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Influence of Tunnel Geometry on Collapse Behaviour: A Numerical Study

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Abstract

Tunnel collapse is a common concern in underground construction, especially when tunnels are driven through weak or jointed rock. Although ground conditions and support systems are often studied in detail, the effect of tunnel geometry on collapse behaviour is still not fully understood. This paper examines how different tunnel shapes influence collapse mechanisms using numerical modelling. Numerical analyses are carried out for circular, horseshoe, and D-shaped tunnels under varying overburden depths and rock mass quality conditions. Additional parametric studies are performed by changing joint orientation, groundwater pressure, and support conditions for each tunnel geometry. Collapse behaviour is evaluated by analysing stress distribution, development of plastic zones, deformation patterns, and failure modes obtained from the simulations. The results indicate that tunnel geometry has a noticeable influence on stress concentration and deformation, leading to different collapse patterns under similar ground conditions. A comparative assessment of tunnel shapes is presented to identify their relative stability. The study highlights the importance of considering tunnel geometry explicitly during design and provides useful insight for safer and more informed tunnel planning.

Keywords: *Tunnel geometry, Tunnel Collapse, Numerical modelling, Tunnel stability*

1. Introduction

Tunnel collapse in weak or jointed rock masses poses major risks in underground construction, as seen in incidents like the 1994 Heathrow Express failure and 2023 Delhi Metro collapse. While rock properties, Tunnel collapse in weak or jointed rock masses remains a major challenge in underground construction, as illustrated by failures such as the Heathrow Express collapse (1994) and the Delhi Metro incident (2023). While rock mass properties, groundwater, and support systems are widely studied, the role of tunnel geometry in influencing collapse behaviour is comparatively underexplored. Empirical systems such as the RMR proposed by Z. T. Bieniawski (1989) and the Q-system by N. Barton et al. (1974) guide support design but do not explicitly account for geometric effects. Analytical solutions beginning with Kirsch (1898) demonstrate that stress concentration depends on excavation shape. Circular tunnels generally provide uniform stress redistribution, minimizing tensile zones. In contrast, horseshoe and D-shaped profiles—often adopted for functional and construction reasons—create stress concentrations at haunches and invert, accelerating plastic zone development in poor rock (low GSI). Studies by A. I. Sofianos (1996) and Q. Zhang et al. (2018) indicate that geometry can alter stability margins by 20–50%, yet systematic parametric comparisons remain limited. To address this gap, the present study performs 2D finite element analyses in PLAXIS using the Hoek–Brown failure criterion to represent rock mass behaviour. Circular, horseshoe, and D-shaped tunnels are evaluated under varying overburden (10–50 m), GSI (35) and pore pressures. Collapse behaviour is assessed through stress contours, plastic zones, displacement patterns, and failure mode if any. Results show that non-circular shapes amplify stress peaks and enlarge plastic zones, leading to geometry-specific failures such as invert heaving in D-shaped and horseshoe tunnels Circular profiles exhibit comparatively improved stability and less deformation. The findings emphasize the need to explicitly incorporate tunnel geometry into stability

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assessment and design for weak rock tunnelling

2. Methodology

A two-dimensional finite element approach was adopted to evaluate the effect of tunnel geometry on collapse behaviour. Numerical analyses were performed in PLAXIS 2D under plane strain conditions. The rock mass was simulated using the Hoek–Brown failure criterion, which appropriately captures the non-linear strength behaviour of jointed rock masses (Hoek, Carranza-Torres, & Corkum, 2002). Rock mass parameters were derived from GSI values using standard correlations. Boundary conditions and model extents followed recommended numerical modelling practices to avoid boundary influence (Brady & Brown, 2006).

The methodology involved the following key steps:

- **Tunnel geometries:** Circular, horseshoe, and D-shaped sections with equivalent excavation areas were modelled for consistent comparison.
- **Material modelling:** Rock mass behaviour represented using the Hoek–Brown criterion; joints incorporated through the ubiquitous joint concept.
- **Parametric variations:**
  - Overburden depth: 10–50 m
  - Rock mass quality: GSI 35
  - Pore water pressure according to depth as water table considered at ground level
  - Support condition: lined cases
- **Stress initialization:** In-situ stresses generated using gravity loading with an appropriate lateral stress coefficient.
- **Excavation simulation:** Staged excavation adopted to capture stress redistribution and progressive yielding, consistent with recommendations for underground modelling (Sofianos, 1996).
- **Performance indicators:**
  - Stress concentration patterns
  - Extent of plastic zones
  - Maximum displacement and convergence
  - Identification of failure modes (roof collapse, wedge failure, invert heave), if any.

A comparative assessment under identical ground and loading conditions was conducted to isolate the influence of tunnel geometry on stability and collapse mechanisms.

2.1. Tables

Table 1 Input Parameters for Plaxis 2D

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/m3	Unit weight (γ)	8.4 kN/m/m
Deformation Modulus (E) for rock mass	1487 MPa	Bending stiffness	$0.14*10^6$ kN-m²/m
GSI	35	Axial stiffness	$14*10^6$ kN/m

Table 2 Maximum Deformation for Different Tunnels from Plaxis 2D

Depth (m)	Maximum Deformation (mm)		
	Circular Tunnel	D Shaped Tunnel	Horseshoe Tunnel
10	0.5881	0.9073	0.7409
20	0.7735	1.337	1.041
30	0.9735	1.786	1.352
40	1.171	2.238	1.654
50	1.343	2.663	1.926

Table 3 Maximum Principal Stress for Different Tunnels from Plaxis 2D

Depth (m)	Maximum Deformation (kN/m²)		
	Circular Tunnel	D Shaped Tunnel	Horseshoe Tunnel
10	5.33	11.19	6.264
20	0.9175	11.21	1.552
30	0.7269	11.17	1.838
40	1.554	11.08	2.709
50	1.303	11.09	2.171

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2.2. Figures

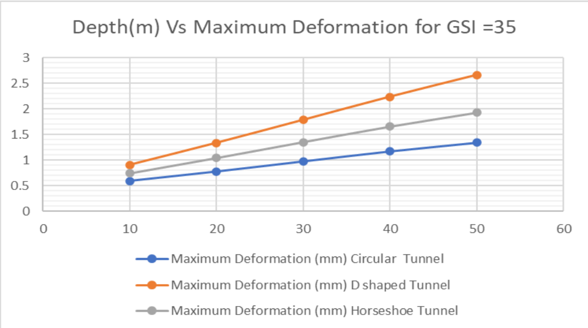

Figure 1 Variation of Maximum Deformation for Different Shape of Tunnels with Depth

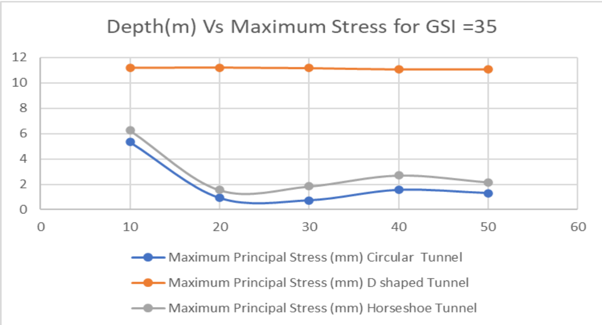

Figure 2 Variation of Maximum Principal Stress for Different Shape of Tunnels with Depth

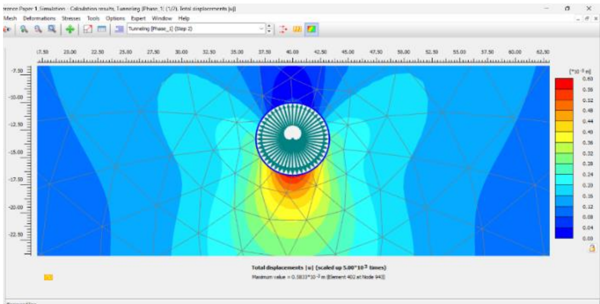

Figure 3 Circular Tunnel Deformation at Depth 10m in Plaxis 2d

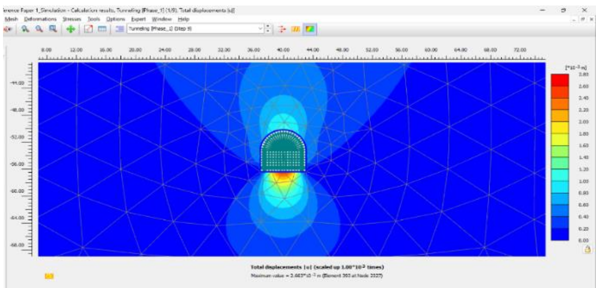

Figure 4 D- Shaped Tunnel Deformation at Depth 10m in Plaxis 2d

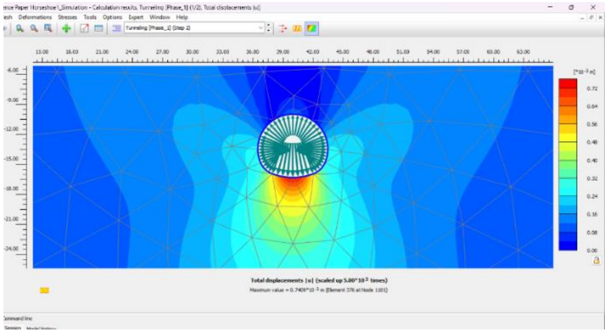

Figure 5 Horseshoe Tunnel Deformation at Depth 10m in Plaxis 2d

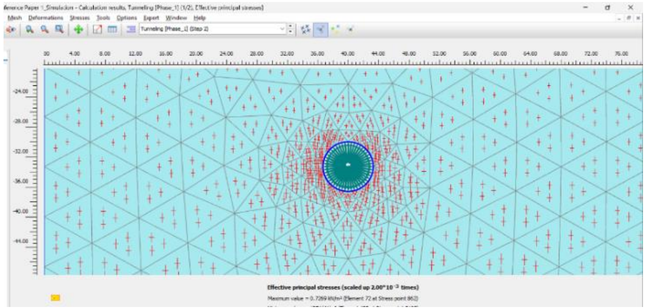

Figure 6 Circular Tunnel Maximum Principal Stress at Depth 30m In Plaxis 2d

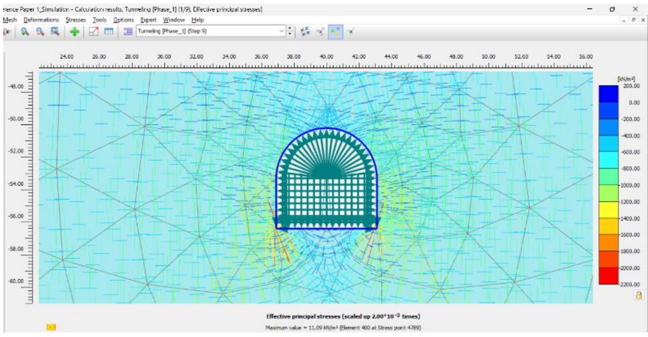

Figure 7 D-Shaped Tunnel Maximum Principal Stress at Depth 50m in Plaxis 2d

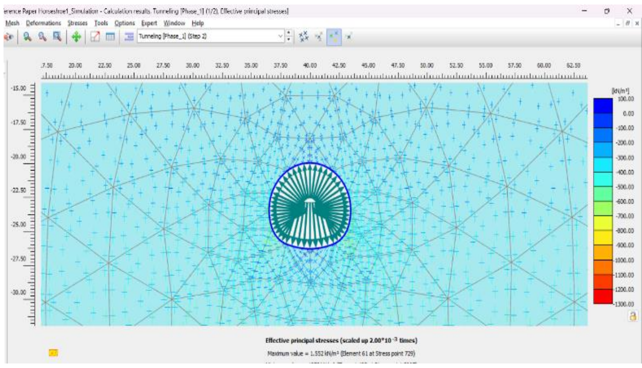

Figure 8 Horseshoe Tunnel Maximum Principal Stress at Depth 20m in Plaxis 2d

3. Results and Discussion

3.1. Results

Numerical analyses were carried out for GSI = 35 under overburden depths ranging from 10 m to 50 m. The primary output parameters obtained from PLAXIS were maximum total deformation and maximum principal stress.

3.1.1. Maximum Deformation

- Deformation increased progressively with depth for all tunnel geometries.
- The **circular tunnel** showed the lowest deformation, increasing from **0.588 mm (10 m)** to **1.343 mm (50 m)**.
- The **horseshoe tunnel** exhibited moderate deformation, ranging from **0.741 mm** at 10 m to **1.926 mm** at 50 m.
- The **D-shaped tunnel** recorded the highest deformation at all depths, increasing from **0.907 mm** to **2.663 mm**.

At 50 m depth, deformation in the D-shaped tunnel was nearly double that of the circular tunnel.

3.1.2. Maximum Principal Stress

- The **circular tunnel** exhibited comparatively lower stress concentrations, with a maximum of **5.33 kN/m²** at 10 m depth and generally lower values at greater depths.
- The **horseshoe tunnel** showed moderate stress concentrations, increasing with depth and reaching **2.709 kN/m²** at 40 m.
- The **D-shaped tunnel** consistently developed the highest principal stress, approximately **11 kN/m²** across all depths.

The results clearly indicate that non-circular geometries generate higher stress concentrations compared to circular sections.

3.2. Discussion

The increase in deformation with depth for all tunnel shapes is attributed to higher overburden pressure and increased stress redistribution around the excavation boundary. However, the magnitude of deformation varies significantly with geometry. The circular tunnel demonstrates the most uniform stress distribution, resulting in lower displacement and reduced plastic zone development. This confirms the mechanical advantage of circular profiles in resisting radial stress concentration. In contrast, the D-shaped tunnel shows pronounced stress amplification, particularly near the haunch and invert regions. The consistently high maximum principal stress (~11 kN/m²) indicates strong geometric stress concentration effects, which contribute to larger deformation and higher instability potential. The horseshoe tunnel performs better than the D-shaped section but still exhibits higher deformation and stress than the circular tunnel due to geometric discontinuities. Overall, the stability ranking under weak rock conditions (GSI = 35) can be summarized as:

Circular > Horseshoe > D-shaped

These findings highlight that tunnel geometry plays a critical role in controlling deformation and stress concentration and should be explicitly considered in the design of tunnels in weak rock masses.

Conclusion

This study evaluated the effect of tunnel geometry on collapse behavior in weak rock (GSI = 35) using 2D finite element analysis. Results show that geometry significantly influences both deformation and stress concentration under increasing overburden. Deformation increased with depth for all cases, but the circular tunnel consistently exhibited the lowest values, while the D-shaped tunnel showed the highest. At 50 m depth, deformation in the D-shaped section was nearly twice that of the circular tunnel. Maximum principal stress results further confirmed strong geometric influence. The D-shaped tunnel developed the highest stress concentrations, the horseshoe tunnel showed moderate response, and the circular tunnel demonstrated the most uniform stress distribution.

Overall Stability Ranking:

Circular > Horseshoe > D-shaped

The findings highlight that non-circular geometries amplify stress and deformation in weak rock conditions. Tunnel geometry must therefore be explicitly considered in design to ensure safer and more stable underground construction.

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of PLAXIS software for carrying out the numerical simulations presented in this study. The computational facilities provided by the institution are gratefully appreciated.

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