

Assessment of Tunnel Stability under Varying Conditions Using Numerical Modelling

Mohd Sadiq Khan¹, Ashok Kumar Gupta², Anil Kumar Sahu³

¹Research Scholar - Department of Civil Engineering, Delhi Technological University, Delhi 110042, India

^{2,3}Professor, Department of Civil Engineering, Delhi Technological University, Delhi 110042, India

Emails: mohdsadiqkhan20@gmail.com¹, ak Gupta@dtu.ac.in², sahu anilkr@yahoo.co.in³

Abstract

The stability of underground openings is governed by a combination of geological, geometrical, and loading conditions, which may vary considerably along a tunnel alignment. Numerical modelling provides an effective means of examining these factors and assessing tunnel response before construction. The present study investigates the stability behaviour of underground tunnels under varying overburden depths and rock-mass conditions using numerical modelling. Particular attention is given to changes in tunnel deformation, stress redistribution, and yielded zones around the excavation. A series of two-dimensional numerical models was developed using PLAXIS 2D under plane-strain conditions. The Hoek–Brown failure criterion was adopted to represent the non-linear strength behaviour of the rock mass. The initial stress state was first established, after which the tunnel material was directly removed in the subsequent calculation phase to simulate full tunnel excavation. Overburden depths of 10–50 m and GSI values of 25–55 were considered. Circular, horseshoe, and D-shaped tunnel configurations were also analysed under selected ground conditions. Tunnel response was evaluated using maximum displacement, stress distribution, and the extent of plastic or yielded zones around the excavation. The numerical results show that increasing overburden generally leads to increased tunnel deformation and changes in stress distribution around the opening. Rock-mass quality also influences the magnitude of deformation and the development of yielded zones. Different tunnel configurations show different deformation and stress responses under comparable ground conditions. The study provides a simple numerical framework for evaluating tunnel stability under varying overburden, rock-mass quality, and tunnel configuration, and provides useful insights for preliminary assessment of underground excavation behaviour.

Keywords: Tunnel Stability, Numerical Modelling, Rock Mass, Tunnel Deformation, Stress Redistribution

1. Introduction

Tunnels are important components of modern infrastructure and are widely used for transportation, water supply, mining, and urban development. With increasing underground construction in complex ground conditions, maintaining tunnel stability has become an important concern. Tunnel excavation disturbs the existing stress state of the surrounding ground and causes stress redistribution and deformation around the opening. The resulting response depends on the characteristics of the surrounding rock mass, the depth of excavation, tunnel geometry, and the support conditions adopted (Hoek & Brown, 1980; Hoek et al., 2002). The stability of a tunnel is strongly influenced by the quality of the surrounding rock mass. Weak or highly fractured rock masses can undergo considerable deformation following excavation and may require

appropriate support to maintain stability. The Geological Strength Index (GSI) provides a practical approach for describing rock-mass quality and is widely used in conjunction with the generalized Hoek–Brown criterion to estimate rock-mass strength (Hoek & Brown, 1997; Hoek et al., 2002). The Hoek–Brown criterion is particularly suitable for rock engineering applications because it represents the nonlinear strength behaviour of rock masses and has been extensively applied to underground excavations. Overburden depth is another important factor affecting tunnel behaviour. As depth increases, the in-situ stresses acting around the tunnel generally increase, resulting in greater stress redistribution and potentially higher deformation. The relationship between rock-mass strength and the stresses induced by excavation is therefore important when assessing

tunnel stability. In addition, groundwater conditions can significantly influence tunnel response. Increased pore-water pressure may reduce effective stress within the surrounding rock mass and consequently affect its strength and deformation behaviour. These effects become particularly important when tunnels are constructed through weak or poor-quality rock masses. Tunnel geometry also influences the distribution of stresses around an underground opening. A circular section generally provides a relatively uniform stress distribution, whereas non-circular sections may develop localized stress concentrations depending on their shape. Previous studies have therefore considered tunnel shape and rock-mass behaviour as important factors in underground excavation design. The selection of an appropriate geometry, together with an adequate support system, can help control deformation and improve tunnel performance. Numerical modelling provides an effective method for studying tunnel behaviour because different ground and construction conditions can be investigated without the cost and practical limitations associated with full-scale field studies. Numerical approaches can simulate excavation stages, stress redistribution, deformation, groundwater effects, and the interaction between the surrounding rock mass and support system. In particular, finite element modelling has become a useful tool for evaluating the response of underground openings under different loading and ground conditions. Although individual factors affecting tunnel stability have been extensively studied, a simple and systematic assessment considering the combined effects of overburden depth, rock-mass quality, tunnel geometry, groundwater, and support conditions is useful for preliminary tunnel design. Therefore, the present study uses PLAXIS 2D to assess tunnel stability under selected variations in these conditions. Tunnel displacement, stress distribution, and plastic zones are considered as the primary indicators of tunnel response. The study aims to identify the conditions that have a significant influence on tunnel behaviour and to provide practical insights for safer and more informed tunnel design.

2. Methodology

A two-dimensional finite element approach was adopted to assess tunnel stability under varying ground and loading conditions. Numerical analyses were performed using PLAXIS 2D under plane-strain conditions. The surrounding rock mass was represented using the Hoek–Brown failure criterion, which is widely used to describe the non-linear strength behaviour of rock masses (Hoek, Carranza-Torres, & Corkum, 2002). Appropriate model dimensions and boundary conditions were adopted to minimize boundary effects.

The methodology involved the following key steps:

- Numerical model development: A representative two-dimensional tunnel model was developed in PLAXIS 2D with appropriate rock-mass properties, boundary conditions, and initial stresses[1].
- Rock-mass characterization: The rock mass was modelled using the Hoek–Brown failure criterion. GSI values of 25, 35, 45, and 55 were considered to represent different rock-mass qualities[2].
- Overburden variation: Overburden depths of 10, 20, 30, 40, and 50 m were considered to examine the effect of increasing overburden on tunnel response[3].
- Tunnel configuration: Three tunnel configurations—circular, horseshoe, and D-shaped—were considered for comparative assessment of deformation and stress response.
- Initial stress generation: The initial stress state was established using the gravity loading procedure with an appropriate lateral stress coefficient corresponding to the selected ground conditions.
- Tunnel excavation: After establishing the initial stress state, the material within the tunnel opening was directly removed in the subsequent calculation phase to simulate full tunnel excavation. This approach was used to evaluate the immediate redistribution of stresses and deformation around the excavated opening.
- Performance indicators: Tunnel response was evaluated using:

- Maximum displacement
- Stress distribution and concentration
- Plastic/yielded zones around the tunnel opening
- Comparative assessment: The numerical results were compared to examine the influence of overburden depth, rock-mass quality, and tunnel configuration on tunnel stability and deformation behaviour.

2.1. Tables

As shown in Table 1 Input parameters for Plaxis 2D (Mohd Sadiq Khan et al., 2026) Table 2 Maximum Deformation under Varying GSI, Tunnel Shape, and Overburden Depth Table 3 Maximum Principal Stress under Varying GSI, Tunnel Shape, and Overburden Depth Figure 1 Maximum Deformation under Varying Tunnel Shape, GSI and Overburden Depth[4 – 11].

Table 1 Input parameters for Plaxis 2D
(Mohd Sadiq Khan et al., 2026)

Rock Parameters	Values	Lining Parameters	Values
UCS	35 MPa	Concrete Material	Elastic
mi	25	Isotropic	Yes
Poisson's ratio (μ)	0.3	Poisson's ratio (μ)	0.15
Unit weight (γ)	26 kN/m ³	Unit weight (γ)	8.4 kN/m/m
Deformation Modulus (E) for rock mass	1487 MPa	Bending stiffness	0.14×10^6 kN-m ² /m
GSI	25,35, 45,55	Axial stiffness	14×10^6 kN/m

Table 2 Maximum Deformation under Varying GSI, Tunnel Shape, and Overburden Depth

Dep th (m)	Circu lar GSI 25	Circu lar GSI 35	Circu lar GSI 45	Circu lar GSI 55	D-shap ed GSI 25	D-shap ed GSI 35	D-shap ed GSI 45	D-shap ed GSI 55	Horses hoe GSI 25	Horses hoe GSI 35	Horses hoe GSI 45	Horses hoe GSI 55
10	0.9158	0.9156	0.9156	0.9156	5.688	5.399	4.93	4.008	1.341	1.311	1.257	1.203
20	1.124	1.124	1.124	1.124	9.152	8.874	8.327	7.302	1.927	1.901	1.826	1.69
30	1.353	1.353	1.353	1.353	12.81	12.57	12.06	11.05	2.483	2.487	2.413	2.261
40	1.576	1.576	1.576	1.576	16.36	16.05	15.51	14.49	2.938	2.937	2.897	2.741
50	1.77	1.77	1.77	1.77	19.81	19.57	18.98	18.01	3.43	3.484	3.435	3.27

Table 3 Maximum Principal Stress under Varying GSI, Tunnel Shape, and Overburden Depth

Dep th (m)	Circul ar GSI 25	Circul ar GSI 35	Circul ar GSI 45	Circul ar GSI 55	D- shap ed GSI 25	D- shap ed GSI 35	D- shap ed GSI 45	D- shap ed GSI 55	Horsesh oe GSI 25	Horsesh oe GSI 35	Horsesh oe GSI 45	Horsesh oe GSI 55
10	4.897	7.215	7.215	7.215	4.72	10.26	22.03	46.99	4.897	10.29	22.02	46.92
20	0.942	0.942	0.942	0.942	4.638	10.03	21.83	46.85	4.544	10.15	21.94	46.88
30	-	-	-	-	4.835	10.26	21.92	46.84	4.647	10.09	21.88	46.85
40	0.935	0.935	0.935	0.935	4.763	10.15	21.79	46.68	4.471	9.822	21.68	46.75
50	1.027	1.027	1.027	1.027	4.748	10.13	21.72	46.61	4.585	9.667	21.5	46.54

2.2. Figures

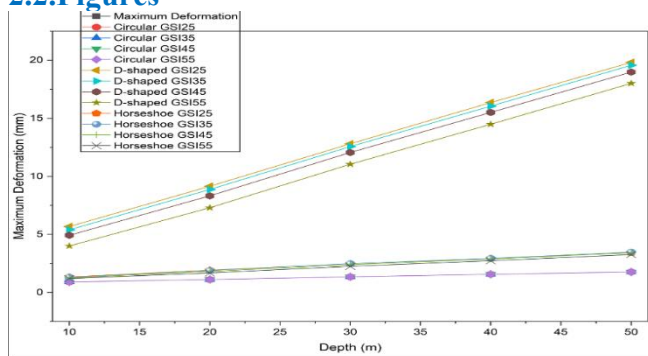


Figure 1 Maximum Deformation under Varying Tunnel Shape, GSI and Overburden Depth

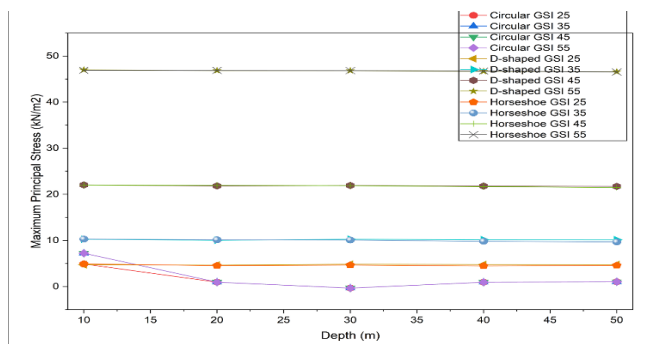


Figure 2 Maximum Principal Stress under Varying Tunnel Shape, GSI and Overburden Depth

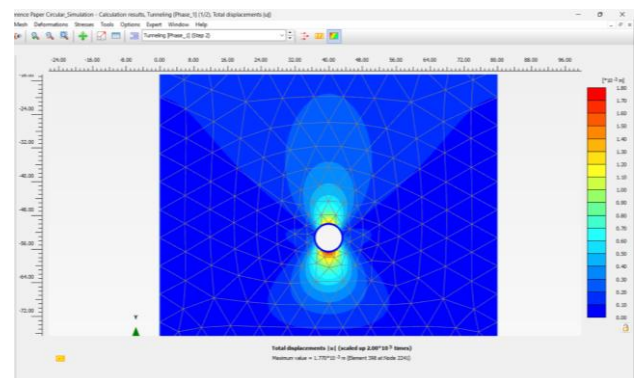


Figure 3 Deformation of the Circular tunnel at a depth of 50 m for GSI = 45 in PLAXIS 2D

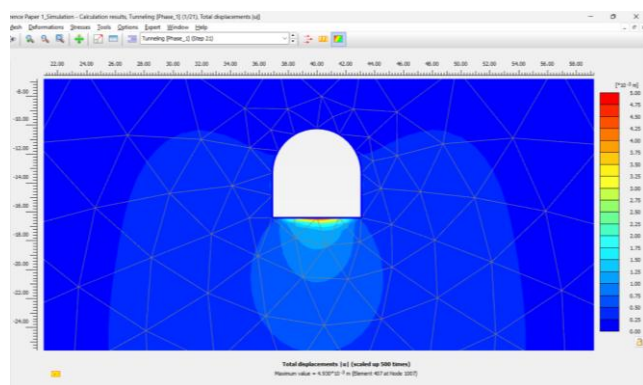


Figure 4 Deformation of the D-shaped tunnel at a depth of 10 m for GSI = 45 in PLAXIS 2D

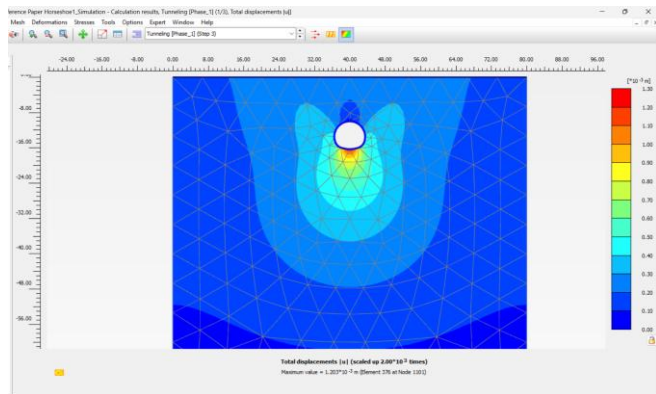


Figure 5 Deformation of the Horseshoe tunnel at a depth of 10 m for GSI = 55 in PLAXIS 2D

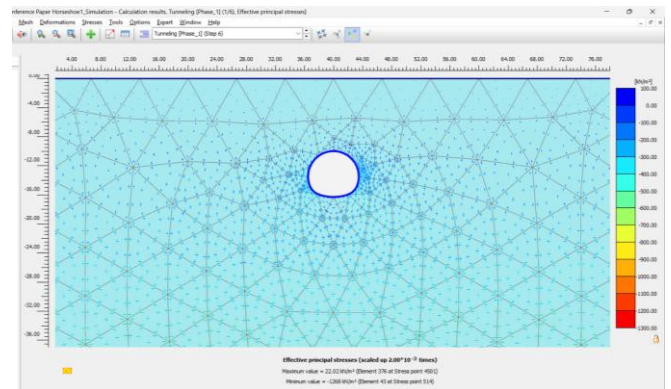


Figure 8 Maximum Principal Stress of the Horseshoe tunnel at a depth of 10 m for GSI = 45 in PLAXIS 2D

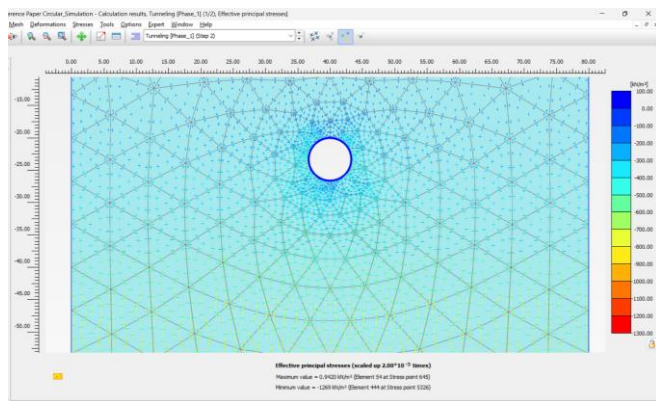


Figure 6 Maximum Principal Stress of the D shaped tunnel at a depth of 20 m for all GSI in PLAXIS 2D

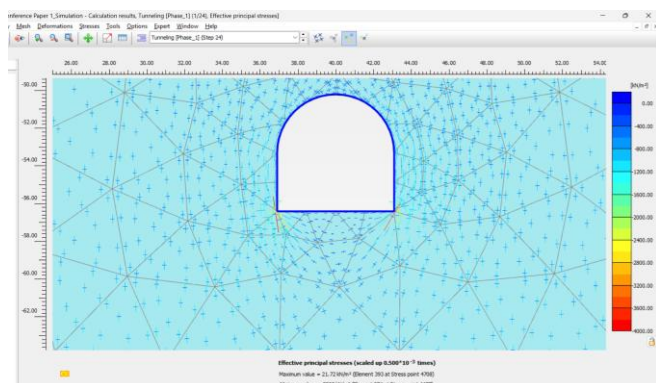


Figure 7 Maximum Principal Stress of the D shaped tunnel at a depth of 50 m for GSI = 45 in PLAXIS 2D

3. Results And Discussion

3.1. Results

The numerical analysis was performed for circular, D-shaped, and horseshoe tunnels at overburden depths of 10, 20, 30, 40, and 50 m. The effect of rock-mass quality was studied using GSI values of 25, 35, 45, and 55. The main results considered were maximum deformation and maximum principal stress. As shown in Figure 2 Maximum Principal Stress under Varying Tunnel Shape, GSI and Overburden Depth, Figure 3 Deformation of the Circular tunnel at a depth of 50 m for GSI, Figure 5 Deformation of the Horseshoe tunnel at a depth of 10 m for GSI = 55 in PLAXIS 2D, Figure 6 Maximum Principal Stress of the D shaped tunnel at a depth of 20 m for all GSI in PLAXIS 2D, Figure 7 Maximum Principal Stress of the D shaped tunnel at a depth of 50 m for GSI = 45 in PLAXIS 2D, Figure 8 Maximum Principal Stress of the Horseshoe tunnel at a depth of 10 m for GSI = 45 in PLAXIS 2D.

3.1.1. Maximum Deformation

The maximum deformation increased with increasing overburden depth for all three tunnel configurations. At GSI = 35, the circular tunnel showed deformation from 0.916 mm at 10 m to 1.77 mm at 50 m. For the D-shaped tunnel, deformation increased from 5.399 mm to 19.57 mm, while the horseshoe tunnel increased from 1.311 mm to 3.484 mm. At GSI = 25, the D-shaped tunnel deformation increased from 5.688 mm at 10 m to 19.81 mm at 50 m, while the horseshoe tunnel increased from 1.341 mm to 3.43

mm. At GSI = 55, the corresponding deformation for the D-shaped tunnel increased from 4.008 mm to 18.01 mm, while the horseshoe tunnel increased from 1.203 mm to 3.27 mm. Overall, the D-shaped tunnel recorded the highest deformation for most of the analysed conditions, followed by the horseshoe tunnel, while the circular tunnel showed the lowest deformation.

3.1.2. Maximum Principal Stress

The maximum principal stress also varied with tunnel configuration and GSI. At GSI = 35, the D-shaped tunnel showed stress values between 10.03 and 10.26 kN/m², while the horseshoe tunnel showed values between 9.667 and 10.29 kN/m² over the investigated depth range. For GSI = 25, the maximum principal stress for the D-shaped tunnel varied from 4.638 to 4.835 kN/m², whereas for the horseshoe tunnel it varied from 4.471 to 4.897 kN/m². At GSI = 55, the D-shaped tunnel showed much higher values, ranging from 46.61 to 46.99 kN/m², while the horseshoe tunnel ranged from 46.54 to 46.92 kN/m². The circular tunnel showed comparatively smaller principal stress values in the analyzed models, with values varying with depth and GSI.

3.2. Discussion

The results show that overburden depth has a clear effect on tunnel deformation. As the depth increased from 10 to 50 m, deformation increased for all three tunnel configurations. This behaviour is expected because a greater overburden produces higher loading on the tunnel opening. Tunnel shape also had a noticeable effect on the deformation response. The D-shaped tunnel generally showed the largest deformation, whereas the circular tunnel showed the smallest deformation. The horseshoe tunnel produced an intermediate response. The larger deformation observed for the D-shaped tunnel indicates that the shape of the excavation influences the redistribution of stresses and the resulting deformation around the opening. The effect of GSI was more noticeable for the D-shaped and horseshoe tunnels. In general, higher GSI values were associated with lower deformation. For example, at 50 m depth, D-shaped tunnel deformation decreased from 19.81 mm at GSI = 25 to 18.01 mm at GSI = 55. This indicates that better-quality rock mass can provide greater

resistance to deformation. The principal stress results show a strong variation with GSI. Higher GSI values resulted in considerably higher maximum principal stress values around the D-shaped and horseshoe tunnels. This suggests that stronger rock masses are able to carry and redistribute greater stresses around the excavation. Therefore, deformation and stress should be considered together when assessing tunnel response rather than relying on either parameter alone. Overall, the numerical study indicates that overburden depth, rock-mass quality, and tunnel configuration all influence tunnel behaviour. Among the configurations studied, the D-shaped tunnel showed the greatest deformation, while the circular tunnel showed the lowest deformation under the analysed conditions.

Conclusion

The present study evaluated the stability behaviour of circular, D-shaped, and horseshoe tunnels under different overburden depths and rock-mass qualities using PLAXIS 2D. Based on the numerical results, the following conclusions were drawn:

- Tunnel deformation increased with increasing overburden depth for all three tunnel configurations. The increase was particularly noticeable for the D-shaped tunnel.
- Tunnel configuration had a clear influence on deformation behaviour. The D-shaped tunnel generally showed the highest deformation, followed by the horseshoe tunnel, while the circular tunnel showed the lowest deformation under the analysed conditions.
- Rock-mass quality affected tunnel deformation, particularly for the D-shaped and horseshoe tunnels. In general, higher GSI values resulted in lower deformation around the tunnel opening. In comparison, the circular tunnel showed very little change in deformation with variation in GSI, indicating relatively low sensitivity of the circular section to changes in rock-mass quality under the analysed conditions.
- The maximum principal stress varied considerably with GSI, especially for the D-

shaped and horseshoe tunnels. Higher GSI values resulted in higher maximum principal stress values around the excavation.

- The results indicate that overburden depth, rock-mass quality, and tunnel configuration should be considered together when assessing the response of underground excavations.

Overall, the study demonstrates that numerical modelling using PLAXIS 2D can provide a simple and useful approach for understanding tunnel deformation and stress behaviour under different ground conditions. The findings can be useful for the preliminary assessment and selection of suitable tunnel configurations.

Acknowledgements

I sincerely acknowledge the support and guidance received throughout this research work. I am grateful to my supervisors in the Department of Civil Engineering for their valuable suggestions, constructive feedback, and technical guidance. Their continuous support and encouragement contributed significantly to the completion of this study.

References

- [1]. Hoek, E., & Brown, E. T. (1980). Empirical strength criterion for rock masses. *Journal of the Geotechnical Engineering Division*, 106(9), 1013–1035. <https://doi.org/10.1061/AJGEB6.0001029>
- [2]. Hoek, E., & Brown, E. T. (1997). Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences*, 34(8), 1165–1186. [https://doi.org/10.1016/S1365-1609\(97\)80069-X](https://doi.org/10.1016/S1365-1609(97)80069-X)
- [3]. Hoek, E., Carranza-Torres, C., & Corkum, B. (2002). Hoek–Brown failure criterion—2002 edition. In *Proceedings of the 5th North American Rock Mechanics Symposium and 17th Tunnelling Association of Canada Conference* (pp. 267–273). Toronto, Canada.
- [4]. Hoek, E., & Brown, E. T. (2019). The Hoek–Brown failure criterion and GSI—2018 edition. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(3), 445–463. <https://doi.org/10.1016/j.jrmge.2018.08.001>
- [5]. Carranza-Torres, C., & Fairhurst, C. (1999). The elasto-plastic response of underground excavations in rock masses that satisfy the Hoek–Brown failure criterion. *International Journal of Rock Mechanics and Mining Sciences*, 36(6), 777–809.
- [6]. Carranza-Torres, C., & Fairhurst, C. (2000). Application of the convergence-confinement method of tunnel design to rock masses that satisfy the Hoek–Brown failure criterion. *Tunnelling and Underground Space Technology*.
- [7]. Hoek, E. (1983). Strength of jointed rock masses. *Géotechnique*, 33(3), 187–223. <https://doi.org/10.1680/geot.1983.33.3.187>
- [8]. Hoek, E. (1990). Estimating Mohr–Coulomb friction and cohesion values from the Hoek–Brown failure criterion. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, 27(3), 227–229. [https://doi.org/10.1016/0148-9062\(90\)94333-O](https://doi.org/10.1016/0148-9062(90)94333-O)
- [9]. Zuo, J., Liu, H., & Li, H. (2015). A theoretical derivation of the Hoek–Brown failure criterion for rock materials. *Journal of Rock Mechanics and Geotechnical Engineering*, 7(4), 361–366. <https://doi.org/10.1016/j.jrmge.2015.03.008>
- [10]. Zhang, Q., Liu, J., & Zhao, J. (2018). Numerical analysis of stability of different tunnel shapes in jointed rock masses. *Tunnelling and Underground Space Technology*, 78, 65–75. <https://doi.org/10.1016/j.tust.2018.03.022>
- [11]. Mohd Sadiq Khan, Ashok Kumar Gupta, & Anil Kumar Sahu. (2026). Influence of tunnel geometry on collapse behaviour: A numerical study. *International Research Journal on Advanced Engineering Hub (IRJAEH)*, 4(03), 1100–1104. <https://doi.org/10.47392/IRJAEH.2026.0155>