Effect of Depth and Load Offset on the Displacement and Stress Development of Horse Shoe Tunnel

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Abstract:

This study explores the structural behaviour of horseshoe tunnels subjected to varying depth-to-width (Q/B) and load offset-to-width (P/B) ratios using FLAC3D numerical modelling. The analysis aims to assess how these parameters affect tunnel displacement and the distribution of stresses within the surrounding ground. Simulations were carried out for Q/B values ranging from 1 to 5 and P/B values from 0 to 5, enabling the identification of key transition points in tunnel deformation behaviour. Results indicate a notable rise in crown displacement with increasing depth, particularly when Q/B exceeds 3. Moreover, placing surface loads at an offset ($P/B \geq 2.5$) proved effective in minimising stress concentrations around the tunnel lining. These insights highlight the critical role of depth and load placement in tunnel stability, offering practical guidance for the design and reinforcement of underground structures, especially in urban or deep excavation settings.

Keywords: Horseshoe tunnel, FLAC3D, tunnel displacement, stress distribution and numerical simulation.

1. Introduction:

With the growing reliance on underground infrastructure, ensuring tunnel stability has become a vital concern in contemporary geotechnical engineering. The horseshoe tunnel shape, known for its efficient stress distribution, is commonly used in transportation and hydropower developments. However, its structural integrity is closely affected by two primary factors: the burial depth, expressed as the Q/B ratio, and the location of surface loads, defined by the P/B ratio. This study is carried out using FLAC3D numerical modelling to systematically investigate how variations in these parameters influence tunnel behaviour within a homogeneous rock setting. By expanding on existing studies in tunnel mechanics, the work seeks to fill existing knowledge gaps related to the combined effects of Q/B and P/B. The findings are intended to support engineers in developing safer, more reliable designs, particularly in urban areas where surface loading conditions are both complex and highly variable. **Fig.1** presents the geometry and notations of horse-shoe tunnel.

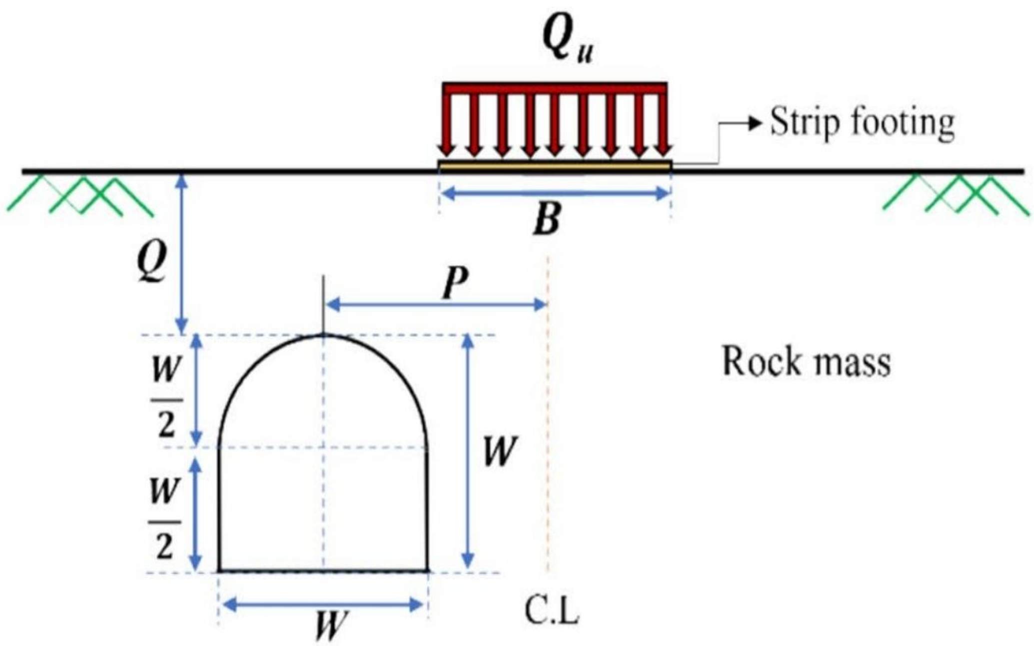

Fig.1 Horse shoe tunnel

2. Literature review

The stability of underground excavations has been extensively investigated through multiple approaches. Zhou et al. (2022) demonstrated that horseshoe tunnels under high in-situ stresses exhibit significant stress redistribution at Q/B > 3, with expanded plastic zones requiring depth-dependent support systems. Liu et al. (2021) revealed that horizontal surface loads from urban infrastructure critically influence tunnel sidewalls, emphasising the importance of P/B ratios in design. Comparative studies by Kumar and Gupta (2023) showed that horseshoe tunnels experience 15-20% greater asymmetric displacements than circular counterparts due to uneven stress distribution.

Critical thresholds have been identified, including Q/B = 4 where displacements increase sharply (Chakraborty et al., 2020) and P/B > 1 for significant stress reduction (Ranjith et al., 2019). Research on shallow tunnels (Q/B < 2) by Chen et al. (2018) established the need for additional reinforcement measures, while Jangid and Sharma (2021) found that wider tunnels exhibit problematic sidewall convergence. Mohammadi and Eslami (2016) demonstrated that off-centre loading (P/B > 2) creates asymmetric stress distributions requiring variable lining thicknesses. Chauhan's (2025) finite element analysis established circular tunnels as optimal for stress distribution, identifying critical thresholds (Q/B ≥ 3 and P/B ≥ 6) to minimise tunnel-foundation interactions. Gokceoglu et al. (2015) highlighted how geological heterogeneity affects stability through Q/B and P/B ratios, underscoring the need for adaptive design approaches.

This body of research provides a comprehensive foundation for understanding tunnel stability under varying geometric and loading conditions, with a particular emphasis on the critical relationships between depth, load positioning, and structural response.

3. Methodology

This study adopts a detailed numerical modelling strategy based on the finite difference method implemented in FLAC3D. The analysis focuses on a horseshoe tunnel with a fixed width (B) of 10 m, positioned within a rock mass domain measuring 160 m in length, 100 m in width, and 50 m in height. These domain dimensions are selected to reduce the influence of boundary conditions on simulation outcomes. The rock mass is characterised using the Mohr-Coulomb failure criterion, incorporating typical material properties such as a Bulk modulus of 400 MPa, a cohesion value of 50 kPa, and an internal friction angle of 20°. The tunnel lining, modelled as a 0.6 m thick concrete shell, is represented using elastic shell elements to capture structural stiffness.

Table. 1 Rock Material Properties

Rock Material Properties			
Parameter	**Symbol**	**Value**	**Unit**
Model	Mohr Coulomb		
Bulk Modulus	K	4×10^8	N/m^2

Density	P	2200	kg/m^3
Shear Modulus	G	1.5×10^8	N/m^2
Cohesion	C_u	50×10^3	N/m^2
Friction Angle	ϕ	20	º
Dilation Angle	ψ	3	º

Table. 2 Material Properties of Concrete Liner

Material Properties of Concrete Liner			
Bulk Modulus	K	20.7×10^9	N/m^2
Shear Modulus	G	12.6×10^9	N/m^2
Thickness	t	0.6	m

Table. 3 Material Properties of Concrete Liner

Material Properties of Cable			
Young's Modulus	E	45×10^9	N/m^2
Grout-Cohesion	C	20×10^3	N/m^2
Grout-Stiffness	k	17.5×10^5	N/m
Grout-Perimeter	P	1	m
Cross section area	A	1570	mm^2

Table. 4 Material Properties of Shell

Material Properties of Shell			
Parameter	**Symbol**	**Value**	**Unit**
Young's Modulus	E	1.05×10^8	N/m^2
Poisson's ratio	μ	0.25	-
Thickness	t	0.3	m
Density	ρ	2500	kg/m^3

The simulation procedure begins with establishing initial stress conditions under self-weight. Once equilibrium is achieved, the tunnel is excavated, and the lining is installed immediately to replicate the actual construction practices. A uniform surface pressure of 100 kPa is then applied at various horizontal offsets relative to the tunnel centreline to simulate different P/B scenarios. The parametric investigation includes Q/B ratios ranging from 1 to 5 and P/B ratios from 0 to 5, resulting in a total of 42 unique simulation cases.

Key outputs such as displacement and stress responses are monitored at three critical locations: the tunnel crown, sidewalls, and ground surface. Special emphasis is placed on analysing vertical (σ_{zz}) and horizontal (σ_{xx}) stress components.

4. Results and Discussion

4.1 Influence of Depth-to-Width Ratio (Q/B) on Displacement

Fig.2 presents the clear trends in the tunnel's structural behaviour under varying conditions. Crown displacement increases markedly with rising Q/B ratios, increasing from 7.53 mm at Q/B = 1 to 19.98 mm at Q/B = 5. A noticeable shift is occurred around Q/B = 3, beyond which the rate of displacement increased. This suggests a behavioural transition in the surrounding rock mass, likely from elastic to plastic deformation as depth increases. Surface settlement followed a more gradual pattern, increasing by approximately 27% over the same Q/B range. This milder response indicates that some of the applied stress is redistributed through the overlying strata. On the other hand, sidewall displacement became more pronounced at Q/B values of 2 and above. By Q/B = 5, the sidewall displacement is exceeding the surface settlement by 134%. It may be attributed that the lateral confinement in the deep tunnel scenarios is playing a critical role.

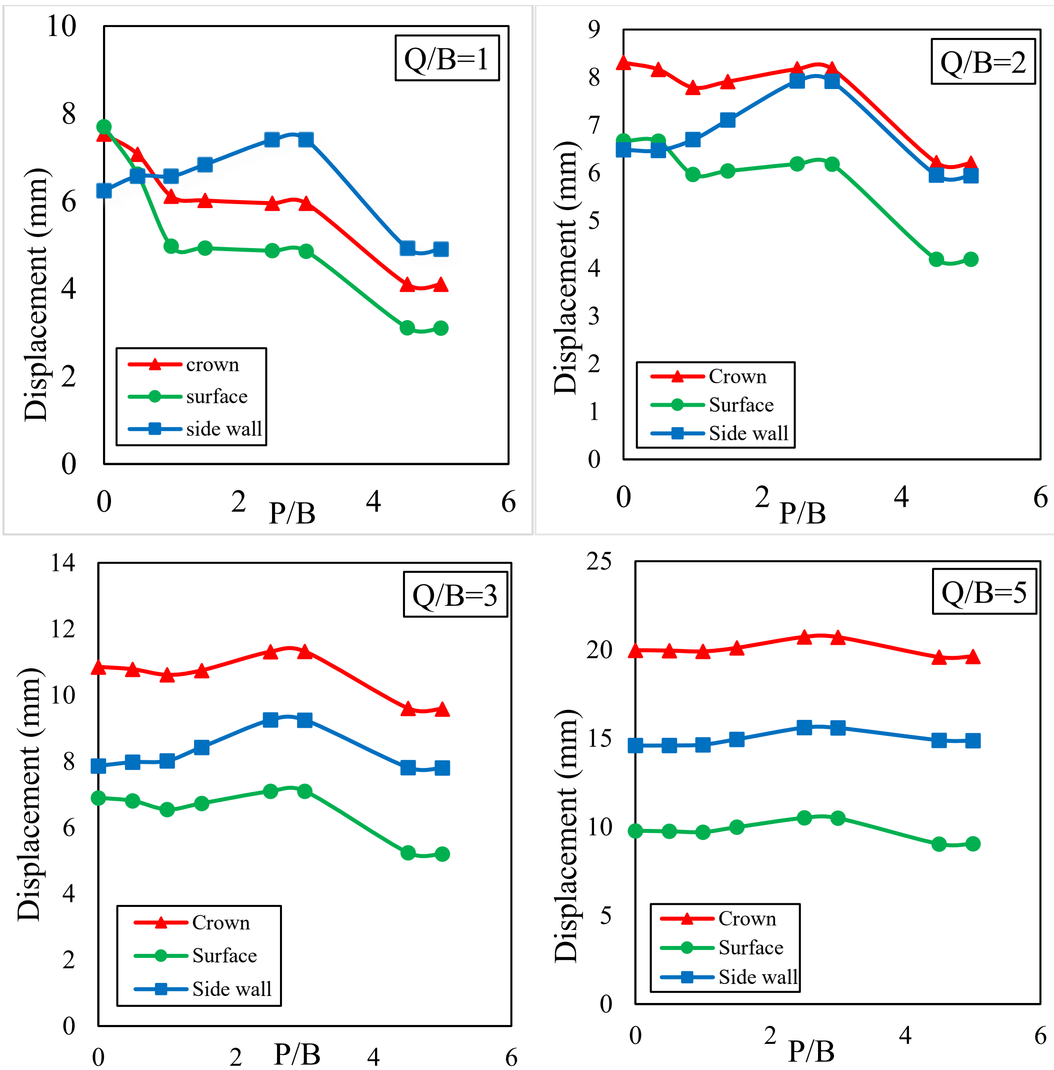

Fig.2 Variation of maximum displacement at the crown, surface, and sidewall of the horseshoe tunnel with P/B ratio for different Q/B ratios.

4.2 Influence of Load offset-to-Width Ratio (P/B) on Displacement

Fig.3 presents the influence of the P/B ratio (Load offset-to-Width Ratio) having a moderating effect. For instance, at Q/B = 3, an increase in P/B from 0 to 5 resulted to 11.7% reduction in the crown displacement, indicating that the load offset helps in identifying the peak deformations.

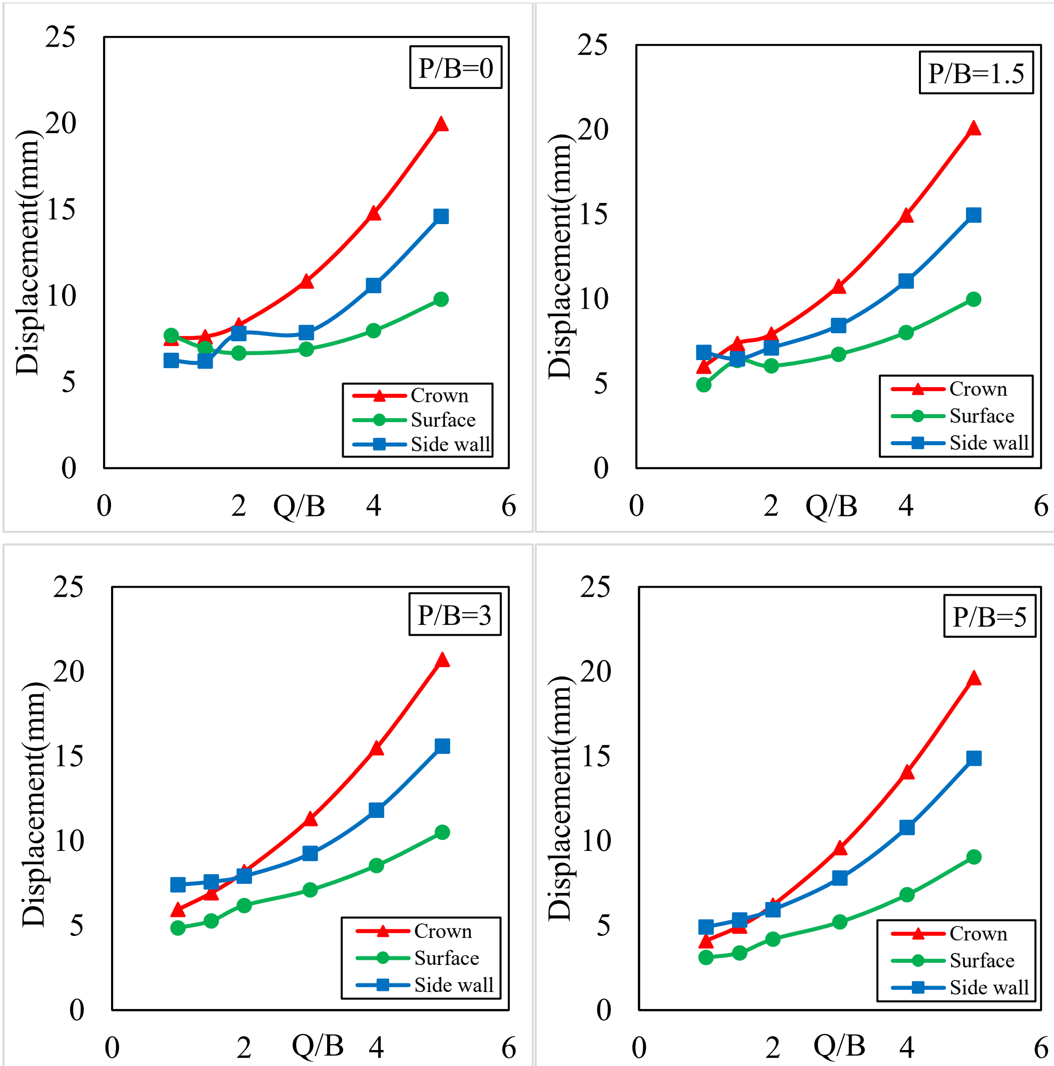

Fig.3 Variation of maximum displacement at the crown, surface, and sidewall of the horseshoe tunnel with Q/B ratio for different P/B ratios.

4.3 Influence of Depth-to-Width Ratio (Q/B) and Load offset-to-Width Ratio (P/B) on Stresses

Fig.4 presents the stress distribution patterns under varying conditions. The maximum compressive stress occurred at the tunnel crown, reaching 107.84 MPa at Q/B = 5 and P/B = 0. Simultaneously, tensile stresses concentrate along the sidewalls, with values up to 19.06 MPa under the same conditions. Contour analyses highlighted the plastic zone development at the crown

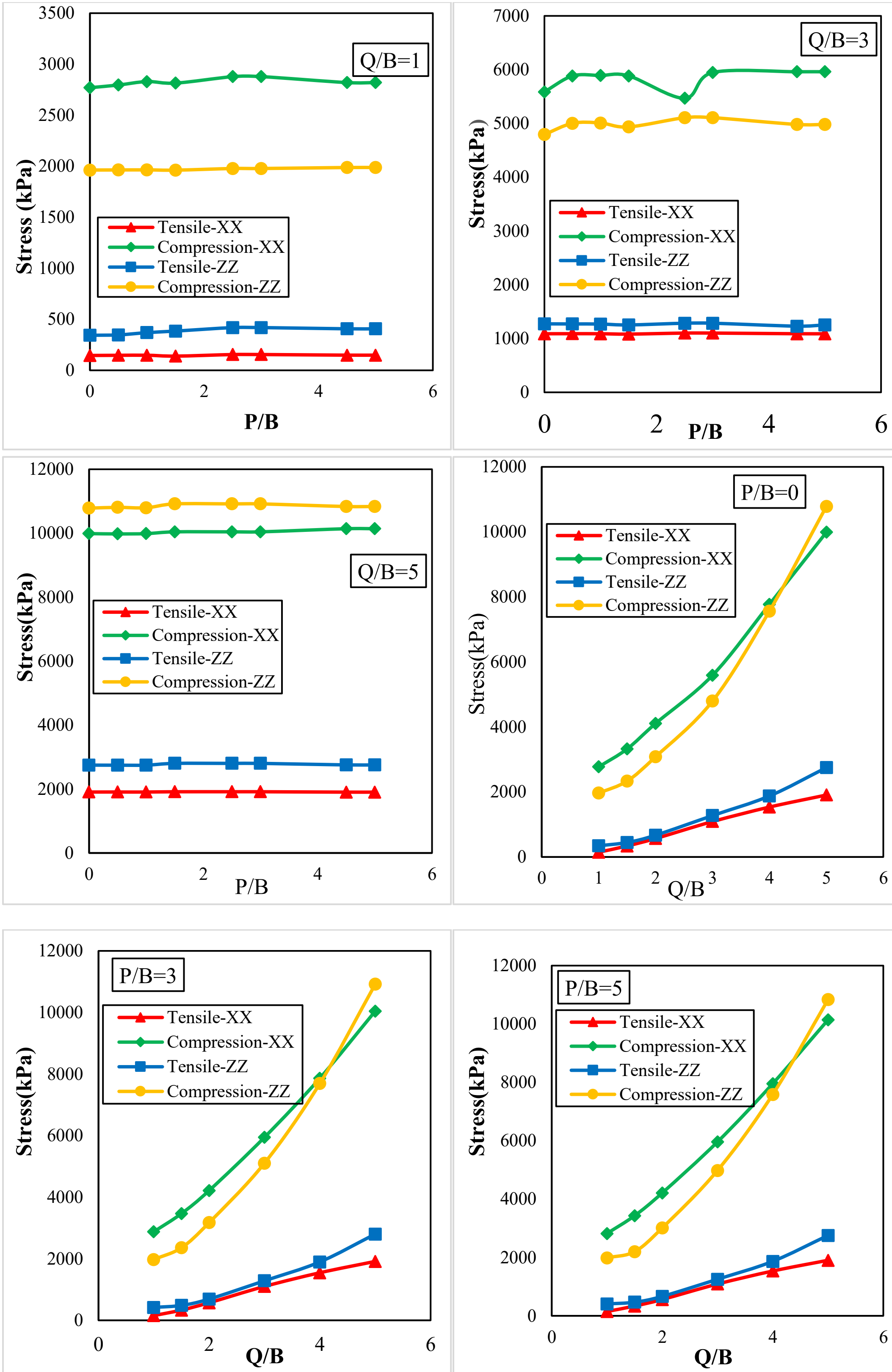

Fig.4 Variation of maximum stresses on the horseshoe tunnel with Q/B ratio and P/B Ratio.

and invert for Q/B ≥ 3, while tensile failure zones emerged along the sidewalls especially under asymmetric loading, such as at P/B = 2.5.

These outcomes not only support existing research but also offer a more detailed understanding of how depth (Q/B) and load offset (P/B) interact to influence tunnel deformation and stress behaviour.

5. Conclusions and Recommendations

This numerical investigation yielded important conclusions for tunnel engineering practice. First, the identification of Q/B = 3 as a critical threshold confirms that tunnel design methods must account for depth-dependent behaviour, with particular attention to reinforcement requirements beyond this depth. Second, the demonstrated effectiveness of load offsetting (P/B ≥ 2.5) provides a practical strategy for urban tunnelling projects to minimise surface settlement and structural deformation. Third, the differential response between crown and sidewall displacements suggests the need for anisotropic support systems in horseshoe tunnels. Based on these findings, the study recommended: (1) implementing enhanced lining systems for tunnels exceeding Q/B = 3, possibly incorporating variable-density rock bolting and graded shotcrete thickness; (2) planning surface infrastructure layout to maintain P/B ≥ 2.5 wherever possible; and (3) conducting site-specific Q/B-P/B analyses during preliminary design stages. Future research directions include extending the analysis to heterogeneous rock masses, incorporating dynamic loading conditions, and validating the numerical predictions through field monitoring data from actual tunnel projects. The methodologies and findings presented here contribute to the ongoing development of more reliable and economical tunnel design approaches in challenging geological environments.

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