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Research article

Rock Load Height Prediction for Large-Scale Caverns Using Numerical Analysis

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Abstract

Determination of rock load values plays a crucial role in the stability analysis and design of underground structures, particularly in ensuring the safety and cost-effectiveness of support systems. Rock load height serves as a vital parameter for determining the required support in underground openings. Over the years, numerous researchers have developed various methods to estimate rock load height, often based on parameters such as rock quality, opening width, and uniaxial compressive strength. However, the combined effects of additional key parameters, including the ratio of horizontal to vertical stress (K ratio) and overburden height, have not been thoroughly investigated in a unified framework. This study addresses this gap by incorporating these parameters to propose a new empirical relationship for estimating rock load height. Numerical analyses were performed using a safety factor contour of 2.0 to evaluate the rock load heights in cavern roofs under diverse conditions. The results of this comprehensive analysis were compared with existing methods, demonstrating good agreement and validating the reliability of the proposed approach. The new relationship offers a significant advantage by accounting for the influence of varying overburden heights and horizontal-to-vertical stress ratios, thus providing more precise estimations tailored to site-specific conditions. Furthermore, the study introduces a novel equation that links vertical displacement in the cavern roof to rock load height. This innovative approach provides a practical tool for integrating monitoring data into stability assessments. By bridging theoretical insights with real-world applications, the proposed methodology advances the understanding and prediction of rock load behavior, ensuring safer and more effective underground design practices.

1. INTRODUCTION

Predicting rock load height in large-scale caverns is crucial for ensuring stability and safety during construction and operation. Numerical analysis plays a significant role in this prediction by simulating various geological and mechanical conditions. Numerical analysis provides a robust approach to estimating rock load behavior by integrating geomechanical parameters, geometrical factors, and advanced modeling techniques. Key geomechanical parameters such as Rock Mass Rating (RMR), uniaxial compressive strength (UCS), and material constants significantly influence numerical predictions [1,2]. Additionally, the Geological Strength Index (GSI) and the ratio of saturated UCS to in-situ stress (R/σ) are crucial for understanding deformation behavior [3]. Geometrical factors, including the span, height, and depth of caverns, as well as their spacing, play a vital role in stability assessments [4,5]. Overburden depth and lateral stress coefficients are particularly influential in vertical displacement predictions [6]. Recent numerical studies further emphasize that rock-mass behavior, stress conditions, and modeling strategy strongly influence stability predictions. For example, comparisons of 2D and 3D tunnel analyses under static and seismic loading show that weaker or jointed masses exhibit substantially different displacement patterns depending on dimensionality [7]. Similar sensitivity is observed in room-and-pillar systems, where numerically derived pillar strengths and optimal dimensions deviate from empirical formulas—especially under dynamic loads [8]. In large underground water tunnels, numerical assessments have also shown that support demand correlates closely with plastic-zone development in weak rock masses [9]. Together, these studies highlight the need for rock-load estimation methods that explicitly incorporate stress anisotropy and overburden effects—an issue addressed by the unified numerical framework proposed in this work. Various numerical methods have been employed to improve prediction accuracy. The Hoek-Brown criterion, combined with Monte Carlo simulations, enables dynamic estimations of rock mass mechanical properties [1]. Machine learning approaches such as Artificial Neural Networks (ANN) effectively predict maximum horizontal displacement using large numerical modeling datasets [2]. Additionally, fuzzy logic (FL) and statistical analysis (SA) offer reliable methodologies for estimating vertical displacements, enhancing predictive accuracy[6].

The excavation method significantly impacts rock load behavior. Techniques such as partial excavation with reserved rock pillars and various support systems (e.g., bolts, shotcrete lining) influence deformation and stability [5,10]. Comparative numerical simulations help assess the effectiveness of different support structures in mitigating deformation [10].

Several large-scale projects have validated numerical models through real-world applications. For instance, the Baihetan Hydropower Station successfully utilized probabilistic stability assessments and dynamic simulations, confirming the alignment of numerical predictions with field data [1]. Similarly, studies on the Ayalon Cave demonstrated the importance of cover height in stability assessments, as numerical predictions corresponded well with observed roof collapses.

Predictive models are developed from extensive numerical simulations incorporating multiple geomechanical and geometrical factors [2,6]. Empirical validation through case studies, such as those in the Carrara basin and the Etzel Field Test, further ensures the reliability of numerical predictions [11]. The integration of numerical analysis with field data validation enhances predictive accuracy, contributing to safer and more efficient underground construction. Continuous advancements in modeling techniques and data-driven approaches will further improve the understanding of rock load height behavior in large-scale caverns.

Terzaghi [12] proposed that the rock load height H_p is the height of loosening zone over a tunnel roof, which is likely to load the steel arches (Fig. 1). According to Terzaghi's theory, rock load increases with the opening size. A limitation of Terzaghi's theory is that it may not be applicable for tunnels wider than 6 m [1].

Protodyakonov assumed that the pressure arch on the tunnels is a parabolic arch [13]. He proposed the following relation for estimating the rock load used in urban railways in Moscow:

$$H_p = \frac{b}{2f} \quad (1)$$

where H_p is the parabolic arch height, b is the parabolic width and f is the strength factor (Protodyakonov coefficient) that depends on the ground characteristic, approximately one tenth of the uniaxial compressive strength of the host rock around the tunnel. The parabolic width is calculated from the following equation:

$$b = B + 2H.\tan(45 - \frac{\phi}{2}) \quad (2)$$

where B is the tunnel width; H is the tunnel height and ϕ is the internal friction angle of rocks. In cohesionless gravel and sandy grounds, Protodyakonov f equals to $tan(\phi)$.

Barton et al. [14] proposed the empirical relation for ultimate rock load based on the NGI-Q classification system.

$$p_v = (0.2 / J_r) Q^{-1/3} \quad (3)$$

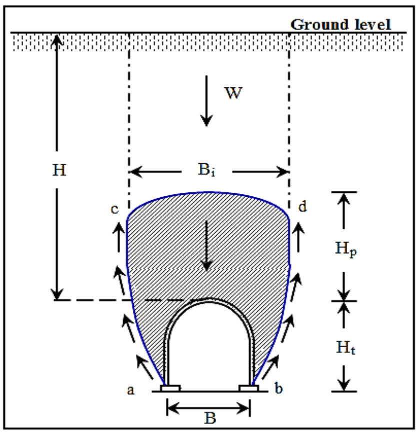

Fig. 1. Terzaghi's rock-load concept in tunnels.

where Q is the Q value, J_r is the joint roughness coefficient, p_v is ultimate roof rock load in MPa. They further suggested that if the number of joint sets is less than three, Eq. (3) should be expressed as:

$$p_v = \frac{0.2.J_n^{1/2}}{3.J_r}.Q^{-1/3} \quad (4)$$

The Terzaghi scheme was modified by using the RQD [15]. In the modified scheme, a reduction was made since the effect of water was overestimated in the Terzaghi scheme. Rose's observations indicated that water had little effect on the rock load H_p. Other authors [16] have compared support pressure measured from tunnels and caverns with estimates from Terzaghi's rock load theory and found that the support pressure in rock tunnels and caverns does not increase directly with excavation size as assumed by Terzaghi.

Unal [17] proposed the following relation for estimating the rock load (p_v) using the RMR for openings with a flat roof:

$$p_v = \left[\frac{100 - RMR}{100}\right].\gamma.B \quad (5)$$

where γ is the unit weight of rock and B is the tunnel width.

Bhasin and Grimstad [18] suggested the following relation for predicting rock load (p_v in kPa) in tunnels through poor rock masses (say Q<4):

$$p_v = \frac{40B}{J_r}Q^{-1/3} \quad (6)$$

where B is the diameter or span of the tunnel in meters. Eq. (6) shows that the rock load increases with tunnel size B in poor rock masses.

According to the Russian method, rock load height consists of the structural collapse zone depth, the blasting crushed zone depth, and depth of elasto-plastic collapse zone [19]. The Russian method suggests that the total rock load height is determined by the following equation:

$$H_p = k_1 B \quad (7)$$

Considering different engineering and geological conditions, several parameters in underground openings and statistical analysis of each calculated depth zone coefficient k_1 have been determined and are presented in Table 1.

Table 1. Coefficient k_1 for Russian method

Protodyakonov coefficient (f)	K_1
≥15	0-0.05
14-10	0.05-0.1
9-7	0.1-0.15
6-5	0.15-0.2
4	0.2-0.3
3-2	0.3-0.4

In heavy jointed or heavily altered rock mass, the coefficient k_1 must be determined by experiment, and in the first stages of cavern design, it is possible to use the proposed value in the table, but it must be multiplied by 1.5 [19]. Also, for Protodyakonov coefficients less than 4, the effect of large tunnel or cavern depth is considered by a correction factor k_2, which must be multiplied in H_p. Table 2 presents k_2 for different depths.

Table 2. Correction factor for Russian method [19]

Depth[m]	≤ 100	250	500
K_2	1.0	1.3	1.5

Other researchers have used heuristic methods to predict roof pressure [20].

Abdollahipour and Rahmannejad [21] showed that the horizontal to vertical stress ratio and the deformation modulus are two important parameters in underground excavations stability. They used these parameters along with several other parameters in a later study [22] and proposed an equation to estimate the displacement in cavern sidewalls. Another study has investigated the effect of adjacent caverns using the plastic zone formed between two adjacent caverns [23]. Effects of these two parameters (horizontal to vertical stress ratio and deformation modulus), geometry, and depth of opening on rock load height have never been studied altogether. In this study it is made to consider the effect of all these features on the rock load height for a single cavern.

2. RESEARCH METHODOLOGY

In this study, a series of numerical analyses was performed to estimate rock load height for the design of a cavern lining. The two-dimensional FEM program, Phase^2 [24] has been used to model and analyze the rock load height. The following simplifications and assumptions have been made:

The surrounding rock mass is homogeneous and continuous, the joint effect is considered using the equivalent deformation module, E using a model proposed by Sitharam [25].

The initial in situ stress is uniformly distributed within the computational domain, and the two principal stresses (minor and major principal stresses) act in horizontal and vertical directions; the out-of-plane stress is the intermediate principal stress. The mechanical properties of rocks into which caverns have been excavated are presented in Table 3. The required parameters, when not present, were obtained using the RocLab program. It is assumed that the rock mass obeys the Hoek-Brown criterion. A single horseshoe-shaped cavern was utilized as the default for all analyses. An expansion factor of 5 with "Box Boundary Type" has been used in Phase[2] to ensure that the boundary is far enough away to simulate "infinite" or far-field conditions, and doesn't influence the results near the excavations. The "Increase Mesh Element Density" option has been used to increase the element density around the caverns. This was done to improve the accuracy of the displacement and plastic depth results. When the mesh was generated, all nodes on the external boundary were given a fixed, zero displacement boundary condition. Figure 2 shows a cavern of 33×52m cross-section modeled in Phase[2] as described above.

In all numerical models conducted, fixed boundary conditions were applied in all directions, as the model is located at a great depth and its upper surface does not represent the ground surface. To assess the influence of boundary conditions, several comparative analyses were performed using both roller and fixed boundaries, revealing no significant difference in the model's response. This was attributed to the sufficient distance between the boundaries and the excavation zone. Moreover, given that over 1000 numerical simulations were conducted and the software's default settings applied fixed boundaries, this approach was adopted to streamline the modeling process and enhance computational efficiency without compromising result accuracy.

Table 3. Mechanical properties of rock masses

Reference	ν [-]	E [MPa]	UCS [MPa]	S [-]	m_b [-]	RMR [-]
[26]	0.33	3162	113.4	0.0007	1.28	35
[27]	0.3	4350	70	0.0013	2.12	47
[27]	0.27	11900	100	0.0054	3.546	54
[26]	0.27	13335	119	0.007	6.01	60
[27]	0.26	28700	85	0.11	5.94	68
[28]	0.25	56000	340	0.0357	10.961	75

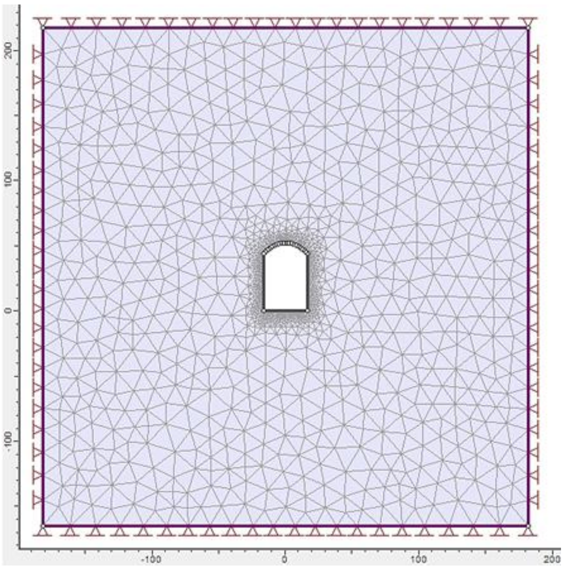

Fig. 2. A horseshoe cavern of 33×52m cross section modeled in Phase 2.

3. NUMERICAL ANALYSIS

A horseshoe cavern with cross-section dimensions of 10×15, 18×30, 33×52, 60×60m was selected, six different horizontal to vertical stress ratios i.e., k= 0.33, 0.5, 1, 1.5, 2, 2.5 have been used in calculations for each rock type, and four different overburden depths of H=100, 200, 300 and 400m have been considered.

The size of the relaxed zone (equivalent to the plastic zone in an elasto-plastic analysis) occurred by tunnel excavation could be found by finding the contour of safety factor of 2.0 or 3.0 [29]. Also, a safety factor contour of 2.0 has been used successfully to design lining support for a 2-arch tunnel [30]. In addition to that Hoek et al. [31] proposed to use the same value of safety factor contour. Therefore, the contour of safety factor of 2.0 has been used in numerical analyses to estimate the height of relaxed zone in cavern roof. Figure 3 shows the height of relaxed zone on the roof of a cavern obtained from safety factor contour of 2. Figure 4 shows the vertical and horizontal displacements in this model.

Nearly 1000 cases have been computed altogether. Eq. (8) has been fitted on the results of numerical analyses.

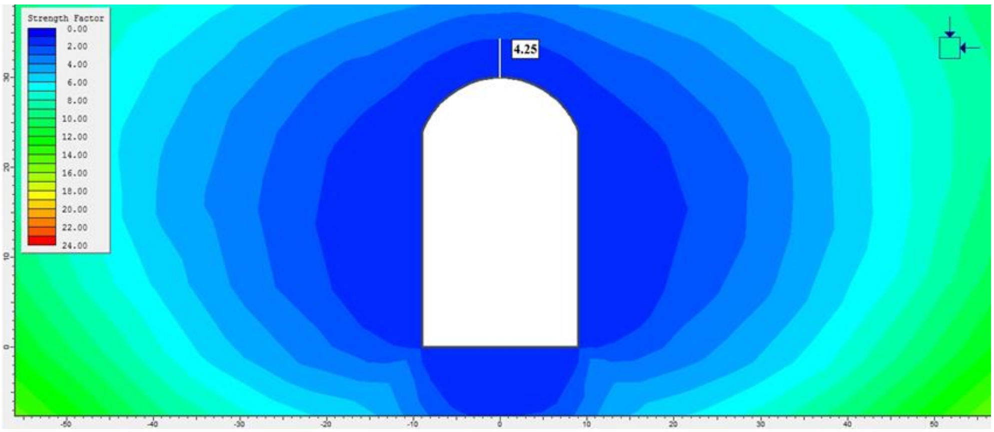

Fig. 3. Safety factor contours around a 18×30m cavern in a rock with RMR=35.

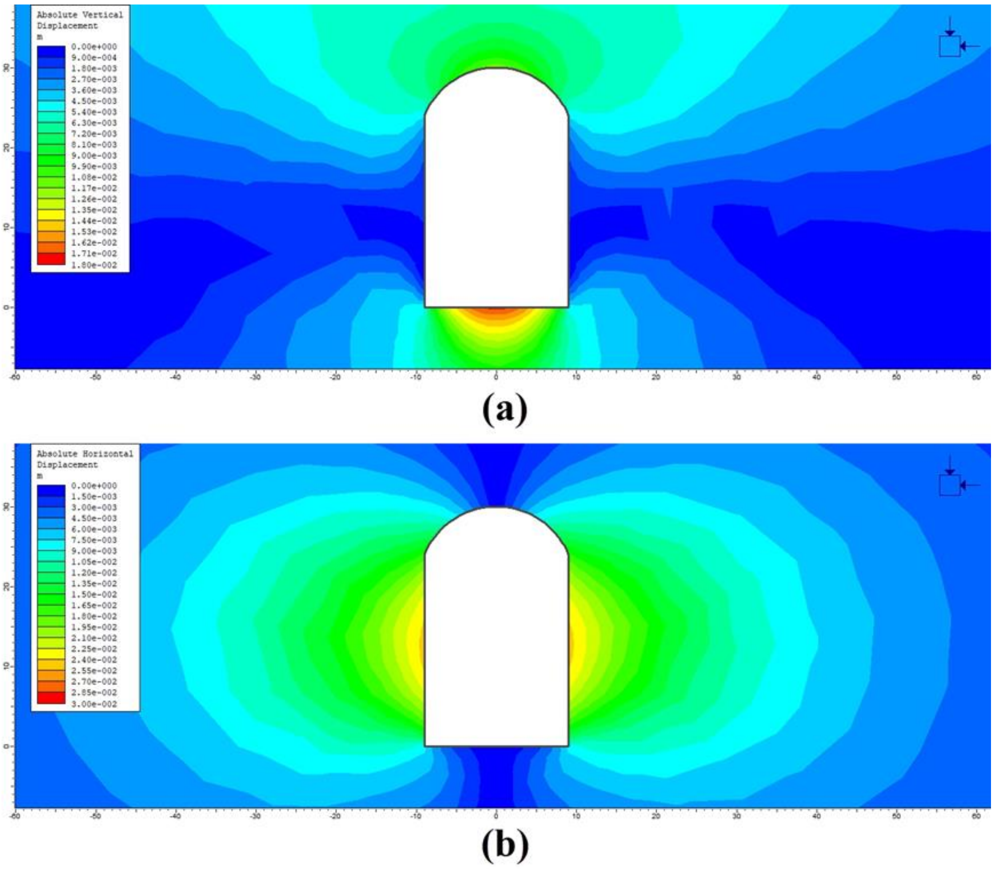

Fig. 4. Displacement contours around a 18×30m cavern in a rock with RMR=35, a) vertical displacement, b) horizontal displacement.

Results of regression are presented in Figure 5. The determination coefficient of this linear model, R^2, is 90.43.

$$H_p = \left(0.0066 \times (100\text{-RMR}) \times B\right) + 0.0115 \times KH - 3.35 \quad (8)$$

where H_p (m) is rock load height, B (m) is cavern width, K (-) is the horizontal to vertical stress ratio, and H is overburden depth (m).

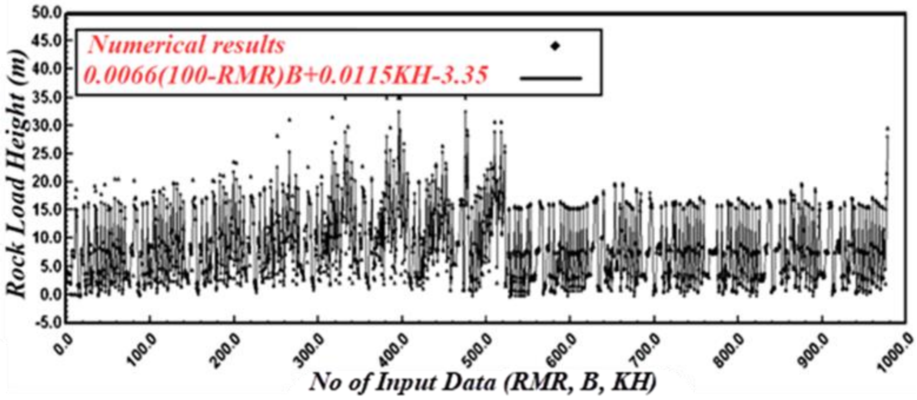

Fig. 5. Regression results of proposed equation (Eq. 8).

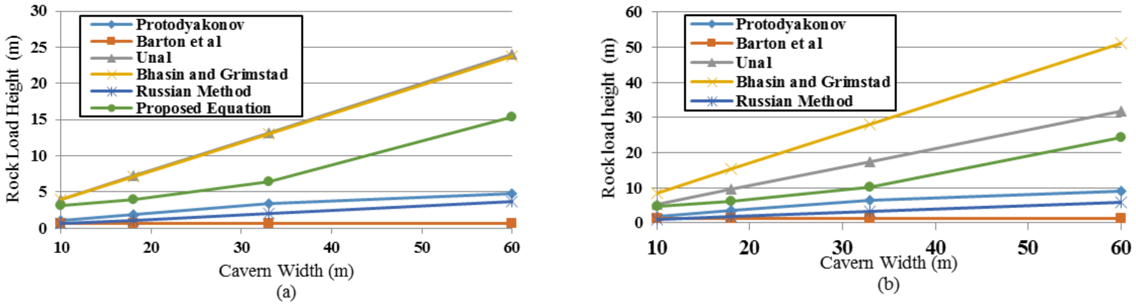

Fig. 6. Comparison of new and existing equations for two cases: a) H=200m, RMR= 60 and K=1, and b) H=400m, RMR= 47 and K=1.

4. RESULTS AND DISCUSSION

To evaluate the proposed equation, the rock load height results of the proposed equation (8) are compared with aforementioned empirical equations in the introduction. Other needed parameters of empirical equations are presented in Table 4.

A large number of numerical analyses have been carried out. Results showed that all equations have a similar trend with different slopes. Figure 6 shows the resulting curves of numerical analyses for two different overburden heights. The vertical axis stands for rock load height and the horizontal axis represents the cavern width.

Table 4. Mechanical parameters of rocks

RMR	Q	J_r	J_n	φ	f
35	0.41	1	12	28.3	11.34
47	1.56	1.5	6	32.5	7
54	3.40	1.5	6	36.5	10
60	6.61	2	4	40.2	11.9
68	16.08	3	3	41.4	8.5
75	35.01	4	1	46.5	34

As it can be seen in Figure 6 the results of the proposed equation are in accordance with other empirical methods. While Eq. (8) proves to be in reasonable limits, it has the following advantages in comparison with other methods:

Unlike some other methods, the required parameters in proposed equation are common field data that are always available and easy to obtain or even estimate.

Eq. (8) estimates the rock load height considering the cavern depth and the field stress (overburden height and horizontal to vertical stress ratio), which makes it more logical in estimating rock load height than other equations that do not consider these parameters (see Table 5).

Horizontal to vertical stress ratio of 1.5 along with RMR= 54 in 4 different overburden depths of 100, 200, 300 and 400m have been considered in Table 5. It shows the advantage of proposed equation in estimating the rock load. The proposed equation has estimated different rock load heights for different conditions. Other methods have predicted rock load heights according to the opening width, except for Barton et al. which depends on rock quality (Q) only.

Table 5. Rock load height of different methods for K=1.5 and RMR=54. (Units are in meters)

H	B	Barton et al.	Protodyakonov	Unal	Bhasin and Grimstad	Russian Method	Proposed Equation
100	33	2.68	1.29	15.18	21.69	1.65	6.71
200	33	2.68	1.29	15.18	21.69	1.65	8.03
300	33	2.68	1.29	15.18	21.69	1.65	9.62
400	33	2.68	1.29	15.18	21.69	1.65	11.52
100	60	2.68	1.00	27.60	39.43	3.00	16.01
200	60	2.68	1.00	27.60	39.43	3.00	19.17
300	60	2.68	1.00	27.60	39.43	3.00	22.95
400	60	2.68	1.00	27.60	39.43	3.00	27.47

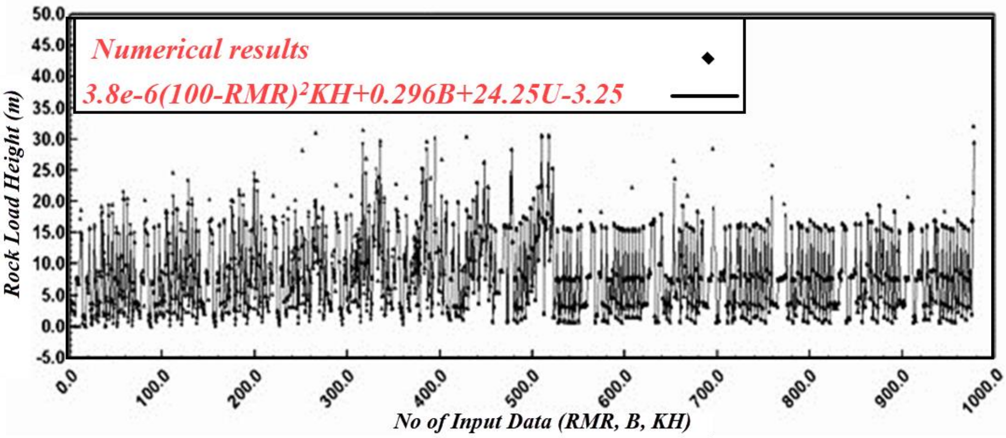

Fig. 7. Regression results for proposed equation (Eq. 9).

5. ESTIMATING ROCK LOAD HEIGHT USING VERTICAL DISPLACEMENT

In many practical cases, the vertical displacement of the caverns' roof is available; establishing a relationship between this displacement and the rock load height one should be able to estimate the rock load pressure on the roof. Therefore, vertical displacements of the aforementioned numerical analyses have been derived. Eq. (9) has been fitted to the results of numerical analyses (Fig. 7). The determination coefficient, R^2, is 90.1.

$$H_p = \left[3.8\times(100\text{-RMR})^2\times KH\right]\times10^{-6}+ 0.296B+24.25U-3.25 \quad (9)$$

where U is roof displacement (m) (always as a positive value). The rock load height can be estimated more accurately for low overburden depth i.e. low vertical stresses. Eq. (9) can be useful when monitoring data are available so that the rock load height and subsequently the rock load pressure can be estimated quickly. Given that roof displacement is often available from monitoring systems, this equation allows for a practical and efficient estimation of rock load pressure. This estimation is particularly useful for low overburden depths, where the accuracy is higher. The results can be directly applied in support design, including shotcrete thickness and rock bolt length calculations. Results can then be applied in support design to calculate shotcrete or lining thickness (for example, Lame's thick-wall cylinder theory [32] which requires roof pressure), rock bolt length, etc.

6. CONCLUSIONS

This study presented a comprehensive investigation into rock load height prediction for large-scale caverns using numerical analysis. Existing empirical methods were reviewed, and a systematic approach was proposed to estimate rock load height based on numerical simulations. The rock load height was determined using a safety factor contour of 2.0, corresponding to the relaxed zone in the cavern roof. A new empirical equation was derived from extensive numerical analyses, incorporating key parameters such as cavern width, overburden depth, and the horizontal-to-vertical stress ratio. The proposed equation was validated against existing methods, demonstrating a strong correlation and improved reliability in various geological conditions.

The advantages of the proposed equation include its reliance on commonly available field parameters, making it more practical for engineering applications. Unlike some previous methods, the equation considers the effect of overburden depth and horizontal stress ratio, allowing for a more realistic estimation of rock load height. Furthermore, a secondary equation was introduced to estimate rock load height based on vertical roof displacement, providing a useful tool for integrating monitoring data into stability assessments. This approach enhances the practical applicability of the study by enabling real-time estimation of rock load pressure, which is essential for optimizing support design.

This research advances the understanding of rock load behavior in underground caverns, bridging theoretical analysis with practical implementation. The findings contribute to safer and more cost-effective underground design practices by improving rock load estimations and support system efficiency. Future work could focus on refining the proposed equations using additional case studies and incorporating three-dimensional numerical modeling to further enhance prediction accuracy.

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