Stability Evaluation of Rock Pillar Between Twin Tunnels Using Numerical Modelling

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Abstract

The stability of rock pillars between twin tunnels is a critical aspect of tunnel design and construction. To ensure the stability of rock pillars between twin tunnels, this study employ numerical modeling to assess pillar stability based on excavation method, tunnel geometry, determine pillar length based on rock mass quality, and quantify deformation, stress, and zone of influence of twin tunnels. To explore the role of rock mass quality in influencing pillar stability, the study considers factors such as rock strength, intactness, and discontinuity characteristics.

Numerical modeling simulates the excavation process, considering the effects of rock mass properties, insitu stress conditions, and excavation methods. The results of the numerical simulations provide valuable insights for optimizing rock pillar design and construction practices for twin tunnels.

Keywords: numerical modeling, rock pillars, twin tunnels, stability evaluation, joints and fractures and rock mass quality.

1. Introduction

In recent times, challenges related to land acquisition and community concerns have surfaced in tunnel planning. There is a growing social inclination towards preserving the natural environment, leading to an increase in cases where tunnels are planned with relatively short distances between them. This trend is particularly noticeable in urban areas where tunnel construction is on the rise. As construction projects become more complex and diverse over time, considerations such as route optimization, minimizing interference with existing structures, and addressing environmental concerns become increasingly important. To mitigate costs associated with land compensation, there is a growing emphasis on utilizing underground spaces, especially in densely populated urban areas. This approach aims to reduce the impact on the natural environment while also addressing issues like heat generation, minimizing noise pollution and civil complaints. One proposed solution is to construct parallel tunnels with narrow separation distances to optimize land usage and minimize environmental impact.

Recently, there has been a rise in the construction of parallel tunnels instead of single-bore tunnels due to increased traffic. In general, a minimum spacing of 1.0D (tunnel diameter) is recommended between parallel tunnels for stability. However, in urban areas, acquiring land for tunnel entrances is challenging due to space constraints and environmental regulations.

The stability of rock pillars separating twin tunnels is crucial for ensuring safe and efficient tunnel construction. Evaluating this stability becomes even more critical with decreasing pillar width and complex geological conditions. For proper infrastructure development, the utilization of underground space is more convenient and effective. Underground structures are particularly effective in mitigating the impact of seismic forces. Generally, it has been observed that there is a greater effect of seismic forces on the earth's surface than on underground structures.

Numerous studies have explored the effectiveness of shallow tunneling, the impact of loading, blast

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design, and their influence on stability in single tunnels. Additionally, geological conditions such as the presence of water, joints, fractures, and discontinuity characteristics have been extensively investigated. Due to various factors, including these geological conditions, it is often preferable to construct twin tunnels instead of larger single tunnels.

2. Input Parameter

The design of ground support and rock mass classification for tunnels in rock has been primarily an empirical process, based on preceding systems such as the Q-System (Barton, Lien, & Lunde, 1974), RMR Classification (Bieniawski Z. T., 1989), , RMi system (Palmstrom, 1996), and the I-system (Bineshian, 2020). This paper utilizes the Q System for rock mass classification, as it is widely used in many countries for rock mass characterization and sup-port design. The Q System has nine classifications, ranging from "Exceptionally Poor" to "Extremely Good," with values varying from 0.001 to 1000. For this research, Q values of 0.007, 0.02, 0.55, 5, and 50 were selected to cover the entire range of rock mass quality, from "Exceptionally Poor" to "Very Good. The rock properties were estimated using RSData software by adjusting the geological strength index (GSI) value for various rock classes and the tunnel depths of 152m is chosen . The geotechnical parameters assigned in this study are presented in Table 1.

3. Numerical Modelling

A plane strain model was developed in the finite element software RS2 to assess the impact on the pillar between twin tunnel under varying rock mass conditions and pillar width. A horseshoe- shaped tunnel profile with dimensions of 14m diameter and 10.1m in height was chosen. The model extended 15 times the tunnel diameter to minimize boundary effects on three sides and the depth from the ground surface was set at 152m. A uniform mesh surrounded the tunnel, while a graded mesh was assigned in other area. The solver type used was Gaussian elimination, with a maximum of 1500 iterations. Boundary conditions restrained movement in the X and Y directions from the bottom, with both sides restrained vertically and horizontally. The ground level was set as a free surface (free to move in both horizontal and vertical directions). The rock mass was characterized as a viscoelasticperfectly plastic material.

During tunnel construction, there is often a delay between excavation and support installation. Some stress is relieved before the supports are installed. For simplicity, this study assumes that 30% of the deformation occurs at the face, meaning 30% of the stress is released before support installation. The support consists of linear steel supports, with shotcrete 250 mm thick, installed after tunnel excavation.

For the sake of simplicity, a hydrostatic condition is assumed, where $\sigma 1 = \sigma 3 = \sigma z$, with $\sigma 1$ and $\sigma 3$ being the major and minor principal stresses in the 2D plane of the model, and σz be-ing the intermediate out-of-plane stress. The Hoek-Brown failure (Hoek & Carraanza-Torres, 2002) criterion has been selected for the analysis. The Clear Distance between Twin Tunnel (S): At 0.5D, D, and 2D where D is the diameter of single tunnel are taken for numerical modelling.

Numerical Modeling Steps for Tunnel Excavation:

Full-face (FF) excavation: The excavation of the right tunnel starts only after completing the cycle of the left tunnel, including the support installation as shown in Fig.1.

Table 1. Geotechnical Parameters for rockmas.

Q -value	GSI	GSIr	Erm	σcm	mi	mb	s	a
50	77	27	16843	10.50	28	16.387	0.189	0.5
5	61	27	10828	4.30	28	9.591	0.0357	0.501
0.55	35	22	2262	0.92	28	2.748	0.00073	0.516
0.02	18	14	727	0.19	28	1.345	0.000079	0.561
0.007	12	10	650	0.14	28	1.208	0.000057	0.575

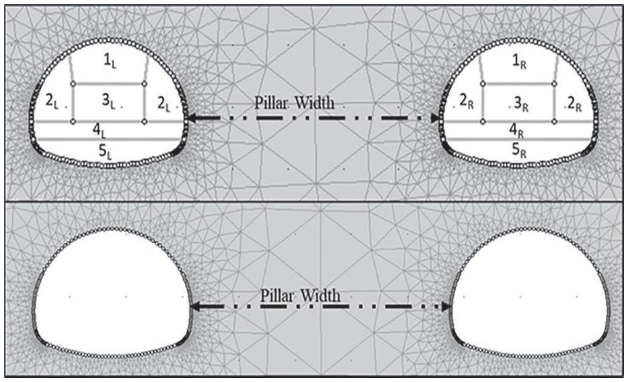

Fig. 1. Numerical model of tunnel.

Sequential Excavation (SE) method: The left tunnel is initially constructed in 5 stages. After completing the excavation and support installation of the left tunnel, the excavation of the right tunnel begins in 5 stages as shown in Fig.1. This approach reduces the face effect from excavation and also minimizes the vibration effect (Lunardi & Bindi, 2001).

4. Result and Discussions

4.1 Analysis of Excavation Methods and Induced Stress Reduction in Pillars

This study highlights significant findings regarding the induced stress reduction achieved through the Sequential Excavation (SE) method compared to full-face excavation in varying rock mass conditions. The results indicate that the SE method results in a reduction of in-duced stress by approximately 2% to 6%, 3% to 6% and 4% to 10%, for pillar widths of 0.5D, D, and 2D, respectively, across different Q values (0.007, 0.02, 5, and 50) as shown in Fig.2 a). A lower induced stress suggests a higher strength factor and a greater factor of safe-ty for the pillar and tunnel wall. This indicates that the Sequential Excavation (SE) method is more effective in reducing induced stress and enhancing the stability and safety of twin tun-nel constructions compared to full-face excavation in weak rock quality.

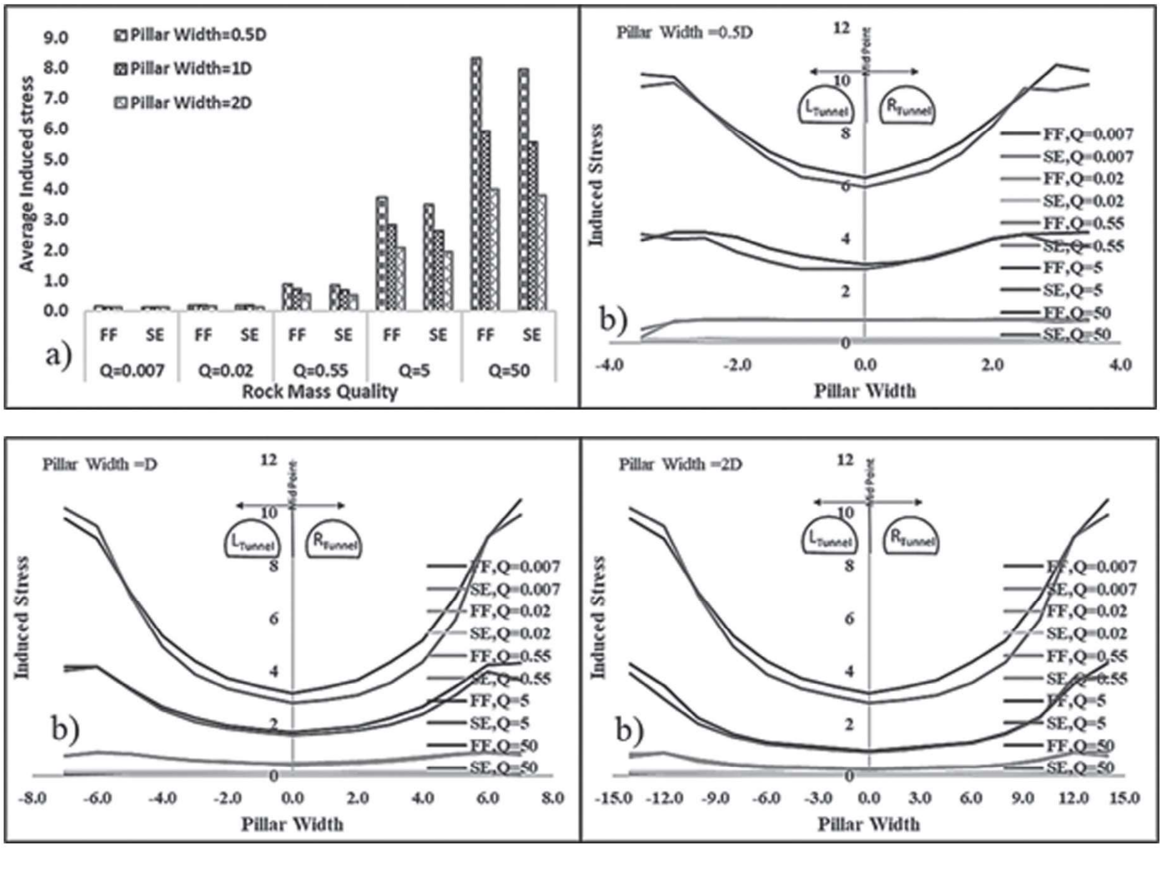

Fig. 2. a) Comparison of Average Induced Stress for Different Pillar Widths and Rock Mass Qualities under Full-Face and Sequential Excavation Methods. b) Induced Stress Distribution for Various Pillar Widths and Rock Mass Quality (Q) Values Using Full-Face and Sequential Excavation Methods.

This result suggest that in weak rock mass conditions (Q < 0.55), the full-face excavation method is less suitable due to insufficient stress reduction. Instead, the SE method should be employed to enhance stability. Conversely, in good rock mass conditions, where the variation in induced stress reduction is minimal, full-face excavation can be effectively utilized. For a pillar width of 0.5D, this analysis shows significantly higher induced stresses, making such narrow pillars inappropriate for weak rock masses with Q values less than 0.55.

This underscores the necessity for wider pillars in poor rock conditions to maintain structur-al integrity. Therefore, for poor rock mass conditions (Q < 0.55), SE should be the preferred excavation method to ensure the stability of twin tunnels and pillars. The pillar width should be greater than the tunnel diameter (D) to ensure stability, especially in weak rock masses.

From Fig.3, it is observed that the induced stress distribution is relatively uniform across all pillar widths; however, narrower pillars still exhibit higher stress levels during full-face exca-vation (FF). In contrast, sequential excavation (SE) shows marginally better stress distribution compared to FF

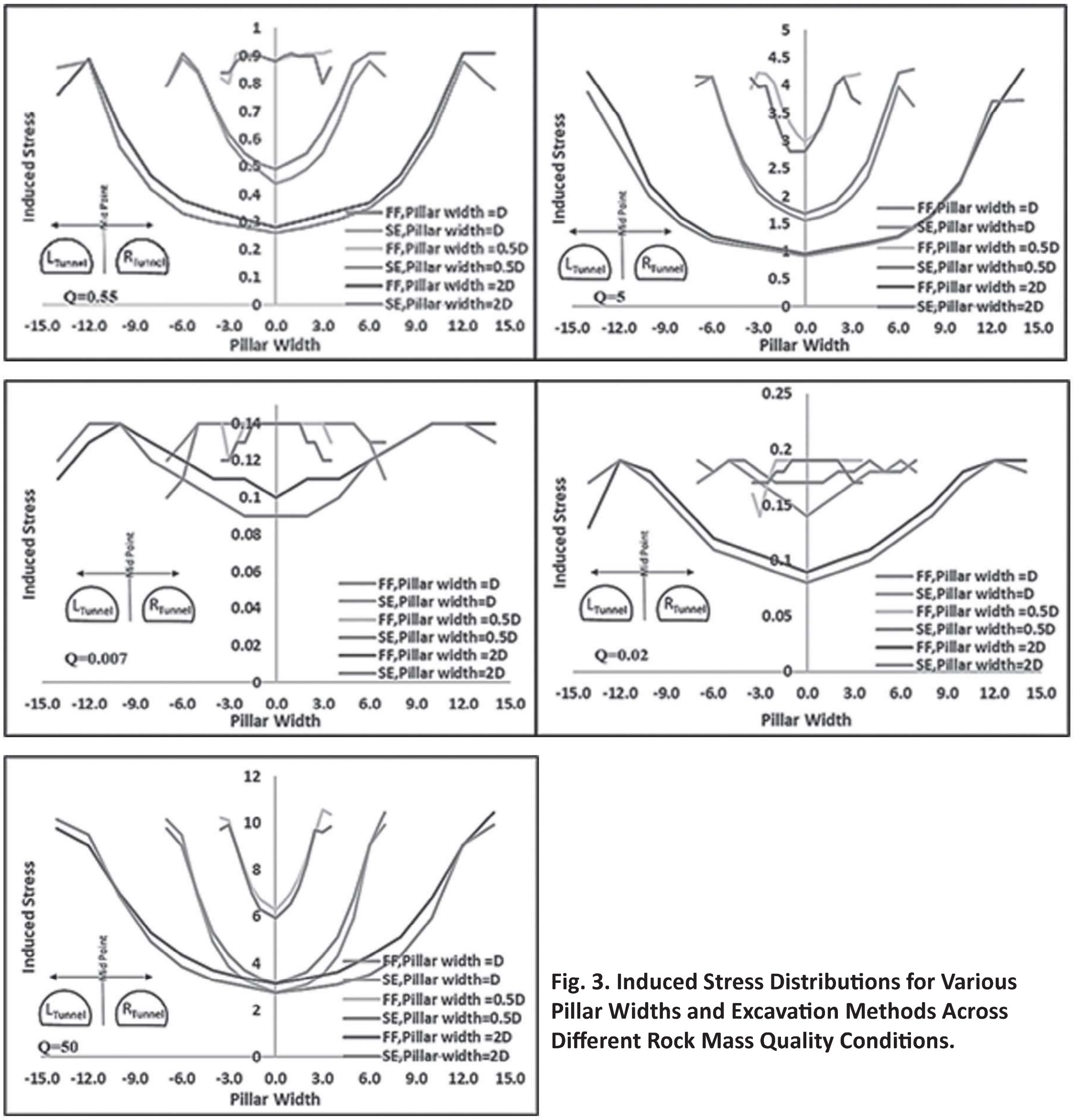

Fig. 3. Induced Stress Distributions for Various Pillar Widths and Excavation Methods Across Different Rock Mass Quality Conditions.

when Q=50 and 5. In weak rock masses, the induced stress is notably high, especially for the narrowest pillar width during FF, indicating significant instability when Q is less than 0.55. When SE is employed, the induced stress is effectively reduced across all pillar widths, with a significant difference seen in narrower pillars.

4.2 Stress Distribution and Zone of Influence on Pillar Width

The zone of influence defines the boundary beyond which the stress conditions are mini-mally affected by the excavation of the second tunnel. This segregation of the stress field into distinct zones allows for a more focused analysis and design considerations within the critical near-field region, potentially simplifying the overall design approach for twin tunnel projects (Goodman, 1989).

From Fig. 4, it is observed that when the pillar width is narrow and the rock mass condition is weak, the stress distribution becomes non-uniform, leading to high stress concentrations around the pillar width. For a lower pillar width (0.5D), the zone of influence due to the ex-cavation of the tunnel is evident at both tunnel boundaries. This necessitates careful design of the support capacity, considering the stress from the second tunnel on the first and vice versa, across all rock mass conditions.

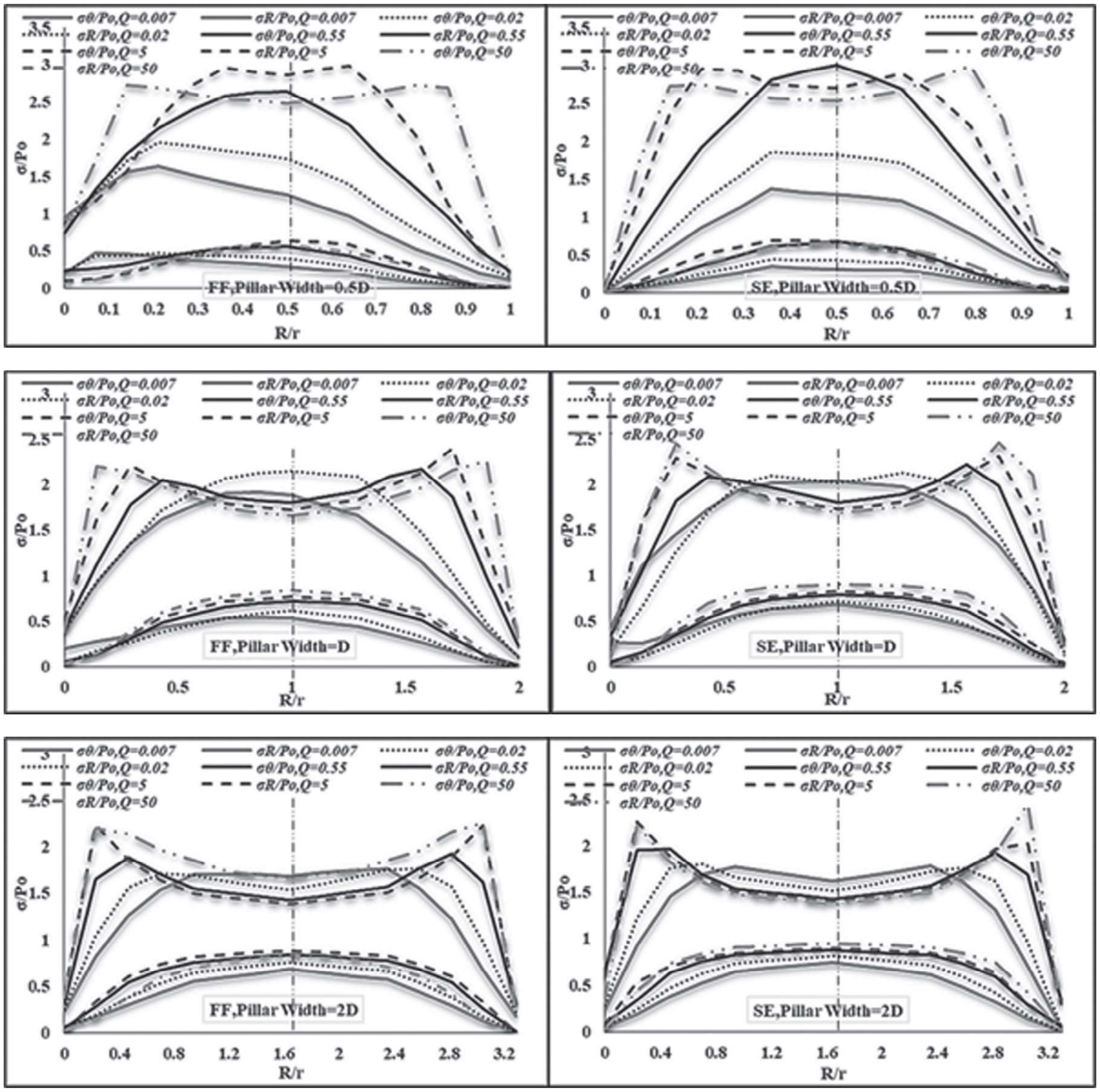

Fig. 4. Tangential and Radial Stress Distribution with Varying Rock Mass Quality, Different Excavation Methods, and Pillar Widths

Conversely, as the pillar width increases, the zone of influence is reduced. When the pillar width exceeds five times the tunnel diameter (i.e., pillar width = 5D), the stress effect due to the tunnel is minimized. This is evident in Fig. 4, where the tangential and radial stress curves tend to converge with increasing pillar width, indicating a reduced zone of influence.

Fig. 4 also shows that with the Sequential Excavation (SE) method, stress distribution is uniform across all rock mass conditions, and the zone of influence appears to be less than that of the full-face excavation method, particularly in weak rock masses (Q < 0.55). However, in the case of good rock mass conditions, both excavation methods exhibit similar stress distri-butions. Therefore, from this study, it can be concluded that the full-face excavation method can be effectively used in good rock mass conditions.

5. Conclusions

The sequential excavation method is more advantageous in terms of reducing induced stress, especially for poorer rock mass conditions and narrower pillar widths. For good rock mass conditions, the choice between the SE and FF methods may have a less significant im-pact on the induced stress, particularly for wider pillar widths.

The clear distance between horizontal twin tunnels must be greater than 2D in weak rock mass conditions. If the clear distance needs to be less than 2D, a well-designed support sys-tem, supplemented by additional support measures, is required. In good rock mass conditions, the distance can be equal to the tunnel diameter (D).

The pillar width and rock mass condition play crucial roles in the stability and safety of rock pillars between twin tunnels. These factors are essential for effective tunnel design and support system selection. By considering these aspects, engineers and designers can make informed decisions to ensure structural integrity, minimize risk, and optimize the excavation process.

The mutual stresses between the twin tunnels should be taken into account when designing support systems and assessing stability, particularly when they lie within each other's zone of influence.

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