendations remain consistent within realistic geological uncertainty bounds.

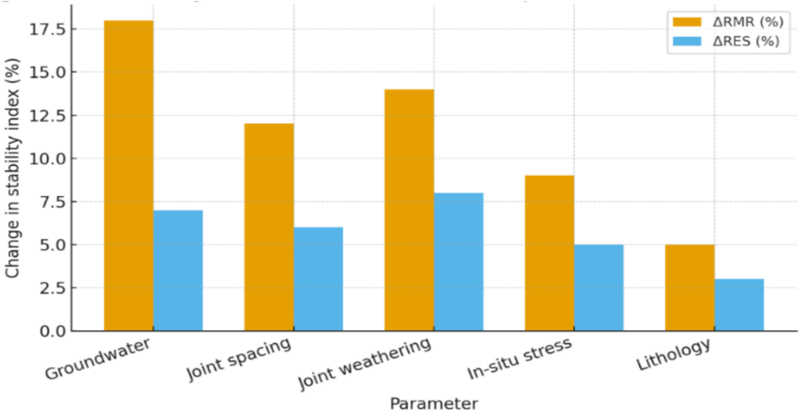

Fig. 13. Sensitivity of RMR and RES stability indices to ±10–30 % variation in dominant parameters.

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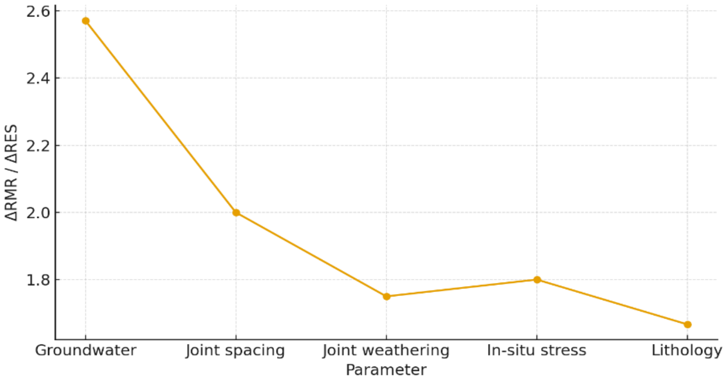

Fig. 14. Comparative robustness of RMR and RES models under increasing uncertainty.

Conclusions

This research project involved a large-scale evaluation of tunnel stability across 38 case studies in Iran, comparing two classification methods: the empirical RMR method and the systems-based RES method. The analysis confirmed that, although both approaches identify general stability trends, the RES method provides a more physically realistic representation of parameter interdependencies, particularly with regard to groundwater and stress interactions. A key outcome of this study is the development of a Hybrid Stability Index (HSI), which reconciles discrepancies between the two systems through statistical calibration. The resulting model, characterised by a weighting coefficient of $\alpha \approx -0.1$, demonstrated exceptional predictive accuracy ($R^2 \approx 0.99$) when tested against field support data. Furthermore, sensitivity analyses revealed that the RES framework exhibits greater stability under uncertain data conditions than the RMR framework. While the HSI is a robust tool for preliminary design in complex geology, future work should focus on validating the calibration coefficients across wider geological provinces to confirm its long-term applicability.

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دسترسی آزاد

شاپا الکترونیکی
۲۹۸۱-۱۴۰۰

تلفیق چارچوب‌های تجربی و مهندسی در طراحی سیستم نگهداری تونل: مطالعه جامع بر روی ۳۸ تونل در ایران

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کلیدواژه‌ها:
طراحی پشتیبانی تونل، رتبه‌بندی توده سنگ (RMR)، سیستم مهندسی سنگ (RES)، چارچوب تلفیقی؛ ایران.

چکیده

طراحی پشتیبانی اولیه برای تونل‌ها در شرایط زمین‌شناسی پیچیده نیازمند روش‌های ارزیابی قابل اعتماد است. این مطالعه یک ارزیابی تطبیقی جامع از چارچوب‌های رتبه‌بندی توده سنگ (RMR) و سیستم مهندسی سنگ (RES) را با استفاده از یک مجموعه داده بزرگ شامل ۳۸ تونل در مناطق سنگ‌شناسی و تکتونیکی متنوع ایران ارائه می‌دهد. در حالی که RMR سادگی تجربی را ارائه می‌دهد، RES یک رویکرد مبتنی بر سیستم را فراهم می‌کند که وابستگی‌های متقابل پارامترها را کمی می‌کند. تحلیل داده‌های میدانی، شامل ضخامت شاتکریت و تراکم پیچ سنگ، نشان داد که RES ارتباطات هیدرومکانیکی را به طور موثرتری ثبت می‌کند، به ویژه در توده‌سنگ‌های با کیفیت متوسط. برای رفع اختلافات بین دو سیستم، یک فرمول‌بندی آماری تلفیقی مورد بررسی قرار گرفت که رتبه‌های نرمال‌شده RMR را با شاخص‌های پایداری RES ترکیب می‌کرد. این رویکرد ترکیبی به طور قابل توجهی همبستگی بالاتری با عملکرد میدانی ($R^2 \approx 0.99$) در مقایسه با روش‌های انفرادی نشان داد. نتایج، ارزش تلفیق چارچوب‌های تجربی و مبتنی بر سیستم را برای افزایش قابلیت اطمینان پیش‌بینی در طراحی پشتیبانی تونل برجسته می‌کند و پایه‌ای مستحکم برای تصمیم‌گیری‌های مهندسی در توده‌سنگ‌های ناهمگن ارائه می‌دهد.

مقدمه

تأمین پایداری مکانیکی سازه‌های زیرزمینی، مانند تونل‌های حمل و نقل، انتقال آب و راه‌آهن، همچنان یک چالش بنیادین در زمین‌شناسی مهندسی و مکانیک سنگ محسوب می‌شود. این پایداری تحت تأثیر تعامل پیچیده و همزمان عواملی چون نوع سنگ‌شناسی، مقاومت سنگ دست‌نخورده، هندسه درزها، فشار آب زیرزمینی و جهت‌گیری تنش‌های درجا قرار دارد. این متغیرها اغلب به شکلی غیرخطی و وابسته به هم عمل می‌کنند، که این امر نیازمند به‌کارگیری رویکردهای یکپارچه و جامعی برای پیش‌بینی دقیق تغییر شکل‌ها و طراحی سیستم‌های پوشش مناسب است. در این مطالعه، ۳۸ دستگاه تونل با جنس زمین‌شناسی متنوع و واقع در مناطق ساختاری مختلف ایران، با طول کل ۲۳۳۵۹ متر، مورد بررسی قرار گرفتند. این تونل‌ها به منظور پوشش دادن طیف وسیعی از شرایط ژئوتکنیکی و تکتونیکی انتخاب شده‌اند. تمامی تونل‌ها با روش آتشباری کنترل‌شده حفاری شدند و نقشه‌برداری زمین‌شناسی دقیق به طور همزمان با ساخت انجام پذیرفت. با وجود تفاوت در شرایط زمین‌شناسی و ساختاری، تونل‌ها بر اساس ویژگی‌های توده سنگ به شش

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ناشر: دانشگاه خوارزمی.

گروه اصلی دسته‌بندی شدند تا مقایسه رفتار مهندسی آن‌ها تسهیل گردد. علاوه بر این، اکثر تونل‌ها دارای سطح مقطع مشابه بوده و به عنوان سازه‌های عمیق تا نیمه‌عمیق طبقه‌بندی می‌شوند که اثرات هوازدگی سطحی بر پایداری کلی آن‌ها را به حداقل می‌رساند. سیستم‌های طبقه‌بندی توده سنگ، به‌ویژه RMR، مدت‌هاست که به عنوان ابزارهای عملی برای ارزیابی پایداری سازه‌های زیرزمینی مورد استفاده قرار گرفته‌اند. با این حال، رویکردهای محاسباتی معمولاً فرض می‌کنند که هر متغیر در یک محدوده ثابت عمل می‌کند، که این ساده‌سازی عدم قطعیت ناشی از داده‌های میدانی ناقص را نادیده می‌گیرد؛ در حالی که مسائل مهندسی سنگ ذاتاً مکانیسم‌های غیرخطی و وابسته‌ای دارند. اگرچه سیستم‌هایی مانند RMR و Q استانداردهای پذیرفته شده‌ای هستند، اما RMR فاکتورهای حیاتی مانند ضخامت لایه‌بندی، تنش‌های تکتونیکی و عدم توانایی در نمایش تعاملات متقابل پارامترها را حذف می‌کند. در مقابل، سیستم مهندسی سنگ (RES) که توسط هادسون معرفی شد، این وابستگی‌های متقابل را به صراحت از طریق یک ماتریس تعامل ساختاریافته کمی‌سازی می‌کند و ارزیابی فیزیکی واقع‌بینانه‌تری از رفتار توده سنگ ارائه می‌دهد. در نتیجه، این مطالعه یک ارزیابی مقایسه‌ای بین RMR و RES انجام داده و یک شاخص پایداری تلفیقی (HSI) را توسعه می‌دهد که نتایج دو سیستم را بر اساس عملکرد واقعی پوشش کالیبره می‌کند.

مواد و روش ها

این پژوهش، RMR تجربی را با RES سیستمی بر روی ۳۸ تونل در ایران مقایسه کرد تا روشی بهینه برای طراحی پوشش اولیه ارائه دهد. تحلیل حساسیت نشان داد که RES در برابر تغییرات ورودی پارامترها (مانند شرایط آب زیرزمینی) بیشتر از RMR است. همچنین اندرکنش پارامترها بر هم نشان می دهد RES با استفاده از ماتریس تعامل، وابستگی‌های فیزیکی را که RMR نادیده می‌گیرد، کمی‌سازی می‌کند. محدودیت‌های روش RMR در پارامتر های مختلف نیز مورد بررسی قرار گرفته است. برای مثال افزایش UCS پس از ۴۰ MPa و افزایش فاصله درزه پس از ۴۰ سانتی‌متر، باعث توقف امتیاز RMR در محدوده ۴۰ تا ۶۰ می‌شود.

نتایج

نتایج نشان می‌دهد که سیستم RES (سیستم مهندسی سنگ) توانایی بالاتری در مدل‌سازی اندرکنش پارامترها نسبت به RMR دارد، به‌طوری که بیش از ۵۰٪ پارامترها دارای کوپلینگ متقابل قابل توجهی بودند؛ پارامترهای غالب شامل هوازدگی، پرشدگی درز، شرایط آب زیرزمینی و جهت‌گیری درز بودند، در حالی که پارامترهایی مانند مقاومت، زبری سطح درز نفوذ کمی داشتند. تحلیل رگرسیون بین شاخص‌های RES و RMR برای ۴۲ نقطه داده، همبستگی خطی قوی را تأیید کرد. در بخش عملکرد شاخص هیبریدی (HSI)، کالیبراسیون بر اساس داده‌های واقعی پوشش (ضخامت شاتکریت) منجر به ارائه نتایج امیدوار کننده ای در خصوص بهبود ضخامت شاتکریت در تونل ها گردید.

بحث

در حالی که RMR متغیرها را مستقل در نظر می‌گیرد، RES به طور صریح تأثیر متقابل آن‌ها را از طریق ماتریس تعامل مدل‌سازی می‌کند و کوپلینگ هیدرو–مکانیکی واقع‌گرایانه‌تری را منعکس می‌سازد. نتایج مقایسه‌ای نشان داد که RES تمایل دارد در تونل‌هایی با کیفیت متوسط توده سنگ، کلاس‌های پایداری کمی بالاتری نسبت به RMR اختصاص دهد؛ برای مثال، شاخص‌های RES(معمولاً

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۶۰–۸۰) با نیاز به شاتکریت ۵ سانتی‌متری مطابقت داشتند، در حالی که RMR(۲۰–۴۰) نیاز به ۵ تا ۱۰ سانتی‌متر را پیشنهاد می‌کرد، که مشاهدات میدانی (دسته تونل‌های T1 و T6) صحت پیش‌بینی‌های RES را تأیید کرد. یک بینش کلیدی دیگر، نحوه در نظر گرفتن RQD و تنش درجا در دو چارچوب بود؛ RQD به طور ضمنی در RES از طریق پارامترهایی که فرکانس و پیوستگی شکستگی را نشان می‌دهند، گنجانده شده است، در حالی که تنش درجا، که یک کنترل‌کننده اصلی است، در فرمول‌بندی RMR غایب است و در RES با ۹ متغیر دیگر تعامل دارد. علاوه بر این، تحلیل حساسیت نشان داد که RES در برابر عدم قطعیت پارامترها عملکرد بهتری دارد.

نتیجه گیری

این مطالعه از هر دو روش RMR و RES برای ارزیابی و بهینه سازی پوشش اولیه در ۳۸ دستگاه تونل حفر شده در واحدهای مختلف زمین شناسی در زونهای ساختاری مختلف کشور ایران استفاده کرد. با کمی سازی وابستگی متقابل بین ده پارامتر کلیدی زمین شناسی و ژئومکانیکی، چارچوب RES نسبت به سیستم مرسوم RMR در شناسایی کنترل کننده های غالب در پایداری تونل موثر تر نشان داد. اگرچه هر دو رویکرد به روندهای پایداری مشابهی همگرا می شوند ولیکن RES تاثیر اندرکنش پارامترهای مختلف بر هم را مطرح و به خوبی اثر هر پارامتر را در پایداری توده سنگ نشان می دهد. پارامتر های مرتبط با هوازدگی سطح درزه، آب زیرزمینی، پر شدگی درزه ها قوی ترین تاثیر علی را بر رفتار تونل اعمال می کنند. در کنار این موضوع یک شاخص پایداری ترکیبی RES-RMR (HSI) با ادغام آماری درجه بندی نرمال شده RMR با شاخص پایداری مبتنی بر RES در یک مقیاس واحد 0-100 و کالیبره شده در برابر ضخامت شاتکریت توسعه یافت. HSI حاصل یک اساس متعادل و کالیبره شده میدانی برای طراحی سیستم نگهداری تونل در توده سنگ های مختلف می باشد.

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