CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (1): 0160-0176
DOI: 10.59440/ceer/200288
*Original Research Article*

# NUMERICAL ANALYSIS OF TUNNEL DISPLACEMENT PROFILES WITH PIPE UMBRELLA SUPPORT: PARAMETRIC STUDY OF SELECTED UMBRELLA PARAMETERS

Michał PACHNICZ[1], Irena BAGIŃSKA[2]
[1] Wrocław University of Science and Technology, Faculty of Civil Engineering
[2] Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology

Abstract

Ensuring the stability of tunnels excavated in weak rock masses poses significant engineering challenges, particularly in controlling deformations of the excavated rock-mass. This research represents a conceptual analysis aimed at exploring the effectiveness of pipe umbrella support systems across various configurations, without being tied to a specific tunnel project. The study also investigates the possibility of using simplified Finite Element Method (FEM) modelling for such purpose. Specifically, analysis focuses on findin the correlation between selected design parameters and support system performance. A numerical model incorporating the Hoek-Brown failure criterion, was employed to simulate the interaction between the pipe umbrella and surrounding rock mass. Key parameters analyzed include the length of the pipe umbrella segments, overlap between segments, and the stiffness of the pipe umbrella material. The results demonstrate the potential in reducing both radial and axial displacements as the segment length of the pipe umbrella and overlap increase, with diminishing returns observed for higher umbrella's stiffness values. This study despite being based on theoretical case scenario ~~also~~ highlights the practical advantages of a simplified axisymmetric FEM model for conducting parametric analyses, significantly reducing computational complexity while maintaining sufficient accuracy.

Keywords: Longitudinal Displacement Profile, Hoek-Brown failure criterion, pipe umbrella support, tunnel, Convergence-Confinement Method

## 1. INTRODUCTION

Tunnelling in complex geological conditions presents several engineering challenges, primarily due to the inherent uncertainties and variabilities in the ground's mechanical properties. One of the key issues faced during tunnel construction is rock deformation, particularly tunnel crown settlement and the potential for collapse. These deformations can cause serious structural damage to the tunnel lining,

[1] Corresponding author: Michał PACHNICZ, Wrocław University of Science and Technology, Faculty of Civil Engineering, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland, michal.pachnicz@pwr.edu.pl, +48 71 320 23 45

reduce overall tunnel stability, and endanger construction safety [1]–[3]. Addressing tunnel deformation is critical not only because it is essential for maintaining the structural stability and safety of the tunnel but also allows for understanding and designing tunnel support systems using the Convergence-Confinement Method (CCM) [4],[5]. The CCM considers the interaction between the ground (Ground Reaction Curve- GRC) and support (Support Reaction Curve- SRC) by evaluating the radial displacement (convergence) of the tunnel opening and the capacity of the support to confine the rock mass (Fig. 1a).

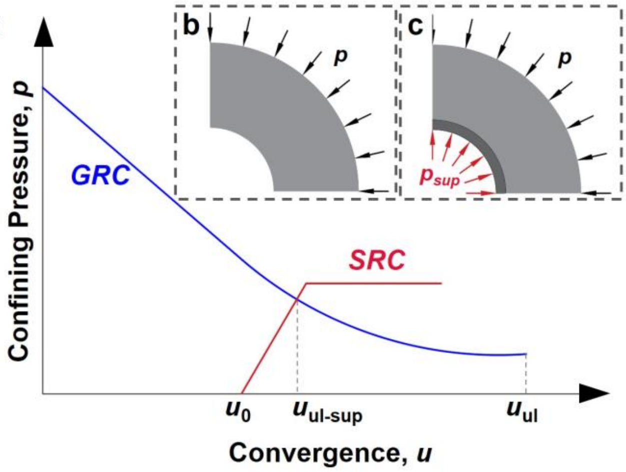


Fig. 1. CCM method for determining the interaction between the support and the surrounding rock- mass (a), Static scheme for estimating the displacement profile of unsupported tunnel opening (b), Static scheme for estimating the displacement profile of supported tunnel opening (c)

Therefore, an essential component of the CCM method is the accurate and precise determination of the tunnel convergence profile, which in this case corresponds to the Longitudinal Displacement Profile (LDP). For an unsupported excavation, such a profile can be approximated using one of the few empirical solutions available in the literature [6],[4],[7]. One of these approaches [8] is based on determining the deformation profile by accounting for the radius of the plastic zone, as described by Eq. (1.1).

$$
\begin{aligned}
u(x) &= \frac{1}{3}u_{ul}\exp\left(\frac{x-0.15R_p}{R}\right) && \text{for } x \le 0 \\
u(x) &= u_{ul}\left[1-\left(1-\frac{1}{3}\exp\left(-0.15\frac{R_p}{R}\right)\right)\exp\left(-1.5\frac{x}{R_p}\right)\right] && \text{for } x \ge 0
\end{aligned}
\tag{1.1}
$$

Where $u$ is the tunnel convergence, and x is the distance to the tunnel face. $R$ is the radius of the tunnel, and $R_p$ is the ultimate radius of the plastic zone developed in the surrounding ground. $u_{ul}$ is the ultimate tunnel convergence, which occurs far from the tunnel face (Fig. 1a). These quantities are determined using either analytical solutions or numerical modelling. Similar solutions were also proposed for estimating LDP for supported tunnels [9],[10]:

$$
u(x)_{sup} = \varphi(z)u(x); \quad \varphi(z) = 0.55 + 0.45z - 0.42(1-z)^3; \quad z = \frac{u_{ul-sup}}{u_{ul}} \tag{1.2}
$$

$$u(x)_{sup} = \varphi u(x) \leq \ u_{ul-sup} \tag{1.3}$$

Where $u_{ul}$-sup is the ultimate convergence of supported tunnel, which is dependent on the $u_0$, Fig. 1a therefore once again certain quantities require to be determined using either analytical solutions, like solving plain strain boundary problems (Fig. 1b, Fig. 1c) or numerical modelling.

The Pipe Umbrella Support technique can be applied to excavation support systems of both flexible and rigid types. In mining, flexible support systems are predominantly used, and as a result, Pipe Umbrella Support is primarily employed to stabilize the excavation face, with a secondary role in limiting displacements. In tunnel construction, particularly when using New Austrian Tunnelling Method NATM and related technologies, tunnel lining is typically implemented in two stages. The first stage involves constructing a temporary lining, which is moderately flexible [11]. The second stage entails constructing a final rigid lining that serves as the permanent structural support throughout the tunnel's operational lifespan, such as in transportation tunnels. In this context, the Pipe Umbrella Support plays a dual role during the first stage: it not only enhances safety by ensuring the stability of the excavation face but also significantly reduces rock mass displacements into the excavation. This, in turn, helps to minimize the extent of the plasticization zone surrounding the excavation, contributing to the overall stability and integrity of the tunnel structure.

Taking the above into account the primary objective of this study was to perform a generic investigation aimed at exploring the effectiveness of pipe umbrella support systems under various configurations, without focusing on a specific tunnel project. The aforementioned approach allowed to establish general correlations between the parameters of the installed support system and its effectiveness in reducing tunnel's convergence (represented by Longitudinal Displacement Profile). As mentioned above the numerical determination of the deformation profile (LDP) allows for the direct calculation of the displacement function without the need for assumptions regarding the moment of support- rockmass interaction, or support time installation. However, the spatial nature of rock mass behaviour often necessitates conducting 3D FEM analyses, which are highly time-consuming and complex, making them impractical for extensive parametric studies. For this reason, the authors of this study opted to perform a limited parametric analysis of the pipe umbrella support system using a simplified axisymmetric FEM modelling approach. This simplification allows for a more straightforward and computationally efficient analysis while capturing the essential behaviour of the rock mass during excavation. However, it should be noted that the use of an axisymmetric model necessitates the assumption of hydrostatic pressure conditions, where the horizontal and vertical stresses are equal, to maintain symmetry about the tunnel's longitudinal axis This approach is a common and validated approach in tunnel excavation studies, particularly for circular tunnels [12]–[14]. Additionally, the analysis aimed to verify whether the simplified FEM model could facilitate parametric studies of the umbrella support system with satisfactory accuracy.

Presented analysis was performed with the additional assumption of investigating behaviour of pipe umbrella support in weak rock masses specifically. Since the author's goal was to establish broad trends in the effectiveness of pipe umbrella support systems, rather than to model site-specific geological conditions, the authors adopted parameter values representative of "weak" rock mass conditions based on literature data. This provided a generalized framework for the analysis. Adopted parameters are presented in section 2.2. Weak rock mass behaviour was modelled by application of Hoek-Brown failure criterion. Given criterion was used to simulate the non-linear behaviour of fractured rock masses, particularly under low-strength conditions, as evidenced in previous research [15],[16].

## 2. METHODOLOGY

Determining the impact of a pipe umbrella on the deformation profile of a tunnel is a highly complex issue, influenced by a wide range of factors [17]–[22]. Key factors affecting the effectiveness of the pipe umbrella support include:

- The mechanical properties of the surrounding rock, including its strength and deformability, play a significant role, with varying effectiveness observed depending on whether the rock mass has weak parameters or a transition from average-strength material to a weaker formation. In addition, different rock types respond differently to excavation stresses, while geological discontinuities create zones of weakness that may lead to unexpected convergence or collapse.
- In-situ stress states, including overburden pressure and tectonic stresses, significantly impact how the rock mass behaves during excavation and how it responds to applied support
- Research indicates that different cross-sectional shapes (circular, horseshoe) can lead to varying degrees of convergence as larger diameters typically require more robust support to control displacement effectively.
- The installation angle (α) of the umbrella sections together with the length of each umbrella section (L) influences their interaction with the surrounding rock with longer, steeper sections often providing more effective reinforcement.
- The spacing between sections (or overlap length) affects the uniformity and continuity of support. Increased overlap between segments generally leads to greater confinement of the tunnel crown.
- Finally, the stiffness and strength parameters of the umbrella itself, determined by the materials used and the spacing of anchors within each section (s), influence the structural support provided by the umbrella system. Higher stiffness and denser anchor placement enhance support effectiveness.

The choice of modelling approach, whether in 3D or simplified forms, necessitates calibration to ensure that results align with field monitoring data. Different modelling assumptions, such as using truss elements, continuum elements, or beam elements, can lead to variations in simulation outcomes and require careful consideration for accurate predictions. Additionally, the choice of evaluation metric affects the assessment of the umbrella's effectiveness. Each of these factors must be carefully considered in the analysis to provide a comprehensive understanding of the pipe umbrella's effectiveness in tunnel support.

Since the presented study involves only preliminary calculations, we focused on analysing a few selected parameters that influence the effectiveness of the support system—namely, the length of the umbrella sections, the overlap between sections, and the stiffness of the support. Other parameters were assumed in advance, and simplifications considering type of analysis were made to accelerate this initial research. These results serve as a foundation for a more comprehensive and precise parametric analysis planned in future stages of the research.

For this study to determine the impact of the pipe umbrella on the deformation profile of the tunnel's edge the finite element method (FEM) was implemented. The software used in this study (ZSoil 2018) enables calculations that consider the staged construction of tunnel structure in a sequential manner [23]. This approach was applied both to the tunnel excavation process and to the modelling of the pipe umbrella. To monitor rock mass deformations ahead of the advancing tunnel face, displacement values at observation point are recorded. A simplified schematic of the tunnel excavation process, including the observation point within the selected cross section and the designated coordinate system, is shown in Fig. 2.

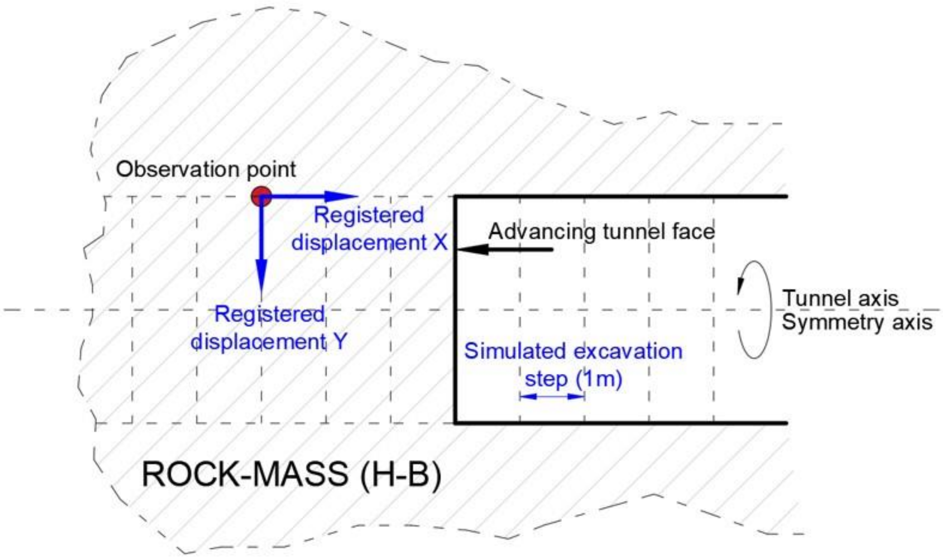


Fig. 2. The schematic of the tunnel excavation process, adopted for presented study

The effectiveness of the applied umbrella reinforcement is quantified by determining the Normalized Longitudinal Displacement Profile (NLDP) within the range of -75 m to +45 m with regards to the tunnel's face position.

## 2.1. The Hoek-Brown failure criterion in FEM

The Hoek-Brown (H-B) failure criterion was implemented to model the rock mass and may serve as an alternative to traditional methods such as Mohr-Coulomb [24],[25]. Mohr-Coulomb criterion is widely applicable and performs well for certain weak rock masses, it assumes linearity in the failure envelope, which may not adequately capture the complex behavior of weak, fractured rocks under stress redistribution [26]. However, H-B criterion captures the non-linear behaviour of rock, particularly in fractured conditions, which is essential for tunnel analysis. The generalized Hoek-Brown criterion [27] is described by the following equation:

$$f(\sigma_1, \sigma_3) = \sigma_1 - \sigma_3 - \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a \tag{2.1}$$

where $\sigma_1$ and $\sigma_3$ are the major and minor principal stresses, respectively $\sigma_1 > \sigma_3$; $\sigma_{ci}$ is the unconfined compressive strength (USC) of the intact rock material; $m_b$, $s$, and $a$ are the rock mass material constants, given by:

$$m_b = m_i \, exp[(GSI - 100)/(28 - 14D)] \tag{2.2}$$

$$s = exp[(GSI - 100)/(9 - 3D)] \tag{2.3}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}}\right) \tag{2.4}$$

where *D* is a factor which depends upon the degree of disturbance to which the rock mass has been subjected to blast damage and stress relaxation; $m_i$ is a material constant for the intact rock; GSI is the geological strength index of rock mass characterization that was developed, by Hoek [27] and Hoek et al. [28].

## 2.2. Numerical Simulation and Model Description

The numerical model was configured utilizing an axisymmetric framework in which the axis of symmetry aligns with the tunnel's central axis. The geometry of the model was assumed to be rectangular region 250m x 150m with the average size of finite element of 1m around the excavation zone and of 5 m close to the edge of the boundary problem (Fig. 3). The size of the model was assumed according to the guidelines presented in [29].

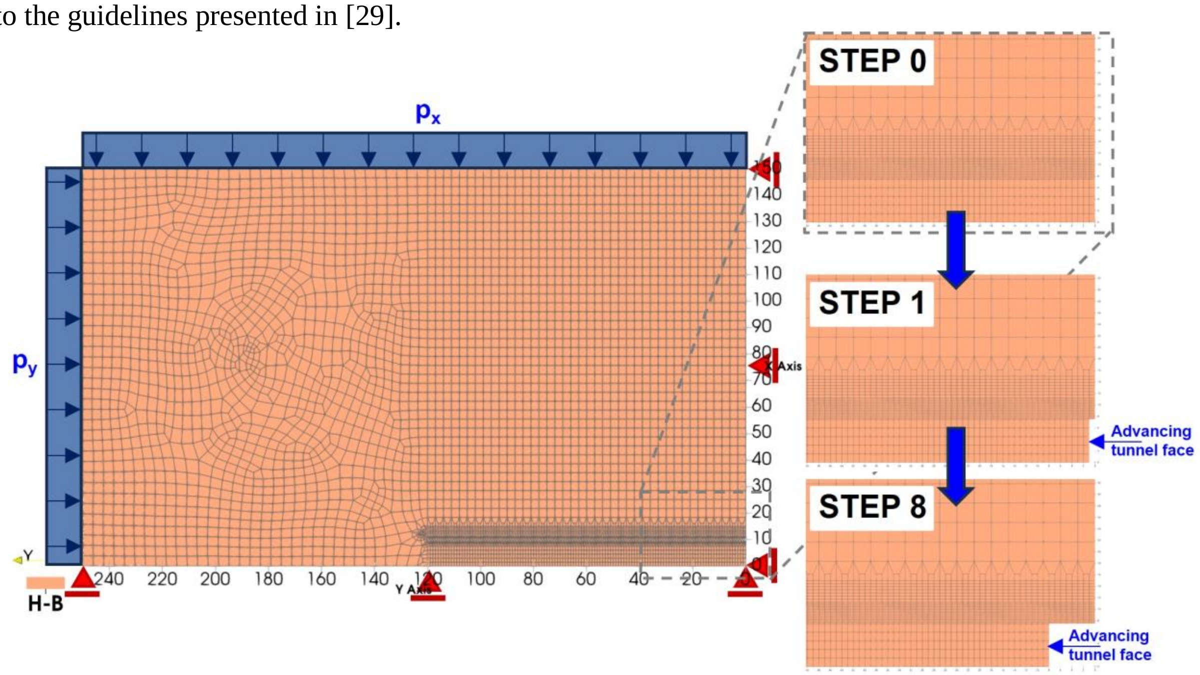


Fig. 3. Numerical model of the tunnel (tunnel face in the analysed cross section, the unsupported tunnel case)

To provide hydrostatic pressure around the excavation area, the weight of the rock material is neglected ($\gamma$=0 kN/m$^3$) and boundary loads satisfy the following condition: $p_x = p_y = 7$ MPa. These parameters were adopted to simulate conditions for a tunnel excavated at a depth of approximately 260 meters, where the pressure value corresponds to the weight of the overburden. The remaining edges of the model are constrained with fixed translation perpendicular to the boundary, simulating the confinement of the surrounding rock mass. In the numerical model, successive stages of tunnel excavation were simulated by the stepwise (sequential) "removal" of finite elements within the excavation area (Fig. 3). The model reflects tunnel excavation using the full-face method and assumes a disturbance factor *D* = 0.5 according to the Hoek-Brown criterion, for excavation with no invert. For the rock mass, uniform continuum described by the Hoek-Brown (H-B) failure criterion is assumed. In this study, numerical calculations were conducted for a weak rock mass, based on the example of a tunnel excavated to a similar depth of 400 m in a poor-quality rock mass documented in [30],[31]. Using well-documented parameters from the literature ensures consistency and allows for meaningful comparisons with other studies while maintaining the focus on identifying general patterns and relationships. The parameters adopted for the material model are presented in Table 1.

Table 1. Material parameters for the Hoek Brown continuum adopted from the literature [30],[31]

| **Adopted properties for rock-mass** | | Rock-Mass Quality **very poor** |
|---|---|---|
| Intact rock material strength | $\sigma_{ci}$ | 100 [MPa] |
| Hoek- Brown material constant | $m_i$ | 20 [-] |
| Geological Strength Index | GSI | 21.4 [-] |
| Deformation modulus | $E_m$ | 1.1 [GPa] |
| Poisson's ratio | ν | 0.3 [-] |
| Dilation angle | ψ | 0 [°] |

## 2.3. Pipe Umbrella Simulation

The pipe umbrella is modeled as a linear elastic volume object, following the approach found in the literature [10], which provides a solid starting point for further analysis. This simplification allows for the initial assessment of the umbrella's structural impact while maintaining computational efficiency. Material's parameters for the umbrella elements are as follows: Young's modulus (E) = 13.5 GPa, Poisson's ratio (ν) = 0.2 [10].

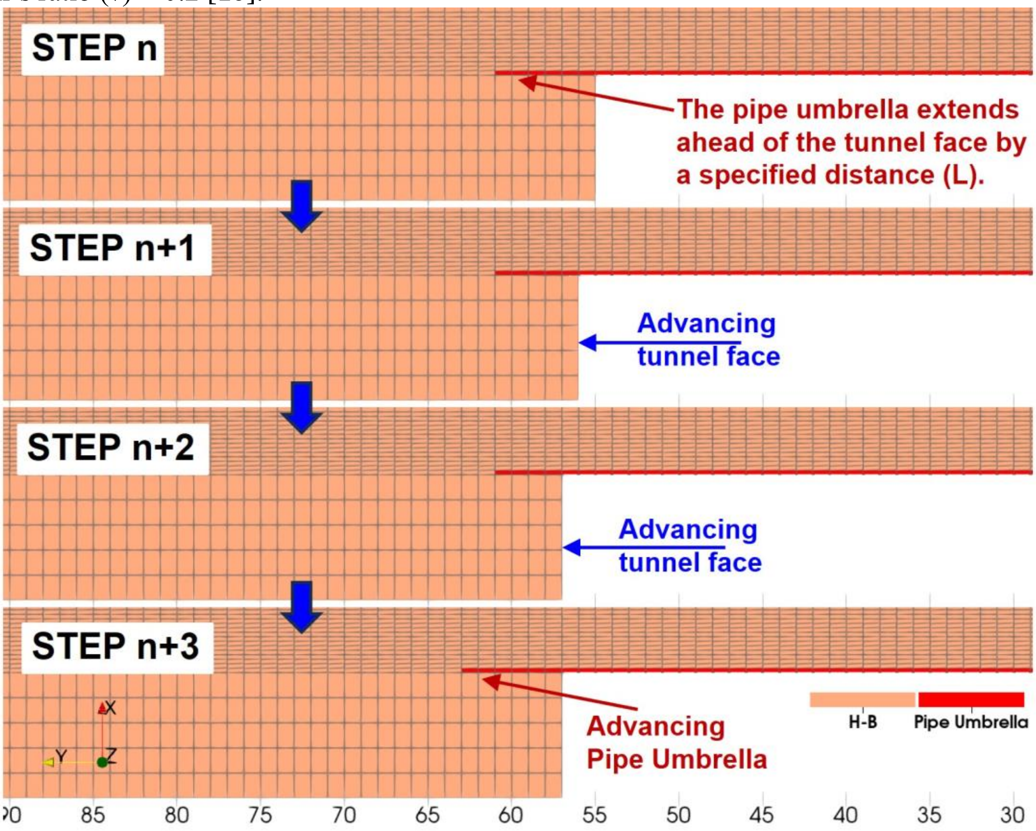


Fig. 4. Numerical model of the tunnel (tunnel face in the analysed cross section, the supported tunnel case)

The umbrella was modeled analogously to the tunnel excavation process, with elements being sequentially converted from Hoek-Brown (H-B) material properties to an elastic continuum at the locations assumed for umbrella installation. This staged approach enabled simulation of the umbrella installation as it extended in advance of the tunnel face by the predetermined distance (L) also maintaining overlap distance between umbrella sections. Once the minimum overlap distance was reached, a new section of the umbrella was installed. This process continued incrementally, with each new section added until reaching full length specified for each umbrella segment Fig. 4.

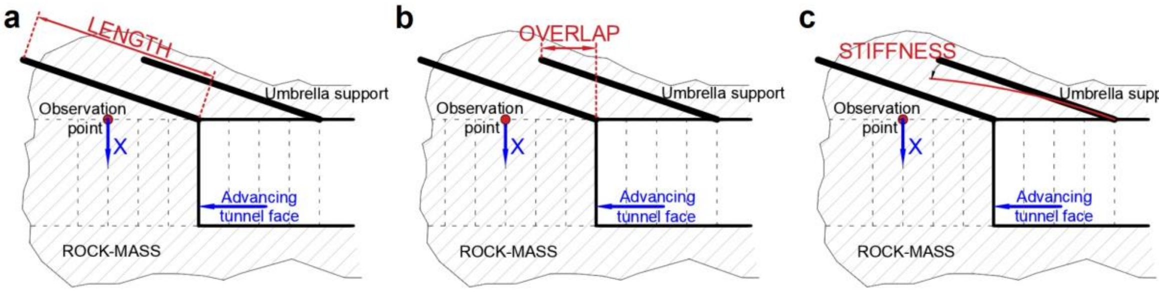


Fig. 5. The pipe umbrella parameters: a) length of segments, b) overlap, c) mechanical properties

As previously mentioned, this study focuses on investigating specific parameters of the pipe umbrella system, with all analyses conducted for a fixed tunnel radius of $R$= 7.5 meters and an umbrella inclination angle of 10° (Fig. 5). Specifically, segment lengths of 3, 6 and 9 meters were analyzed. The lengths and inclination angles of the pipe umbrella support used in the analysis are representative of typical engineering practice but were not modeled based on site-specific conditions. These parameters were chosen to perform a generic parametric analysis rather than reflect any particular real-world project. The flexibility of these parameters in the numerical model allows the study's findings to be generalized and applicable across a range of scenarios. The overlap between consecutive pipe segments varied, testing 1 meter, 2 meters, 3 meters, and 4 meters; however, certain overlaps were excluded from the analysis based on the segment length. Additionally, different stiffness of the pipe material (E) was tested by applying stiffness factors, namely 0.1 and 2.0 times the initial stiffness value (E).

## 3. INFLUENCE OF UMBRELLA SUPPORT PARAMETERS ON TUNNEL DEFORMATION

In the beginning, the numerical model was validated by comparing the longitudinal displacement profile (LDP) obtained from the FEM model with the profile derived from an empirical solution for an unsupported excavation (referenced in the Introduction, Eq. 1.1). The comparison indicates a high correlation between the numerical and empirical solutions under the specified conditions (material properties, tunnel geometry, and modelling approach). In the next step, the displacement profile for the unsupported excavation was compared with the profile obtained from the FEM analysis for an excavation supported with a pipe umbrella (using a segment length of 6 m and 1 m overlaps between sections). The comparison demonstrates that the application of the pipe umbrella leads to a noticeable reduction in displacement values, reducing the ultimate radial displacement from 0.149 m to 0.048 m. Furthermore, the displacement profile for the supported excavation was verified against the empirical solutions using (Eq. 1.2) and (Eq. 1.3). The agreement between the FEM results and the empirical solution confirms the reliability of the numerical model, making it a suitable tool for further parametric analysis of the pipe umbrella reinforcement system.

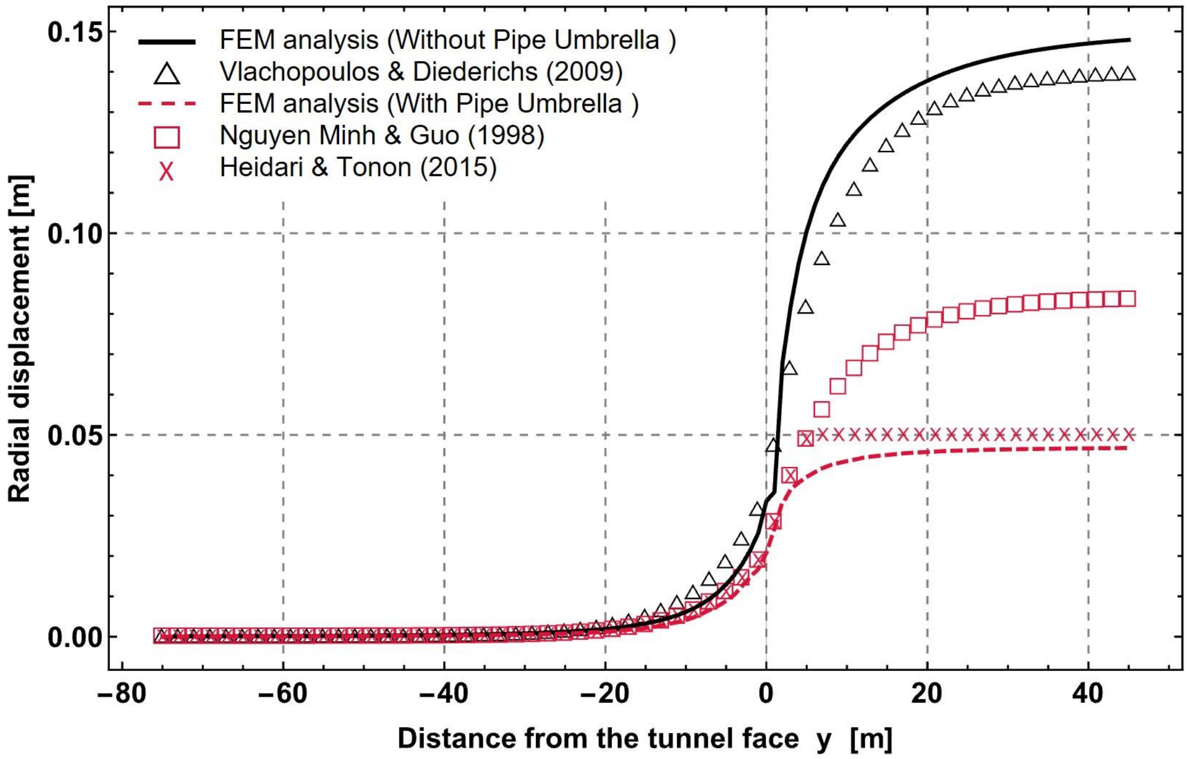


Fig. 6. Validation of the numerical model based on the LDP profile obtained through FEM analysis and profiles determined from analytical relationships

In the analysed case, the displacements around the excavation can also be observed in the displacement contour maps presented in Fig. 7. Graph shows that the pipe umbrella effectively confines and redistributes the stress around the tunnel, as evidenced by the tighter and less pronounced displacement contours. For the unsupported tunnel case the largest displacements occur along the crown of the excavation, particularly within 35 m from the advancing tunnel face, while for the case with the support displacement magnitude along the crown and near the advancing face is significantly reduced. Moreover, the pipe umbrella reduces displacement in the zone ahead of the tunnel face, as seen in Fig. 7b.

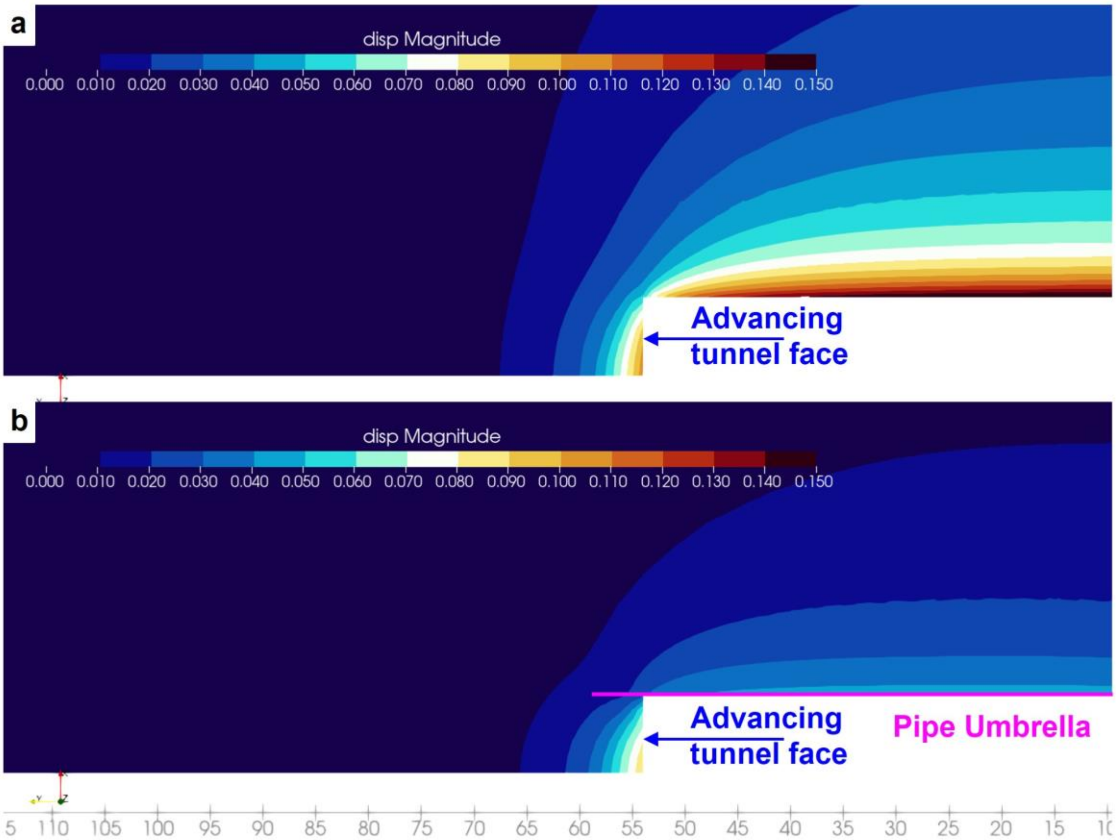


Fig. 7. Displacement distribution around the excavation without (a) and with umbrella support (b)

The validated model was then used to assess the influence of various pipe umbrella parameters on the degree of radial displacement reduction in the Longitudinal Displacement Profile (LDP). The effect of the umbrella reinforcement was analyzed in comparison to the unsupported rock mass using the Normalized Longitudinal Displacement Profile (NLDP). This is a commonly employed technique for presenting numerical results, where normalization involves dividing the displacements obtained with reinforcement by the maximum displacement in the respective direction at the observation point for the unsupported excavation case [32].

In Fig. 8 - Fig. 10 the black vertical axes represent the normalized radial displacement of the observation point (in the x-direction), while the colored vertical axes on the right-hand side of each plot correspond to the normalized axial displacement (in the y-direction). The horizontal axis shows the distance between the tunnel face and the observation point, expressed as a multiple of the tunnel diameter (2R = 15m). This normalized approach allows for direct comparison of the relative effectiveness of the pipe umbrella reinforcement under varying conditions.

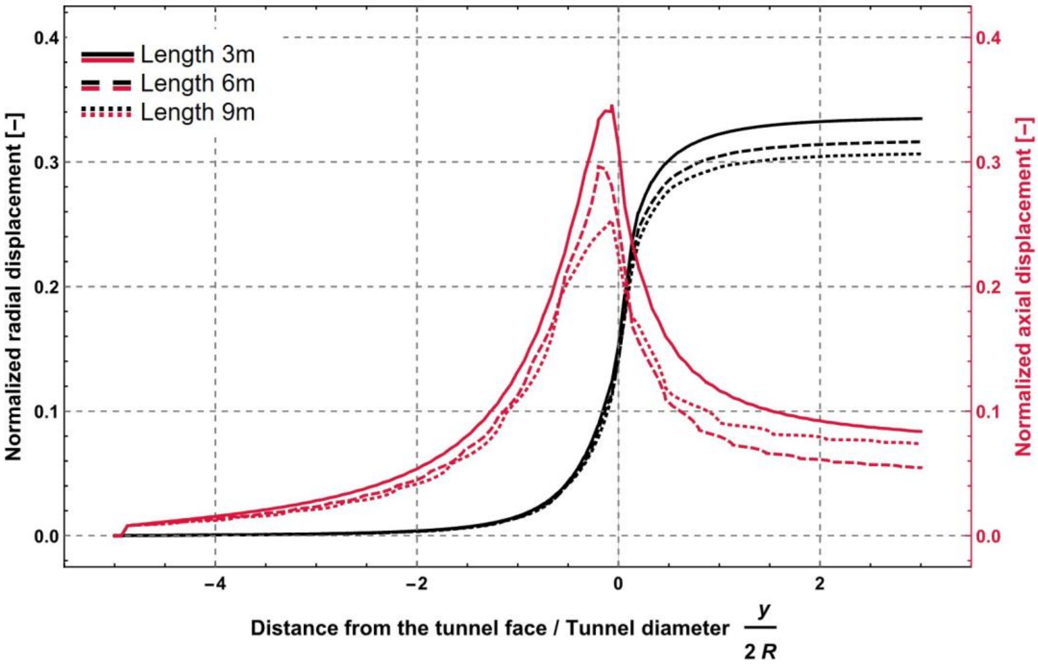


Fig. 8. Normalized radial and axial displacement profiles around the tunnel face for different pipe umbrella segment lengths (3 m, 6 m, and 9 m) with fixed overlap of 1m and baseline stiffness E

Fig. 8 presents the results of a parametric analysis examining the impact of the pipe umbrella length on the displacements of the control point in both the radial direction (x) and the axial direction (y). The monitored displacement profiles exhibit a well-established pattern, with displacement increasing as the distance approaches the tunnel face. Radial displacement peaks approximately 0.5 to 1 tunnel diameter behind the tunnel face, while axial displacement reaches its peak around 0.5 tunnel diameter ahead of the tunnel face. Both values taper off reaching final displacement values around 2 tunnel diameters behind the tunnel's face. The results indicate that the pipe umbrella support system achieves a significant reduction in displacement compared to the unsupported tunnel case. Specifically, the final reduction reaches nearly 70% for radial displacement and almost 90% in the axial direction behind the excavated tunnel face. The analysis reveals that the axial displacement range is more substantial than the radial one, with measurable axial displacement observed up to nearly 4 tunnel diameters ahead of the tunnel face. In contrast, radial displacement effects are more concentrated closer to the tunnel face, peaking within approximately 1 tunnel diameter and stabilizing more rapidly with increasing distance.

A similar approach was used to perform a parametric analysis of the impact of the overlap between individual pipe umbrella sections (Fig. 8) and the stiffness of the protective umbrella (Fig. 9) on the final deformation profile of the rock mass.

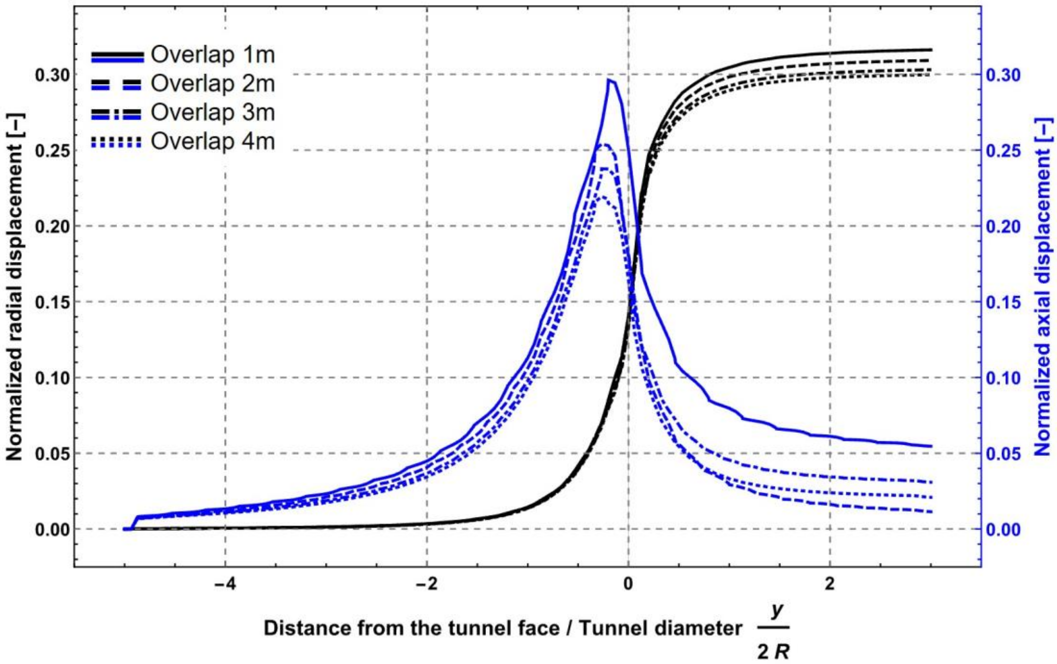


Fig. 9. Normalized radial and axial displacement profiles around the tunnel face for varying overlap distances between pipe umbrella segments (1 m, 2 m, 3 m, and 4 m) with a fixed umbrella segment length of 6 m and fixed baseline stiffness E

As the overlap distance between umbrella segments (each umbrella segment was modeled with the fixed length of 6 meters) increases from 1 m to 4 m, there is a moderate reduction in peak radial displacement, decreasing from 0.32 to 0.30 - a difference of approximately 2% between the 1 m and 4 m overlaps. In contrast, the axial displacement shows a more pronounced response to overlap changes. The 1-meter overlap configuration exhibits the highest peak axial displacement, indicating less effective deformation control. As the overlap increases to 2, 3, and eventually 4 meters, the peak axial displacement progressively decreases, with a significant difference of around 5% between the 1 m and 2 m overlaps in terms of final axial displacement.

As for the stiffness analysis the results indicate that increasing umbrella stiffness is effective up to a certain point, but further increases yield diminishing returns (Fig. 10). Increasing stiffness from 0.1E to E leads to a substantial reduction in radial and axial displacement, especially near the peak zones. However, further increasing the stiffness to 2E results in only a marginal reduction in observed displacements. The reduction in both radial and axial displacements is not proportional to the stiffness increase. These findings indicate that optimizing stiffness within a practical range is sufficient, as excessively high stiffness may not yield significant improvements in deformation reduction, highlighting the need for efficiency in design.

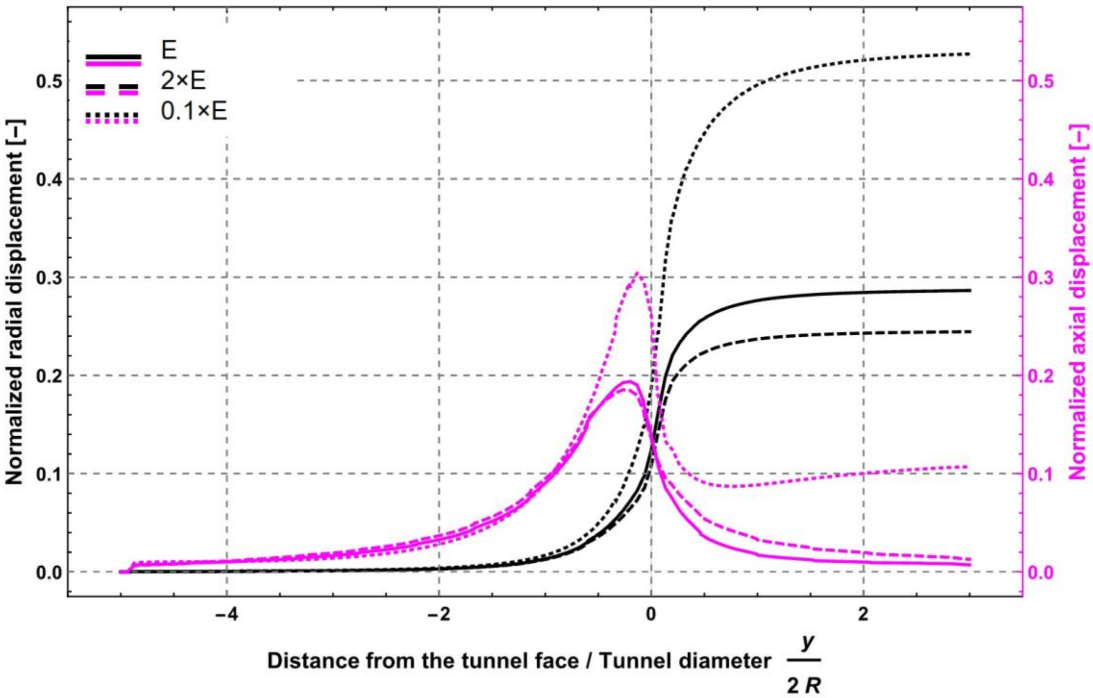


Fig. 10. Normalized radial and axial displacement profiles around the tunnel face for varying pipe umbrella stiffness values (E- baseline stiffness, 2E, 0.1E), with a fixed umbrella segment length of 9 m and a fixed overlap of 4 m

## 4. CONCLUSIONS

This study presents a theoretical analysis aimed at exploring the effectiveness of the pipe umbrella support system in reducing tunnel displacements within weak rock masses, using the Hoek-Brown failure criterion in a finite element model (FEM). The numerical analysis yielded the following conclusions:

- The implementation of the Hoek-Brown failure criterion allowed for a realistic representation of the rock- mass behavior, providing better predictions of how support systems impact tunnel stability, especially in fractured and heterogeneous geological conditions.
- The use of a pipe umbrella significantly reduces both radial and axial displacements along the tunnel axis (Fig. 6). Radial displacement reduction is most notable just behind the tunnel face, in the area where the permanent or temporary lining would ultimately be installed, which aligns with findings from other studies in the literature [33].
- Supporting the tunnel crown with a pipe umbrella also reduces radial displacement in the zone ahead of the tunnel face, indicating improved stability even before reaching the face itself (Fig. 7).
- Changes in the length of the umbrella segments have a more pronounced effect on radial displacement reduction than changes in segment overlap. This finding suggests that optimizing segment length may be more critical in reducing radial displacement, while overlap adjustments offer additional, but comparatively minor, benefits.

- The pipe umbrella also effectively reduces axial displacement along the excavation boundary. The analysis reveals that the axial displacement range extends further ahead of the tunnel face than the radial displacement range, with measurable axial displacement observed up to nearly 4 tunnel diameters ahead. In contrast, radial displacement effects are concentrated closer to the tunnel face, peaking within approximately 1 tunnel diameter and stabilizing more rapidly with increasing distance (Fig. 8, Fig. 10).
- Increasing the stiffness of the pipe umbrella results in substantial displacement reduction up to a certain point; however, further increases yield diminishing returns. This suggests that overly high stiffness values may not provide significant additional stability benefits and that an optimized range of stiffness values should be determined for practical and cost-effective design.
- Although not specifically analysed in this study, it is worth noting that tunnel diameter may have a significant impact on the effectiveness of pipe umbrella support. Larger tunnel diameters may require adjustments to segment length, overlap, and stiffness parameters to achieve similar levels of displacement control, highlighting the importance of scaling the support system relative to tunnel size.

## 5. DISCUSSION

While the study successfully demonstrates the potential of numerical modeling for parametric analyses, several simplifications and assumptions were made, which warrant a detailed discussion.

- **Theoretical Nature of the Analysis:** The analyses performed are purely theoretical and intended to assess the feasibility of applying FEM for the evaluation of tunnel support systems. The strength parameters of the rock mass were not directly determined through experimental methods or site-specific data but were adopted from a literature review. This approach allowed for a generalized parametric study, with the primary goal of identifying trends and relationships between support parameters and their effectiveness, rather than modeling a specific real-world case.
- **Simplification of Rock Mass Parameters:** The uniaxial compressive strength (UCS) of the rock was assumed to be 100 MPa, which corresponds to the intact rock strength rather than the properties of the in-situ rock mass. This was explicitly stated in the manuscript to avoid any confusion. The value of GSI = 21.4 was derived based on guidelines provided by Cai et al. [30],[31]. However, we recognize that it is appropriate to use values presented as a range, e.g., 20–30, or rounded to the nearest whole number.
- **Boundary Conditions and Hydrostatic Pressure:** The boundary conditions used in the axisymmetric FEM model assumed a hydrostatic pressure distribution (px = py = 7 MPa), and the overburden density was neglected ($\gamma = 0$ kN/m$^3$) [14],[12]. These assumptions were necessary to maintain symmetry about the tunnel's longitudinal axis, a requirement for implementing axisymmetric analysis. While this simplification facilitates efficient computation, it does not capture the anisotropic stress conditions typically encountered in the field. The assumed depth of the tunnel (approximately 260 meters) was used to estimate the hydrostatic pressure based on the weight of the overburden. We acknowledge that this approach limits the applicability of the results to more complex geological conditions and plan to incorporate non-hydrostatic stress fields and more realistic boundary conditions in future studies.
- **Validation of Numerical Models:** The validation of the FEM model was based on empirical relationships rather than field measurements. Empirical models, while generalized and simplified, provided a benchmark for ensuring the numerical model captured expected trends in

displacement behavior. This conservative approach was intended to verify the applicability of the modified Hoek-Brown criterion for weak rock masses. We acknowledge that field measurements would provide a more robust validation.

- **Applicability of Findings:** The results of this study demonstrate that simplified numerical modeling can be a valuable tool for assessing the effectiveness of underground support systems and guiding preliminary design decisions. However, the findings are far from representing real-world scenarios. Future research should incorporate:
  - Field measurements to validate numerical predictions.
  - Three-dimensional modeling to capture more complex stress fields.
  - Improved boundary conditions to better reflect in-situ conditions.

While this study demonstrates the utility of numerical modeling for evaluating tunnel support systems, it highlights the need for further refinement and validation. Especially future studies could benefit from validating the model's predictions with field monitoring data from similar projects. By addressing the limitations identified in this discussion, the authors anticipate further research on this topic, with the study expanded to explore other factors affecting support systems for tunnelling purposes.

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