

Geological models modifying the application of the term discontinuity and its importance in reducing costs in tunnel support

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ABSTRACT: While rock mechanics traditionally groups bedding, foliation, and joints as "discontinuities," this study focuses on their differentiated impact on tunnel support costs through stress-aware modeling. Building on established principles (e.g., joint development depends on stress redistribution), we demonstrate how explicitly accounting for this relationship in numerical models (FEM) enables cost-efficient design. Refraction microseismic tests map the decompressed zone (near-excavation) by tracking joint prevalence via seismic velocity gradients, revealing stress-dependent zonation. Our models incorporate strength recovery with distance from the excavation, proving that support costs can be reduced by 80% (3 m tunnels) and 30% (12 m tunnels) compared to conventional methods. Critical thresholds emerge: beyond 0.5D (3 m tunnels) to 1.0D (9 m tunnels), minimal support is needed as stress confinement restores. Critical decompressed zone thresholds were identified: for zones extending beyond 0.5D (3m tunnels) to 1.0D (9 m tunnels), additional increases in decompressed zone size no longer necessitate thicker supports, as confirmed by stabilization of lining thickness requirements in numerical analyses. This approach replaces lithology-based assumptions with stress-adaptive zonation, where support intensity aligns with mechanically verified zones—eliminating overdesign without compromising safety.

KEYWORDS: Discontinuity, cost optimization, decompressed zone, stress-adaptive design, tunnel support, numerical modeling.

1 INTRODUCTION

For any rock mass engineering project, understanding and distinguishing geological structures – joints, faults, bedding planes, and foliation planes, collectively termed "discontinuities" in geotechnical practice – is essential.

These features exhibit distinct mechanical behaviors under stress: joints are fractures without displacement, while faults involve relative block movement that alters contact zone mineralogy/grain size, creating polished surfaces often bounding disturbed material zones (breccia). See Figure 1.

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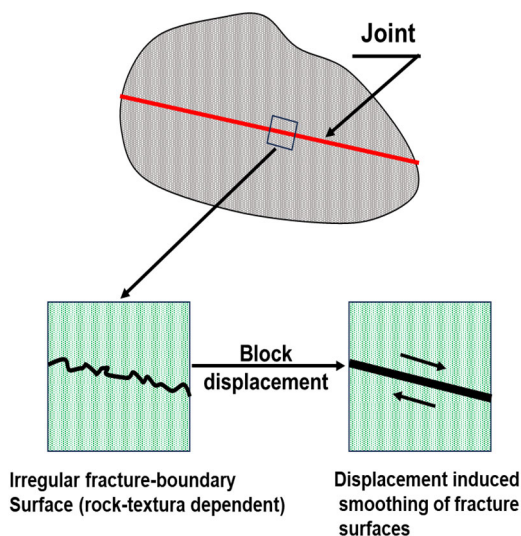


Figure 1. Effect of displacement on a joint plane, resulting in loss of irregularities along the original bounding surfaces of the rock blocks.

The displacement between blocks bounding geological faults is associated with reduced plane strength, typically

exhibiting significant extension when compared to limited-development joint planes. While these features are genetically distinct, their engineering significance emerges through stress-dependent interactions during excavation—a gap addressed by our zonation framework.

Notably, polished surfaces develop through inter-surface friction, making the term 'polished' inconsistent with the definition of joints (fractures without displacement). Joints are discontinuous planes that typically form patterned arrays in response to regional stresses, their development being governed by the rock mass stress state. As analyzed in publications (Naime and García, 2022; 2023; García and Naime, 2023; 2024a; 2024b), joint persistence and frequency depend on the massif's stress conditions. In underground excavations, while the intact rock remains unchanged, joint patterns may develop toward the tunnel periphery, forming a decompressed zone that gradually diminishes with distance from the opening.

2 JOINTS AND THEIR DEVELOPMENT

Fracturing patterns in rock masses show that persistence and frequency are stress-dependent, with all assessments being location-specific. Numerous cases exist where surface rock mass conditions exhibit intense fracturing, while borehole investigations or refraction seismic surveys demonstrate improved conditions with depth-related confinement. See Figure 2.

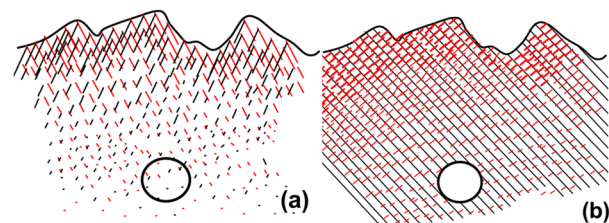


Figure 2. Representation of joint frequency reduction with increasing depth from ground surface in: (a) uniform igneous rock mass, and (b) layered sedimentary rock sequence.

In sedimentary rock masses with layered sequences, bedding planes exhibit extensive lateral continuity, forming

distinctive surfaces that typically constrain joint propagation between adjacent strata. This bedding-plane confinement of joints is well-documented in numerous field examples, particularly in spectacular geomorphological features such as Angel Falls (Venezuela) and the Dublin Cliffs (Ireland), where the vertical offset of bedding-delimited joint systems creates exceptionally steep, high-relief cliff faces, Figure 3:

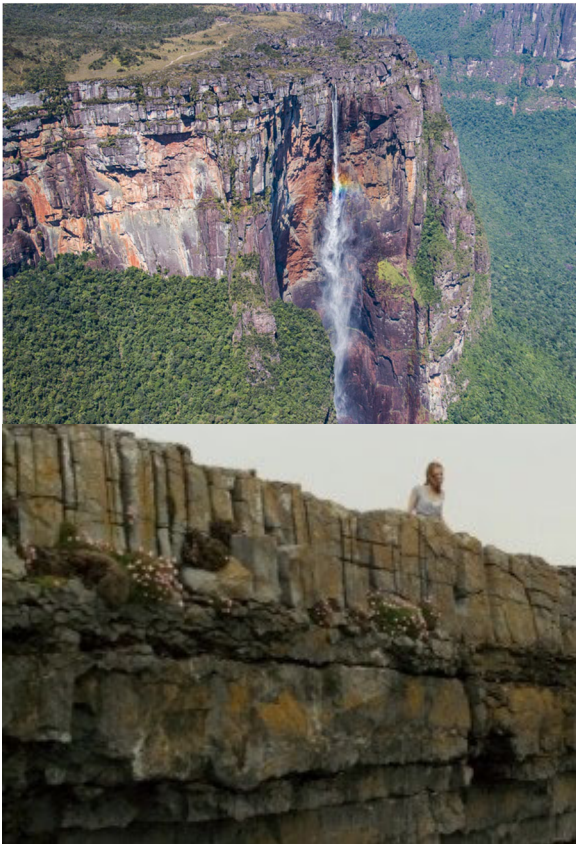


Figure 3. Vertical bedding-confined joints at Angel Falls, Venezuela (left), and Dublin Cliffs, Ireland (right). In both cases, joints exhibit horizontal offset across bedding planes.

Fracture patterns in rock masses depend on weathering effects and confinement conditions - reflecting the stress state and its temporal evolution. This relationship is particularly characteristic of sedimentary and metamorphic rocks. In sedimentary rock outcrops, additional controls are observed, with joint frequency showing strong correlation to bed thickness, as illustrated in Figure 4.

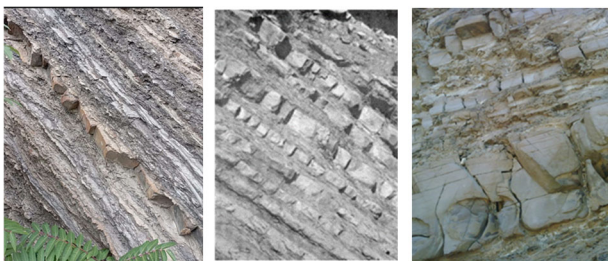


Figure 4. Sedimentary rocks demonstrating the inverse relationship between bed thickness and joint frequency.

In massive igneous rocks, joint patterns are fundamentally controlled by geological history, particularly past vertical loading conditions. Stress state modifications typically generate primary horizontal joint sets, as exemplified in the excavation slopes of the Tocoma Dam spillway channel (Bolívar State, Venezuela; see Figure 5.



Figure 5. Top: Excavation of the Tocoma Dam spillway channel (Bolívar State, Venezuela). Bottom: Close-up of an excavation face showing horizontal fracture planes delimiting vertical joint patterns.

The high joint density observed in the 30-m-high blast face (below the Caroní River thalweg level) decreases rapidly with confinement away from the excavation. Contrary to visual appearance, the rock mass exhibits negligible permeability, preventing water inflow into the excavation despite the prominent jointing shown in Figure 5.

The preceding examples underscore the importance of understanding joints and distinguishing them from other structural features like bedding planes and foliation. A high joint density does not, by itself, define rock mass quality.

3 ROCK MASS ZONATION AS A TUNNEL EXCAVATION ANALYSIS CRITERION

Tunnel support requirements fundamentally depend on rock mass quality. In excellent conditions, the excavation surface may be classified as intact, unfractured rock. The appearance of fractures results from decompression effects governed by the rock mass characteristics, with subsequent joint development showing decreasing persistence and frequency with distance from the excavation boundary.

The decompressed zone, a key consideration in tunnel support design, manifests through changes in joint density and strength variations governed by stress redistribution and established elastoplastic models. Figure 6 presents two schematic representations of excavation-induced decompression: one illustrating stress path evolution and another showing post-excavation seismic velocity measurements. This decompression process occurs through stress state modifications where joints play a pivotal role - reduced compressive stresses trigger rock mass microfracture dilation, leading to increased joint development and frequency near the excavation boundary.

Microseismic investigations demonstrate that wave velocities in rock masses increase with confinement, serving as

a diagnostic indicator of decompression effects and joint development.

Rock mass zonation for tunnel excavation analysis provides both a realistic assessment criterion and a practical tool for numerical modeling. The rock mass response to excavation differs significantly from uniformly decompressed conditions typically assumed in visual surface evaluations, as it accounts for confinement-dependent behavioral variations across distinct geomechanical zones.

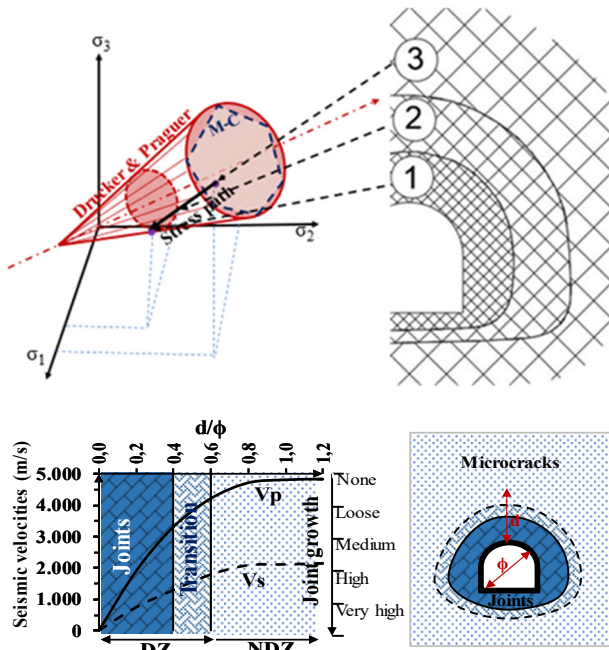


Figure 6. Top: Fracturing-confinement relationship under decompression stress paths. Bottom: Seismic velocity-fracturing correlation showing decompressed and transition zones toward undisturbed rock mass. Source: Naime & García (2022)

4 DECOMPRESSED AND ZONED DEFORMATION MODELS

In excavation faces where rock masses exhibit fracturing, joint planes typically appear unaltered and often display a characteristic sheen - a direct result of stress-induced fracture genesis within the rock mass.

Previous results (García, 2014) highlight the critical need to constrain face classification due to fracture systems. These systems characteristically show reduced development with increasing confinement, resulting in enhanced rock mass strength progression away from the excavation opening. Microseismic investigations provide an efficient method to verify these conditions through rock mass quality zonation, enabling optimized tunnel support designs without over-engineering when incorporated into computational models. As demonstrated in García (2014) using Phase2 software, as illustrated in Figure 7.

Adopting a radial zonation approach (transitioning from fair-to-poor rock mass conditions at the excavation boundary to fair-to-good conditions with increasing distance) reduces deformations by cost savings in tunnel reinforcement compared to conventional homogeneous assumptions.

Research by García & Naime (2023, 2024a, 2024b) and Naime & García (2022, 2023) demonstrates the critical need to define the decompression zone boundary through microseismic monitoring, rejecting its treatment as an intrinsic rock mass condition. Numerical validation confirms: (1) the stress-dependent correlation between fracture patterns and

confinement states, and (2) progressive strength recovery with increasing distance from excavation boundaries.

Figure 8 compares deformation values for unreinforced tunnels with horseshoe and circular sections, analyzing two scenarios:

Non-zoned, fully decompressed rock mass with uniform low shear strength. D is the tunnel diameter.

Zoned configuration featuring:

- 0.75D decompressed zone.
- 0.25D transition zone.

Undisturbed higher-strength rock beyond distance D from tunnel perimeter.

Key findings demonstrate an 80% reduction in maximum shortening in zoned models versus homogeneous cases.

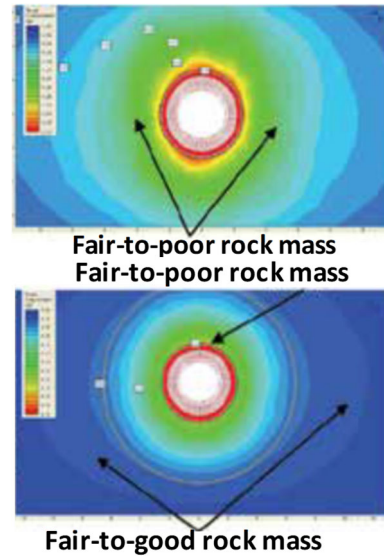


Figure 7. Reduction in deformation with increasing rock mass strength away from the excavation face. Source: García R. (2014).

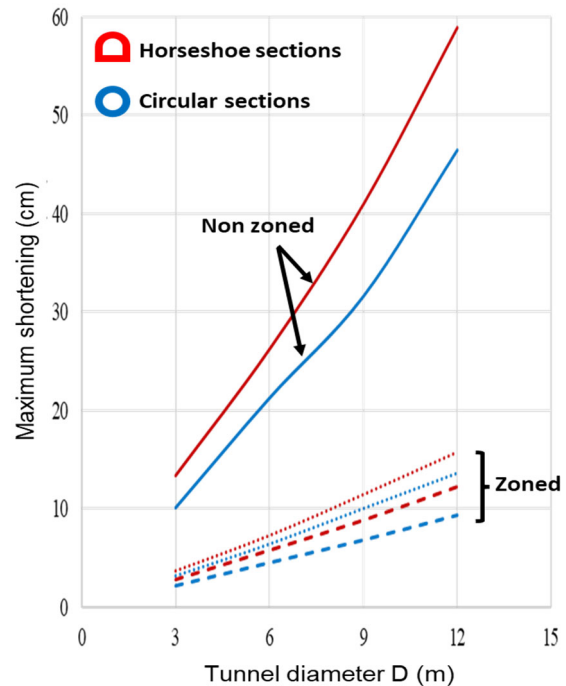


Figure 8. Deformation as a function of tunnel diameter and cross-section (horseshoe vs. circular) in unreinforced excavations: non-zoned to zoned configurations. Source: Naime & García (2024a)

5 DEFORMATION MODELS IN STRATIFIED ROCK MASSES

Empirical methods for rock mass quality assessment typically assume uniform geological structures affected by structural planes collectively termed "discontinuities." However, physical model studies since 1988 (using 2×2 cm ceramic square elements in 2D tunnel simulations) demonstrate that continuous planes – bedding planes in sedimentary rocks and foliation in metamorphic rocks – exert dominant control on rock mass deformations. These planes channel stress-induced displacements perpendicular to their orientation toward excavations, as validated through physical-kinematic modeling.

The research was augmented through mathematical modeling, yielding results congruent with those from physical modeling (Figure 9).

The continuous planes characteristic of sedimentary and metamorphic rock sequences control deformation patterns toward the excavation cavity, exhibiting a triangular distribution oriented perpendicularly to the tunnel perimeter.

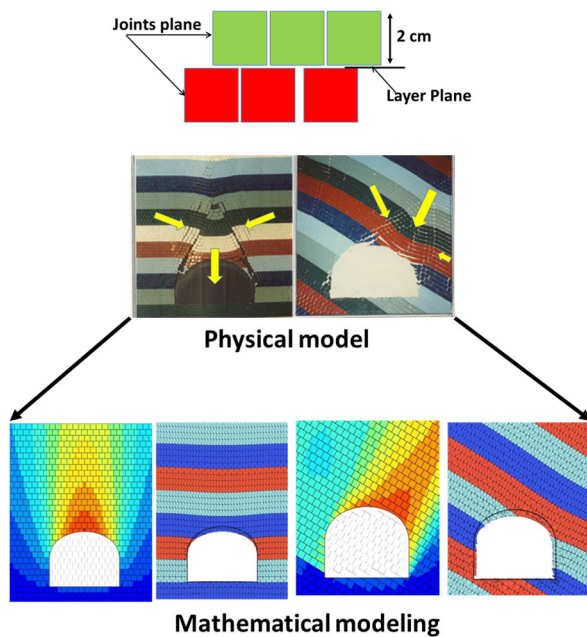


Figure 9. Two-dimensional deformation results from physical and mathematical tunnel models. Note the congruent outcomes showing cavity-directed deformation normal to structurally continuous planes, with characteristic triangular distribution patterns.

This research demonstrated that for rock masses controlled by continuous planes associated with layered sequences, the thickness-to-diameter ratio (T/D) significantly influences deformation response. Higher tunnel diameter-to-layer thickness ratios correlate with increased deformation. For instance, a 20 cm thick layer sequence provides greater structural resistance in a 3 m diameter tunnel compared to a 12 m diameter tunnel.

6 COSTS AND ROCK MASS ZONATION

Field observations at tunnel faces frequently reveal a tendency among technicians to assume that joint systems measured at ground surface represent working conditions throughout the entire rock mass. This assumption can lead to significant repercussions in support design, particularly in cost estimation and structural safety considerations.

Moreno (2013) conducted a comprehensive investigation on cost estimation for horseshoe-shaped tunnels using

Bieniawski's (1989) Rock Mass Rating (RMR) system. The study revealed a significant correlation between RMR variations and support costs, expressed through the following equation:

$$C_s = 20,234S - 81,468RMR + 4571,08 \quad (1)$$

Where:

Sc = unit support cost (USD/m or appropriate currency)

S = cross-sectional area (m²)

When accounting for fracture system attenuation with increasing distance from the excavation cavity, a weighted RMR assessment incorporating rock mass zonation becomes applicable. This approach yielded the comparative results shown in Figure 10, where a 35% RMR increase leads to support cost reductions of:

- 80% for small-diameter tunnels (vs. unzoned estimates)
- 30% for large-diameter tunnels

These savings demonstrate the economic impact of proper zoned RMR valuation in tunnel support design

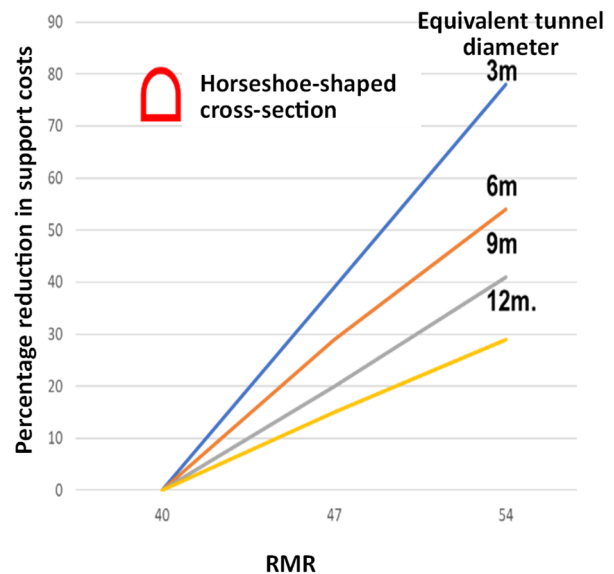


Figure 10. Deformation as a function of tunnel diameter and cross-section (horseshoe vs. circular) in unreinforced excavations: non-zoned to zoned configurations.

7 EFFECT OF DECOMPRESSED ZONE SIZE ON SUPPORT DESIGN FOR CIRCULAR-SECTION TUNNELS

This study analyzed stresses and deformations in circular tunnels (3, 5, 7, and 9 m diameters) using zoned numerical models in PLAXIS 2D with Python automation. The framework simulated three mechanically distinct zones: (1) intact medium-to-good quality rock, (2) a transition zone with partial strength recovery, and (3) a decompressed zone exhibiting significant strength reduction, employing Mohr-Coulomb parameters assigned based on engineering experience and consistent with microseismic refraction measurements of stress redistribution patterns. Systematic sensitivity analyses varied decompressed zone dimensions (0.1D to 2.0D, where D = tunnel diameter) and transition zone properties (0,1-0,2D) to evaluate their interactions with tunnel diameter and support requirements. The automated process generated characteristic curves to determine optimal concrete lining thicknesses while accounting for observed excavation-induced stress effects.

The results established that the transition zone has no significant impact, whereas the decompressed zone thickness

directly affects both lining thickness requirements and maximum rock mass deformations.

Figure 11 summarizes results from hundreds of numerical models, all simulating medium-to-good quality intact rock with significantly reduced parameters in the decompressed zone and intermediate values in the transition zone. The rock properties remained constant across all models, with only the decompressed and transition zone sizes being varied.

The most significant finding reveals that for each tunnel diameter, beyond a critical decompressed zone size, further increases in this zone's dimensions no longer affect the required reinforced concrete support thickness, which remains effectively constant.

Small increases in decompressed zone size (for small initial zones of 0.2–0.4D) significantly influence required support thickness. However, as the decompressed zone grows larger, additional size increments become progressively less influential until reaching a threshold beyond which their effect becomes negligible.

Figure 11 presents the critical decompressed zone sizes beyond which support design becomes unaffected by zone dimensions: 0.5D for 3 m-diameter tunnels and 1.0D for 9 m-diameter tunnels, with intermediate diameters following a natural-scale linear progression.

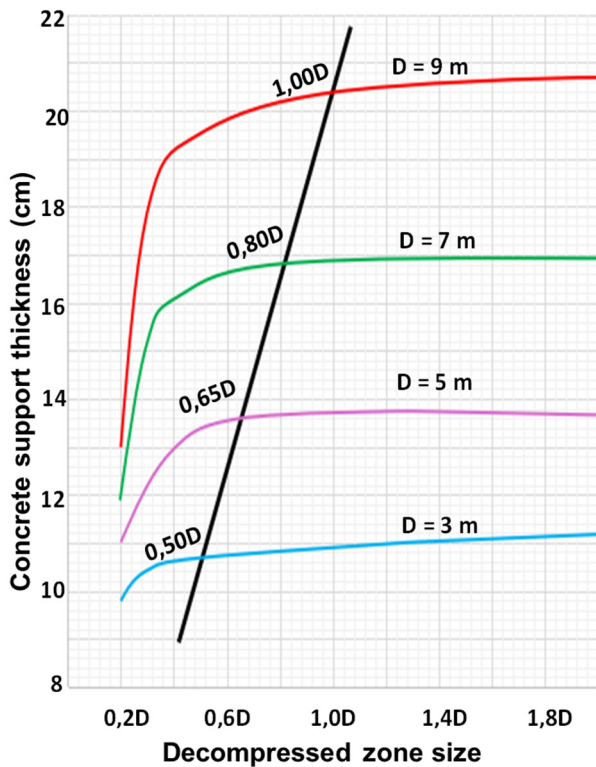


Figure 11. Required concrete support thickness as a function of decompressed zone size (normalized to tunnel diameter D) for circular tunnels. Results identify critical thresholds (0.5D for 3 m tunnels - 1.0D for 9 m tunnels) beyond which thickness stabilizes.

8 DISCUSSION

The term discontinuity, widely used in rock mass evaluation, requires special consideration in stratified or foliated masses where continuous formational planes govern cavity-directed deformations. Surface joint system measurements reflect a specific stress state and must be corrected using borehole core observations or microseismic testing. The in-situ stress state often markedly different from excavation face conditions

evolves during tunneling due to stress redistribution. This process modifies fracture patterns, which may initially mirror surface joint systems but become constrained by confinement effects. With increasing distance from the excavation face, the rock mass transitions to higher-strength behavior, enabling optimized (non-overdesigned) support systems.

In tunnel excavations, the rock mass at the perimeter may remain stable without developing a decompressed zone, provided the stress changes remain within the rock mass strength envelope. Conversely, stress variations that exceed this critical threshold inevitably trigger decompressed zone formation.

Zoned analysis for tunnel support design represents a straightforward technique that can be field-calibrated using geophysical measurements, enabling design optimization. This work presents a sensitivity analysis demonstrating how decompressed zone size influences support requirements, with the key finding that beyond a critical zone size, support design becomes minimally affected – establishing an upper limit for zoned analysis applications.

9 CONCLUSIONS

This study establishes that joint systems in rock masses are dynamic features governed by fracture development (including 'persistence'), spacing frequency, and—most critically—the evolving stress state and confinement conditions. The research demonstrates three principal advances:

This work establishes a mechanics-based framework for tunnel support design by delineating the decompressed-to-intact zone transition, with demonstrated stabilization of support demands when decompressed zones surpass 0.5D (3m tunnels) to 1.0D (9m tunnels) - delivering up to 80% cost reduction through non-conservative design limits while ensuring structural safety.

The zoned analysis approach leads to significant reductions in projected support costs compared to conventional RMR methods, while maintaining safety standards consistent with empirical observations (e.g., RMR-based designs), as it inherently adapts to stress redistribution and strength recovery.

Field-calibrated techniques (e.g., microseismic monitoring) validate that fracture networks evolve with confinement, supporting the need for adaptive design methodologies.

These findings shift support design from static classifications to a mechanics-based framework, where cost optimization aligns with geotechnical performance—a critical balance for modern tunneling projects.

10 RECOMMENDATIONS

This study highlights the need to refine the conventional discontinuity concept by explicitly distinguishing continuous formational planes - particularly bedding in sedimentary rocks and foliation in metamorphic rocks - given their demonstrated control on deformation patterns relative to tunnel alignment. Numerical models and field evidence confirm these structural features require separate treatment in support design.

The term 'discontinuity' warrants revision in geomechanical classification systems. It must acknowledge that joint development is governed by the in-situ stress state, and that persistence measurements on outcrops or excavation surfaces reflect fracture development under stress-relieved conditions—a condition intrinsically linked to spacing frequency.

A rock mass's joint systems are stress-relief features. Consequently, joint data from boreholes represents a confined mass, distinct from the conditions around a tunnel excavation.

It is, therefore, essential to differentiate these datasets, accounting for the new joint development induced by stress redistribution around the tunnel perimeter.

For practical implementation, prioritize microseismic monitoring over rigid prescriptive measures, as it captures real-time stress-fracture interactions. Field implementation should: (i) establish baseline conditions via microseismic surveys, (ii) apply diameter-dependent threshold checks (0.5D–1.0D), and (iii) dynamically update models with monitoring data ensuring design optimization throughout construction.

Future research should quantify orientation-dependent effects of continuous planes across wider geological settings, while developing classification systems that decouple their mechanical influence from random joint networks.

The proposed zoned analysis framework offers an adaptable solution, though its application should be guided by site-specific verification of decompressed zone thresholds through geophysical surveys rather than assumed universal values. This approach maintains design efficiency while respecting geological complexity.

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