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EVALUATION OF FACE STABILITY FOR MEGA TUNNEL UNDER VARYING GROUND STRENGTH PARAMETERS

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Abstract

Transportation demands in developing countries necessitate the use of underground infrastructure, notably tunnels, which also serve as storage spaces for vehicles and military equipment, expanding their utility. Mega Tunnels, defined as those with a diameter exceeding 10m, offer diverse functionalities, including facilitating the storage and movement of large equipment and establishing comprehensive operational systems for urban areas. However, ensuring the stability of these tunnels' faces poses a significant challenge due to their larger diameter, making it a crucial research focus. This study investigates the impact of various geological strength variables, such as Young's modulus and coefficient of lateral earth pressure, on Mega Tunnel face stability. Employing the numerical analysis-based computational tool Midas Gts Nx, three-dimensional modelling was conducted to analyze Mega Tunnels. A parametric study involving approximately 40 models was undertaken, focusing on key locations including the crown, invert, and vertical sidewalls. Variable parameters such as critical cover-to-diameter ratio (C/D), Young's modulus, and coefficient of lateral earth pressure were examined. The findings highlight the significant influence of geological strength characteristics on tunnel face stability prediction. This research offers valuable insights for the planning and design of Mega Tunnels in urban areas during the preplanning phase, enhancing their efficiency and effectiveness.

Keywords:

Face stability;
Mega Tunnel;
Parametric Study;
Rock mass;
Numerical modelling.

1 Introduction

Tunnels, are underground passages utilized for transportation and storage, have become favoured solutions for easing traffic congestion in rapidly expanding urban areas. Initially used mainly for navigating difficult terrain, tunnels now serve as vital infrastructure supporting urban expansion and improving living standards. With metro train tracks predominantly located underground in urban environments, subterranean structures play a crucial role in the advancement of smart cities, albeit with potential environmental risks stemming from extensive excavation activities. Mega Tunnels, characterized by diameters exceeding 10 meters [20,21], offer a solution to mitigate these risks while also delivering cost and time-saving advantages compared to twin tunnel construction methods. By employing larger Tunnel Boring Machines (TBMs), Mega Tunnels can be excavated in a single bore. However, the increased diameter poses challenges to tunnel face stability, which is significantly influenced by ground conditions and excavation pressures [20,21]. This study utilizes soft computing modelling with Midas Gts Nx software to examine the effects of rock strength parameters, such as Youngs modulus (E) and coefficient of lateral earth pressure (K_0), on Mega Tunnel face stability. Extensive numerical experiments were conducted to analyze important stability indicators systematically, including displacement, stress distribution, and potential failure modes, across various parameter settings. Careful examination and interpretation of the computational findings revealed key trends and correlations, offering insights into optimal parameter combinations to enhance stability and mitigate risks during tunnel excavation. The findings of the study highlight the critical ground strength parameters governing face stability and identify potential safety thresholds for excavation in diverse ground conditions, considering factors such as tunnel displacement, face deformation, and stress trajectories. Decisions regarding suitable excavation patterns are contingent upon ground strength parameters. This research is anticipated to contribute to the development of more resilient design protocols for Mega Tunnels, accounting for variations in ground strength

2 Literature Review

Szechy, Brown and Hoek categorized tunnels based on their utility and emphasized the significance of the modulus of elasticity in estimating tunnel forces. Face stability of tunnels refers to maintaining a stable and deformation-free tunnel face during excavation, which is crucial for the safety of workers, the structural integrity of the tunnel, and preventing surface-level impacts such as ground subsidence. Factors affecting face stability include geological conditions, rock strength parameters, in-situ stresses, tunneling methods, excavation sequences, and support conditions [1,2]. Kulkarni et al, confirmed through numerical simulations that alongside geology and rock strength, the pressure exerted by tunnel boring machines plays a significant role in face stability [21]. Mojtahedi et al, examined the cover-to-diameter ratio, highlighting its importance in distinguishing tunnel seating positions from the surface. They proposed a criterion for differentiating between deep and shallow tunnels based on face pressure considerations, noting that an increase in this ratio stabilizes the tunnel at optimal face pressure. They suggested that evaluating collapse pressure is essential for preventing face collapse [14]. Algha et al. conducted a study on maintaining tunnel face stability during shield tunneling in urban environments using 3D finite element simulations. They evaluated collapse pressure in uniform and stratified soil conditions, devising a new formula for calculating necessary face collapse pressure. The study also investigated the arching phenomenon and failure mechanisms, emphasizing the significant influence of tunnel diameter on face collapse pressure [17]. Hernandez et al. (2019) explored the comparative analysis of analytical and numerical methods for assessing excavation face stability in shallow tunnels. Using ABAQUS 3D finite elements software, they examined the effect of various overburden depths and ground conditions on face stability. The study underscored the necessity of support and stabilization pressure on the face and highlighted the relationship between support pressure and the cover-to-diameter ratio [18]. Golapasand et al., used 3D numerical computations to assess ground settlements induced by tunnel excavation, focusing on the impact of the coefficient of lateral earth pressure (K_0). Their study compared actual settlements with predictions from semi-empirical and computational methods [15]. Li et al., investigated the critical support pressure on tunnel faces at various cover-to-diameter ratios, finding a positive correlation between the critical stability ratio and the cover-to-diameter ratio [19]. Zeng et al, emphasized the importance of face pressure in preventing tunnel face collapse, noting that increased face support enhances stability [19]. Zang et al. analyzed the challenges associated with Tunnel Boring Machine [TBM] use in mining and offered mitigation measures for complex terrain conditions [16]. Eshraghi et al., assessed the stability of a tunnel face excavated by an earth pressure-balanced shield in Tehran's subway Line 3. Using Monte Carlo simulation techniques, they evaluated the factor of safety and its likelihood of falling below a predetermined threshold, finding that the probabilistic method, particularly the Broere solution, provided reliable outcomes [12].

Despite the growing need for underground structures, particularly Mega Tunnels, in developing countries, the literature indicates a limited understanding of Mega Tunnel face stability and the influence of geological strength parameters. This underscores the need for further research in this area.

3 Research Methodology

The analysis of the Mega Tunnel was conducted using research methodology as per given flowchart (Figure 1), with geotechnical parameters derived from a literature review. Empirical calculations, accounting for a 2% volume loss, were employed alongside numerical modeling in Midas Gts Nx to determine the requisite pressures for application on Tunnel Boring Machines (TBM). These calculated strains were validated and adjusted within predefined ranges to assess their effects on pressure while maintaining the critical cover-to-diameter (C/D) ratio. Finite Element Analysis facilitated the implementation of 3D numerical modeling. Four distinct ground strata—Soil, Basalt, Limestone, and Gneiss—were selected to evaluate the stability of a 15-meter diameter tunnel face. The ground strength parameters for Limestone and Gneiss were sourced from existing literature, while those for Basalt were obtained from an actual project site in Pune, Maharashtra, India. Conclusions were drawn based on observations, culminating in assessments face stability.

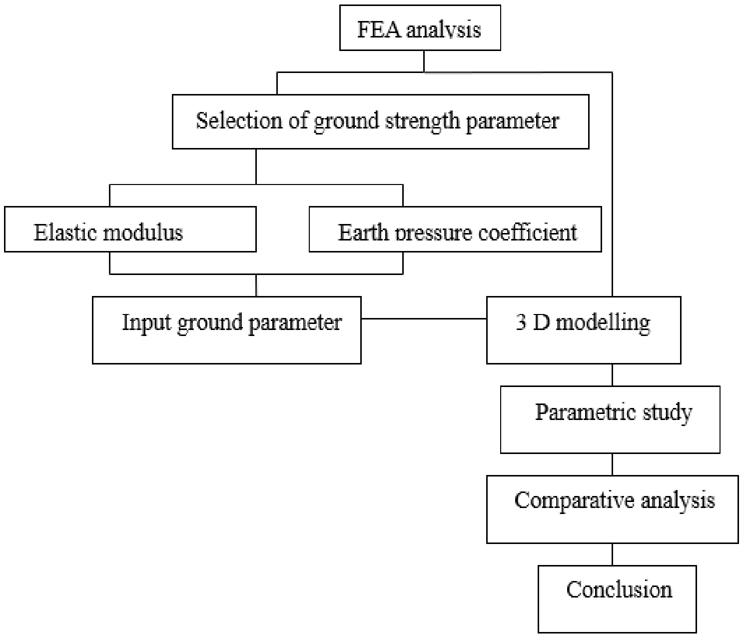


Figure 1: Research methodology flowchart

4 Finite Element Modelling of Mega tunnel

Initially, a 2D model geometry was prepared using the geometry tool of Midas GTS NX. The horizontal dimension of the continuum was set according to the requirement, specifically 6D, where D represents the tunnel diameter (C). The vertical dimension of the continuum was determined by placing the tunnel at a depth of 2.5D. The cover (C) above the tunnel varied, with a cover-to-diameter ratio (C/D) ranging from 2 to 8 in increments of 1. The 2D geometry was then converted to 3D using the extrude tool of Midas GTS NX, with a model width of 50 meters. Detailed modeling procedures are outlined in the provided flowchart [Figure 2].

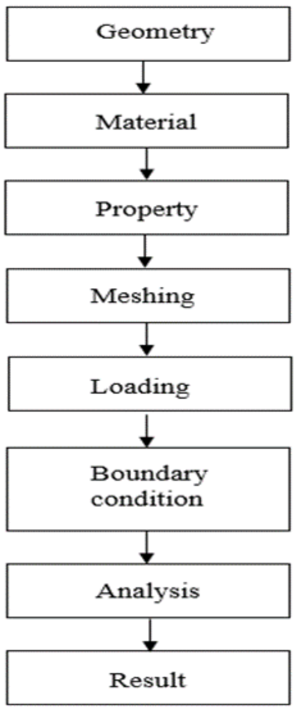


Figure 2: Modelling Flowchart

Meshing in Midas GTS NX involved dividing the model into discrete hexahedral parts in three dimensions to facilitate numerical analysis. Ensuring mesh quality, aspects such as aspect ratios and skewness were examined to meet specified standards, as depicted in Figure 3 [20], illustrating the tunnel model geometry and meshing. Meshing parameters were adjusted to balance analysis accuracy, computation time, and element count, with special attention given to enhancing mesh quality in critical areas, particularly near the tunnel [3]. Convergence criteria were applied to displacement and stress calculations. Hoek and Brown's model consider the elso-plastic behavior, which is the actual behavior possessed by various types of rocks. This model is mostly used for the design of underground excavations. This model affirms that the ground fails under shear stress; that's why Young's modulus, cohesion, friction angle, Poisson's ratio, and unit weight of rock are the required parameters for the analysis of structure. Hence, they are taken into consideration as input parameters, detailed in Table 1, were incorporated into the modeling process, along with a lining thickness of 300 mm. Material properties for ground strata and support materials, as outlined in Table 2, were utilized for meshing. Ground strength parameters, such as the Youngs Modulus (E) for Limestone, Gneiss, soil, and Basalt, were sourced from both literature and actual site data from projects in Maharashtra, India [6,21,22]. Numerical methods were employed to determine face pressure, while EPB (Earth Pressure Balance) pressures, including jack thrust, skin resistance friction, and segmental pressure, were calculated considering a 2% volume loss of the ground [21,22]. The weight of the Tunnel Boring Machine (TBM) was factored into jack thrust calculations. EPB pressures were applied according to Table 3, as illustrated in Figure 3, with self-weight of geometry and water pressure also considered in the modeling. The Hoek and Brown failure criterion was utilized for analysis, along with boundary assignment considering fixity at the bottom of the continuum; lateral (x) direction is restrained for top/bottom, and longitudinal (y) direction is restrained for front/ back of the model. Construction sequences were simulated. A parametric investigation was conducted, observing displacements at four key locations: crown, invert, and vertical tunnel walls.

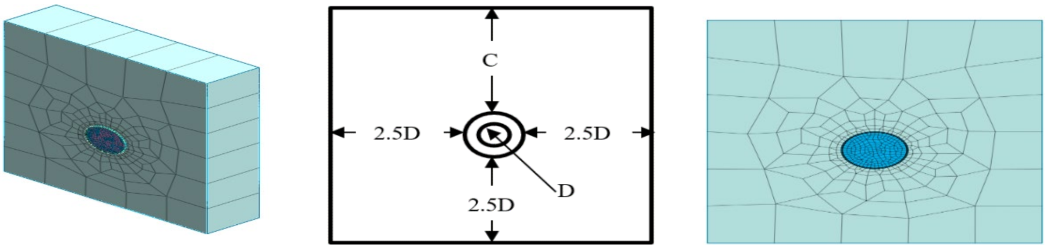


Figure 3. Meshing and Geometric design of Mega Tunnel

Table 1. Geotechnical details of various ground strata used for modelling [21,22,6]

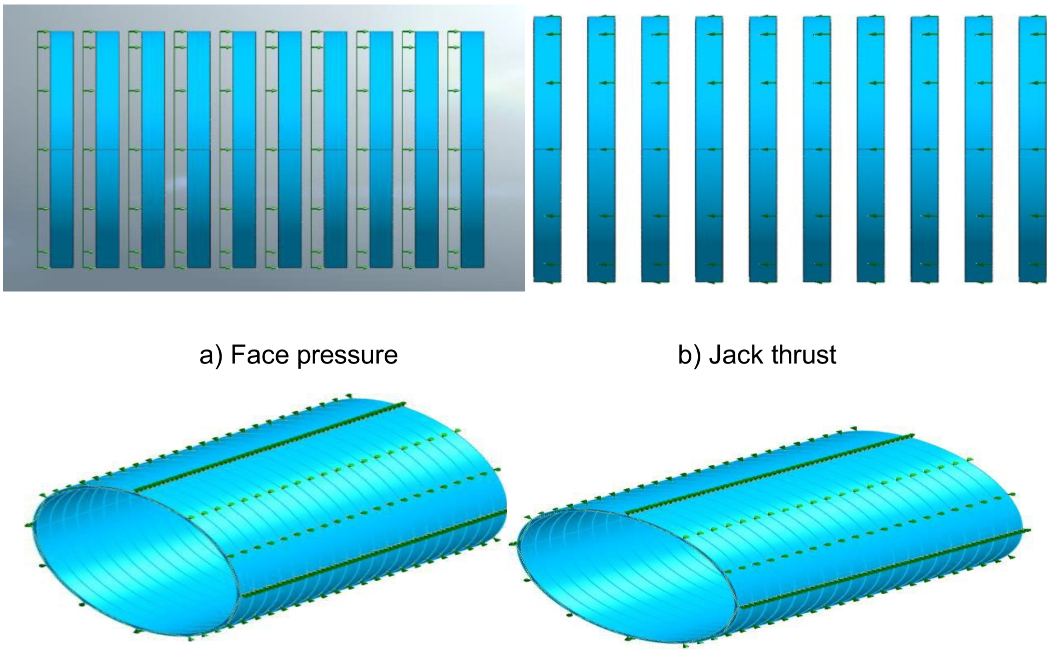
Sr.no	Strength parameters	Soil	Basalt [Field Data]	Gneiss	Lime- stone
1	Modulus of elasticity [kN/m^2]	1.3x 10^6	1.2x 10^6	88.79x10^3	71.86x10^3
2	Poisson's ratio	0.3	0.3	0.25	0.20
3	Unit weight [kN/m^3]	19	20	27.17	25
4	Cohesion [kN/m^2]	15	14	30	30
5	Friction angle [^{0}]	30	64	36	36
6	K_0	0.5	0.5	0.5	0.5

Table 2. Support details used for modelling [21,22]

Sr.no	Support parameters	Segment	Steel	Grout
1	Modulus of elasticity [kN/m^2]	2.1x 10^7	2.5x 10^8	1x10^7
2	Poisson's ratio	0.3	0.2	--
3	Unit weight [kN/m^3]	24	78	22.5
4	Cohesion [kN/m^2]	--	--	--
5	Friction angle [^{0}]	--	--	--
6	K_0	1	--	--

Table 3. Support details used for modelling [21,22]

Sr.no.	Pressure type	Pressure quantity [kN/m^2]
1	Face pressure	232.5
2	Jack Thrust	-75670
3	Skin resistance Friction	2120
4	Segmental pressure	5510



a) Face pressure b) Jack thrust

c)Skin resistance friction d) Segmental pressure

Figure 4. Application of Face pressure, jack thrust, skin resistance and segmental pressure

5 Analysis and Interpretation

Finite Element Analysis was utilized to assess the face stability of the Mega Tunnel, focusing on displacement at four critical points. Models were developed based on the previously outlined problem statement, maintaining a constant tunnel diameter of 15m while varying the overburden depth from 2D to 8D. Displacement at the crown, invert, and vertical wall was examined to assess the impact of changes in ground strata on tunnel face stability. Ground strength parameters, such as Youngs modulus (E) , were adjusted for soil and three types of rock—Basalt, Gneiss, and Limestone. Initially, the lateral earth-pressure coefficient (K_0) was held constant at 1 to analyze its effect on the ground. It was observed that the Youngs modulus of the ground material played a crucial role in tunnel stability, influencing the tunnel's seating location significantly. The decision-making process was supported by cohesion and friction angle considerations to prevent slippage of the ground strata over the tunnel crown. A higher Youngs modulus of the material facilitated positioning the tunnel at a shallower depth, enhancing stability.

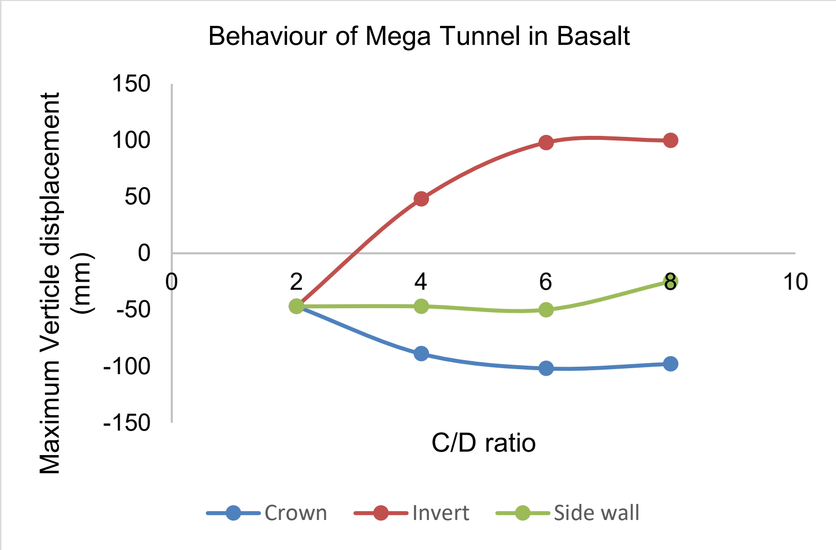


Figure 4: Tunnel displacement of in Basalt

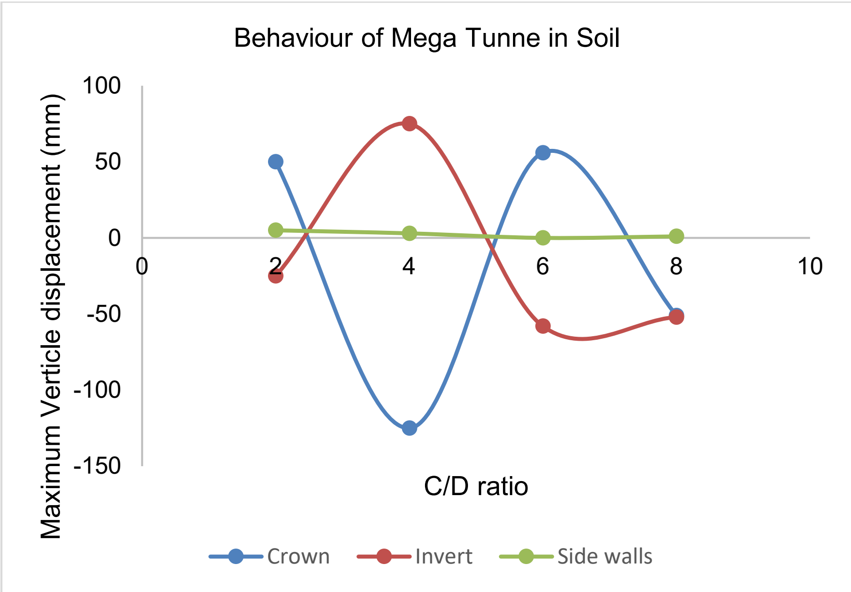


Figure 5: Tunnel displacement of in Soil

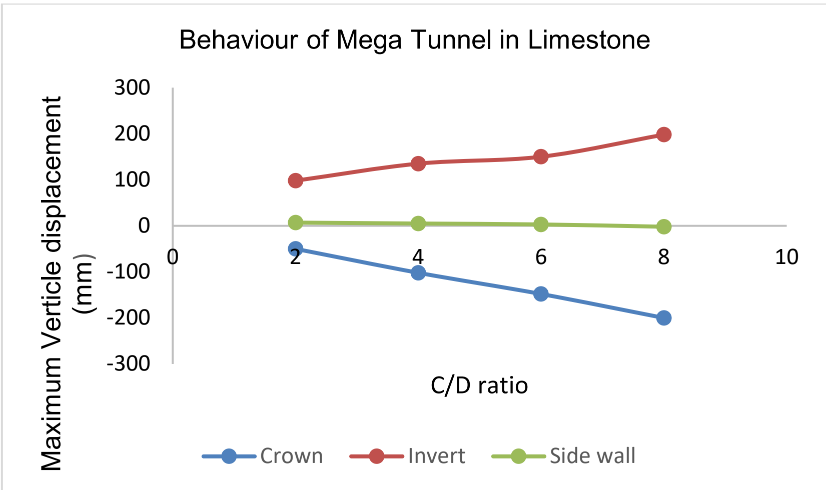


Figure 6: Tunnel displacement of in Limestone

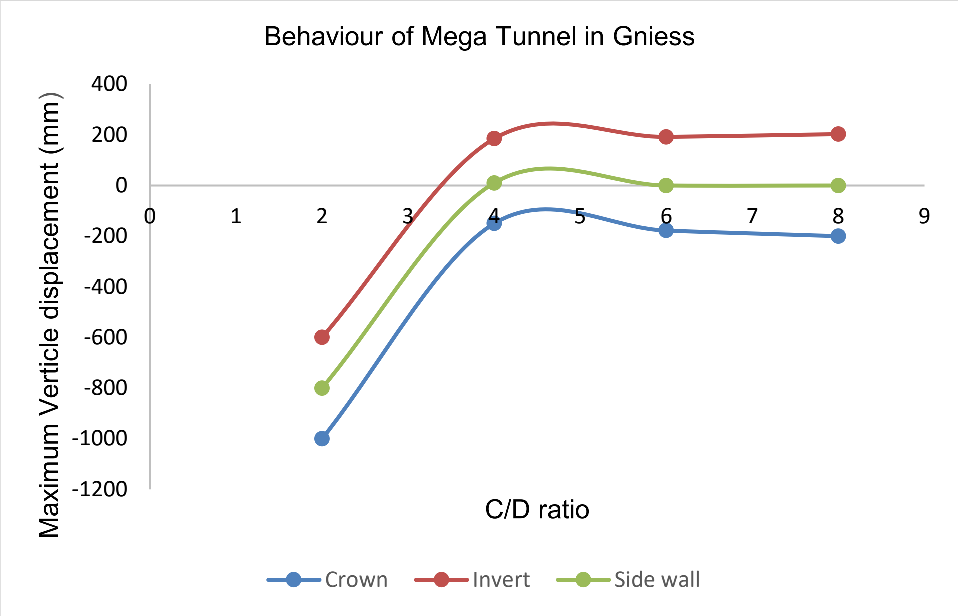


Figure 7: Tunnel displacement of in Gneiss

The applied Earth Pressure Balance (EPB) pressures during tunneling are primarily influenced by the rock's strength and the geological conditions of the rock zone. Evaluating such pressures is crucial for ensuring face stability, and the authors are currently investigating this issue, with details to be discussed in an upcoming study. Besides elastic modulus, the lateral earth-pressure parameter has a significant impact on tunnel behavior. Stress-strain trajectories within the tunnel provide insights into potential tunnel failure and the disturbed rock zone surrounding it. The behavior observed in tunnel sections during and after TBM excavation—crown settling down, invert moving upward, and consistent lateral displacement of the vertical walls—stems from a complex interplay of stress redistribution, ground relaxation, elastic rebound, and the TBM's support [Refer Figure 5]. Excavating a tunnel with a TBM causes the surrounding stresses to redistribute. The crown (top of the tunnel) loses support from the material above it, leading to its settlement as the ground adjusts to the new stress state. This adjustment results in ground relaxation above the tunnel, causing further settlement. The crown settles to reach a new equilibrium under gravity and redistributed vertical stresses. In softer ground or soil, consolidation over time due to the dissipation of pore water pressures can result in additional crown settlement. Additionally, time-dependent deformation or creep in certain rock or soil types can contribute to continued settlement.

The excavation process relieves the in-situ stresses at the tunnel invert (bottom of the tunnel). The ground beneath the tunnel may expand upward due to the reduction in vertical pressure. This phenomenon, known as heave, is a common response to the removal of overburden stress. The ground material has an inherent tendency to rebound elastically when the compressive stresses are removed or reduced. This elastic rebound can cause the invert to move upward. The redistribution of stresses around the tunnel often creates an arching effect where the load is transferred from the tunnel crown and sides to the surrounding soil or rock. This can result in upward movement at the invert as part of the overall deformation pattern.

This process typically leads to a symmetrical redistribution of stresses around the tunnel too, and resulted in relatively consistent lateral displacement of the tunnel walls as the ground adjusts to the new loading conditions. The vertical walls of the tunnel were subject to horizontal confining pressures from the surrounding ground. These pressures tend to be balanced on both sides of the tunnel, leading to uniform lateral displacement rather than differential movement. The TBM shield provides temporary support to the tunnel walls during excavation. This support helps to maintain lateral stability and results in consistent lateral movement as the tunnel advances

Soil and rock exhibit distinct deformation behaviors due to differences in material characteristics, deformation mechanisms, and stress-strain responses. Soil, typically composed of granular materials, is less rigid and cohesive, with higher porosity and susceptibility to deformation under stress. In contrast, rocks, characterized by higher density and mineral grain interlocking, are more rigid, less compressible, and possess greater deformation resistance. Mechanisms such as particle rearrangement, compaction, and shear sliding along grain boundaries dominate soil deformation, resulting in significant lateral deformation and settlement under applied loads. Conversely, rock deformation is influenced by fracture, faulting, and plastic deformation of mineral grains, with rocks maintaining structural integrity and experiencing less settlement compared to soils. Observations of tunnel behavior in different ground strata revealed stable behavior in soil at critical cover-to-diameter (C/D) ratios between 2-3 and 5-6 under applied pressures, considering segmental lining thickness.

In comparison of behaviour of tunnel stability differs despite of having similar rock strength parameter. This is the effect of rock formation properties and structure of the rock material. As Gneiss is a metamorphic rock characterized by its banded or foliated structure due to the recrystallization of minerals under high temperature and pressure. This structure can result in anisotropy, meaning its properties can vary in different directions. Whereas Limestone is a sedimentary rock primarily composed of calcium carbonate ($CaCO_3$). It typically has a more homogeneous structure compared to gneiss (Figure 6 and Figure 7). The foliated nature can lead to planes of weakness which can affect tunnel stability, potentially causing rock falls or slabbing along these planes. Whereas Limestones can contain bedding planes, joints, and fractures which can influence tunnel stability. However, in comparison to gneiss, these features are often less pronounced and not as directional.

The Earth Pressure Coefficient (K_0), reflecting the relationship between lateral earth pressure and vertical effective stress within the ground, is closely linked to the characteristics of available ground strata. Cohesive soils typically have K_0 values less than 1, indicating lower lateral pressure compared to vertical stress due to their high cohesion. In contrast, rocks, considered non-cohesive materials, rely more on internal friction, represented by the angle of internal friction (φ), to generate lateral pressure. Depending on the specific internal friction angle of the rock type, the lateral pressure induced by friction in rocks may exceed 1. Thus, the impact of lateral earth pressure was examined across different ground strata.

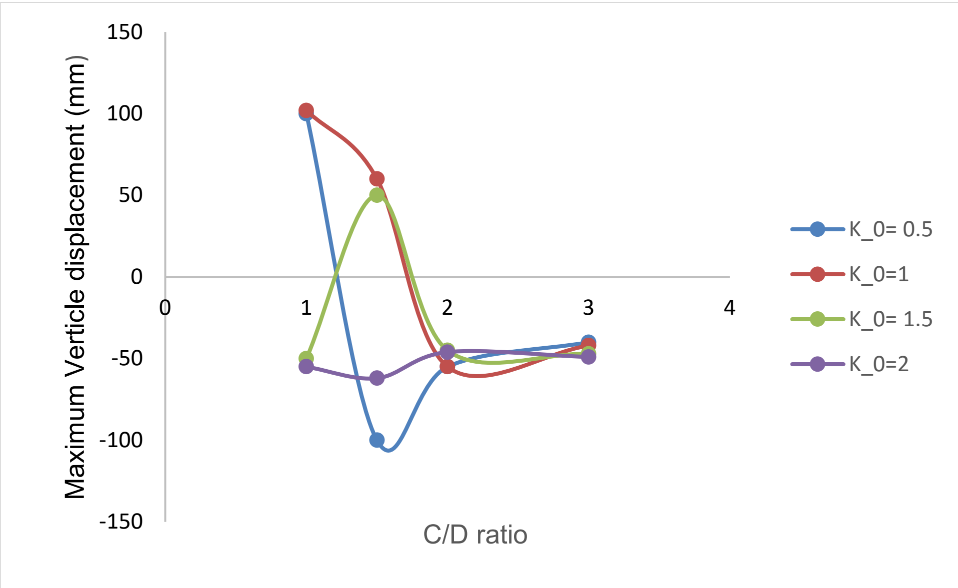


Figure 8: Maximum displacement of crown

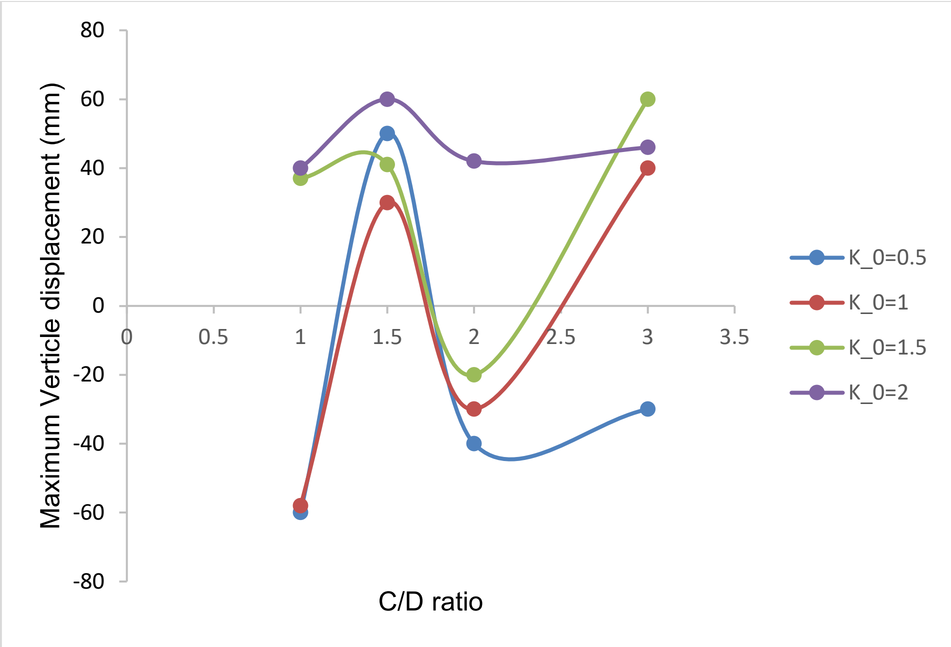


Figure 9: Maximum displacement of invert

Based on the aforementioned observations, it is evident that variations in the earth pressure coefficient significantly affect the tunnel crown, with crown displacement being particularly susceptible to these variations, resulting in notable differences. Conversely, similar displacement trends were observed for the tunnel invert under K_0 values of 1 and 1.5, while a K_0 value of 0.5 followed a consistent trend until a critical cover-to-diameter (C/D) ratio of 2, after which it exhibited more dispersed behavior. A K_0 value of 2 exerted a greater impact on the tunnel invert, resulting in its upward movement.

6 Conclusions

The examination of tunnel face stability is vital for expediting the development of new infrastructure projects and facilitating decision-making processes. With population growth exerting pressure on transportation infrastructure, the construction of Mega Tunnels offers significant benefits to both established and emerging cities. However, as tunnel construction progresses, numerous challenges and potential hazards arise, with face stability being a primary concern.

The stability of Mega Tunnels is influenced by factors such as elastic modulus, wherein higher values correlate with reduced vertical displacement of the tunnel, and vice versa. Moreover, increasing ground strength enhances resistance to displacement, thereby reducing tunnel displacement and enabling shallower seating. For example, Mega Tunnels excavated in basalt typically settle at a depth equivalent to twice the tunnel diameter (2D), while those in soft soil settle at approximately 2.5 times the diameter. However, insufficient applied face pressure may lead to instability and tunnel failure, as observed in limestone and Gneiss strata.

Optimization of applied pressure is proportional ti Youngs modulus of ground and being a crucial factor for ensuring tunnel face stability. Additionally, the lateral earth pressure coefficient significantly impacts the tunnel crown, necessitating stress rearrangement within the continuum to minimize its impact on the tunnel invert. This study offers valuable insights into tunnel planning for urban areas, facilitating the optimization of tunnel behavior with respect to ground strata.

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