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Stability Analysis of Shiraz Metro Line 1 Tunnel Using Flac2D Software

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Abstract

The growing reliance on subterranean infrastructure, spurred by the expansion of urban landscapes, the escalating population densities, the pressing need for efficient transit systems, the many environmental imperatives, and spatial constraints on surface development accentuate the pivotal role of metro tunnels akin to those found in Shiraz. These tunnels, crafted, using Earth Pressure Balance (EPB) and Tunnel Boring Machines, and fortified with segmental linings, undergo meticulous scrutiny for displacement and stability, employing static and quasi-static methodologies. Employing the sophisticated FLAC 2D software, the investigation delves into the nuanced impact of altering segmental lining thickness on displacement dynamics. Analysis results unveil a notable augmentation in displacement under quasi-static conditions, notably accentuated when the lining thickness is reduced.

Keywords: *Metro, Lining, Displacement, Numerical Analysis, Flac 2D.*

1. Introduction

Underground facilities are an integral part of modern society and have various manifestations such as subways, railroads, highways, etc. The design of each of the above spaces requires access to appropriate data and the application of special measures. In each case, the designer must first seek to improve the quality of the materials in which the tunnel has to be drilled considering the ground conditions. In many areas, the tunnels are not self-support, and it is necessary to use tunnel lining, whose selection requires a lot of studies (Alkhaza'leh et al., 2023).

The investigation of soil behavior against tunnel construction is one of the topics in the field of geotechnics, discussed in many papers and studies in recent years (Meng et al., 2020; Han et al., 2022; Al-Hawari, 2008; Azeez et al., 2019). Therefore, the current study examined the displacement around the tunnel in a case study (Shiraz metro line 1). Stability analysis of metro tunnels, along with taking the necessary measures to stabilize them, is an essential study project. Several studies have been conducted in this regard, some of which are mentioned. Stability analysis was performed in a tunnel in Shanghai using FLAC3D software (Zhang et al., 2009). Another study investigated the stability of drilled tunnels in soft clay soils (Lee et al., 2006). Other studies have examined the stability of the underwater tunnels using numerical methods and the Mohr-Coulomb criterion (Hofle et al., 2008). The stability of tunnels with support systems has been studied using numerical methods in Japan (Funatsu et al., 2008). Another study modelled the stability of shallow tunnels by the finite element method (Fellin et al., 2010). Also, some research in China has focused on changing soil properties in FPB mechanized drilling to increase stability (Yang et al., 2013).

The surrounding soils near tunnel crown and invert or across tunnel horizontal diameter are very critical to the tunnel convergence (Huang et al., 2017).

The numerical results reveal that compared to the moving-train load, the effect of earthquake action on the dynamic response of the subway tunnel is more prominent (Li et al., 2021).

The study area is located in the southeast of Shiraz, between Allah Square and Valiasr (Modarres Boulevard). This area includes a part of Shiraz urban railway with a length of about 7.5 km, including two tunnels with a diameter of nearly 7 meters in the vicinity, with a distance of 15 meters between their centers. As the tunnels are symmetrical and parallel, the present study has considered only one of them for modelling. A TBM device of EPB type has been proposed for tunnel drilling and lining implementation as the geological conditions of the region, clay along with silt and water content are taken into consideration. The tunnel has been modeled using geotechnical information of the soil and the characteristics of the segments used in the tunnel in the BHA11 borehole area with approximately 15 meters of overburden as the highest overburden in the study area. FLAC 2D software was used to measure the displacements in the studied tunnel. FLAC 2D is a finite difference numerical modelling software used in continuum contexts with static and quasi-static analyses. A 2D numerical study has been

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used to investigate the factors that affect the behavior of segmental tunnel linings (Do et. al., 2013).

The aim of this study is to assess the stability of the Shiraz metro line tunnel. To achieve this goal, the engineering and geomechanically properties of materials will be identified, and static as well as pseudo-static analyses will be conducted using the Flac2D software. For enhanced result clarity, various two-dimensional models with distinct color schemes will be presented.

2. Materials and Methods

2.1. General Geology of Shiraz

The city of Shiraz has developed on the young alluvium of the fourth period, whose origin is the function of sediment transport by dry river and sedimentation in Maharloo Lake. The alluvium of the fourth period of Shiraz Plain ranges from coarse-grained debris sediments and alluvial fans in the margins of heights to lake fine-grained sediments along Maharloo Lake. Sediments are mostly coarse-grained in the north and northwest of the plain, including sand, gravel, and cobble, resulting from the erosion of the surrounding calcareous heights and sedimentation by the dry river. The deposits are often medium-grained in the central part of the plain and include sand and gravel with a mixture of clay and silt. Sediments are often fine-grained in the western and southwestern parts of the plain, adjacent to Sultanabad Mountain, due to the presence of the Fars Group formations and the ChenarRahdar River, which transports and deposits sediments from the Fars Group formations in the west of Shiraz basin. Sediments gradually become fine-grained in the eastern and southeastern parts of the plain and around Maharloo Lake, consisting of clay, silt, gypsum, and swamp and lake sludge.

In addition to surface changes, the type and granularity of deep sediments are also variable, with deep sediments of the northern and northwestern areas having coarser grains. However, surface sediments in the central and eastern parts of the plain are mostly fine-grained. Fine-grained and coarse-grained sediments are deposited alternately with increasing depth. Figure 1 shows the geological profile of the study route.

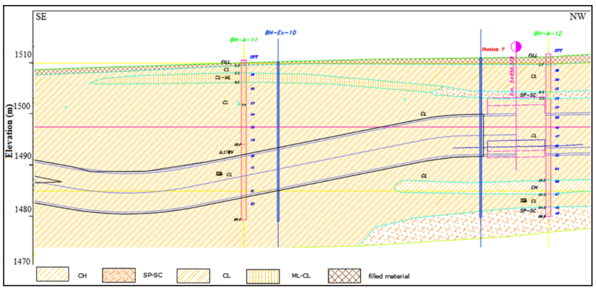

Figure 1. Geological profile of the study area.

2.2 Geometric and Geo-Mechanical Characteristics of Shiraz metro

Phase 1 plan of the Shiraz metro with a length of approximately 24 km includes three deep, semi-deep, and surface parts, depending on the geological conditions of the project. The deep tunnels, with a length of approximately 15 km, are drilled in the alluvial environment below the water table. Excavation of this tunnel is carried by two shield TBMs using the Earth Pressure Balance (EPB) method in the form of twin tunnels with a drilling diameter of 6.88 meters and a final effective diameter of 6 meters. The permanent support of these tunnels is by prefabricated concrete parts called segments with an arrangement of 1 + 2 + 2 + 1. A6 is the largest segment, called the Counter Key, and A1 is the smallest segment, called the Key in the shape of a trapezoid. Other segments, including A2, A3, A4, and A5, have the shape of a parallelogram and are placed next to the Counter Key and Key segments (Figure 2). A6 segments have the largest approximate width of 1.42 m, while segments of the Key have the smallest approximate width of 1.38 m. Table 1 presents the mechanical characteristics of the segments. The study area was in the BHA11 borehole. The depth of the overburden is about 15 meters in this area, and the groundwater level is approximately 7 meters below the ground. In general, the soil section in the BHA11 borehole can be divided into three layers located up to a depth of 25 meters from the ground surface. From a depth of 25 m, the type of soil is similar to the second layer in the BHA11 borehole, with mainly clay and silty clay layers, which is generally considered in four-layer modeling. Table 2 shows the geo-mechanical parameters of the layers. Figure 3 shows the plastic zones after the drilling stage. According to the figure, the tensile zones dominate the shear zones in the figure, and most of the collapse is of the tensile type.

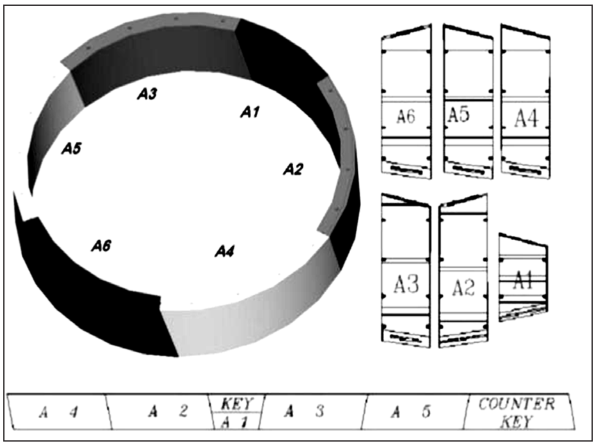

Figure 2. Arrangement of segments used in Shiraz metro line 1 tunnel.

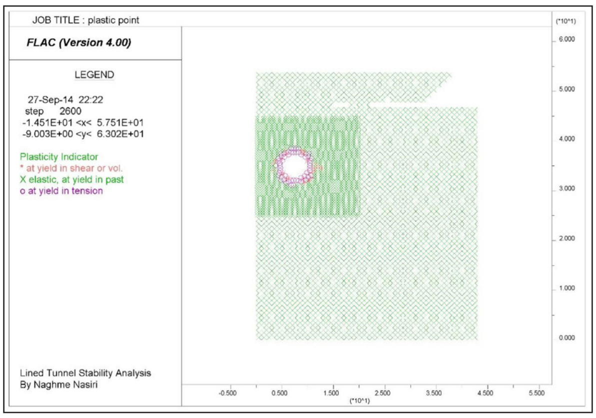

Figure 3. Plastic zones after the drilling stage without support lining.

Table 1. Mechanical parameters of the lining used in the tunnel.

Material	Concrete
f'c	510 Kg/cm^2
Elastic Modulus	3.17*10^5 KN/m^2
Poisson Ratio	0.2
Thickness	0.3 m
I	0.00225 m^4
A	0.42m^2
EI	7.13*10^4 KN.m
EA	9.5*10^6 KN
Weight per Unit Length	8 KN/m/m

Table 2. Geomechanical parameters of layers.

Type of materials	Depth (m)	Cohesion (Kpa)	Internal friction (degrees)	Density (Kg/m^3)	Bulk modulus (Mpa)	shear modulus (Mpa)
1st layer	0-3	33	35	2000	37.33	22.4
2nd layer	3-20	52	29	2080	33.33	20
3rd layer	3-25	28	37	2000	31.33	18.8
4th layer	25-54	52	29	2080	3.33	20

3. Results

3.1 Investigation of Displacements Around the Tunnel During Static Analysis Tunnel Modeling Without Support Lining

As EPB type, TBM machine has been used in Shiraz metro tunnel drilling, and the body of the tunnel is raveling ground, the support system is applied without time interruption and simultaneously with the drilling process. Figure 4 illustrates the historical progression of unbalanced forces after the drilling stage, focusing on conditions where no segmental lining has been implemented. This visual representation tracks the evolution of forces exerted within the tunneling environment over time, providing a detailed timeline of the unbalanced forces as the tunnel progresses. It offers insights into the structural stability and integrity of the tunnel in the absence of segmental lining. The maximum permissible displacement in tunnel construction is crucial in ensuring structural stability and safety.

The assessment of the tunnel's structural integrity becomes paramount where tunnel drilling occurs before the implementation of a support system,. In cases where the model doesn't attain equilibrium or where the tunnel collapses, the consequences are evident, as depicted in Figure 5, showcasing vertical stress contours post-drilling. High displacement, as evident in this figure, indicates significant instability and structural displacement within the tunnel itself. This instability highlights the critical need for a robust support system to maintain stability and prevent potential collapses or structural failures within the tunneling process. At this stage, the vertical and horizontal displacements are plotted for points with different angles in the tunnel. Also, Figures 6 and 7 show displacements in two horizontal and vertical directions. As shown, the displacement is considerable in this case and even reaches one meter in the vertical direction. Therefore, the application of the support lining is essential in this tunnel.

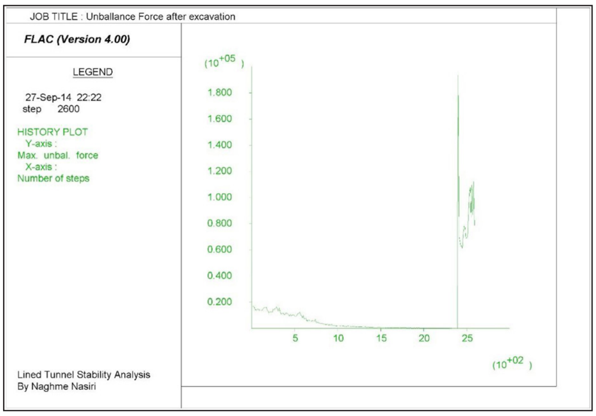

Figure 4. History of unbalanced forces after the drilling stage without segmental lining.

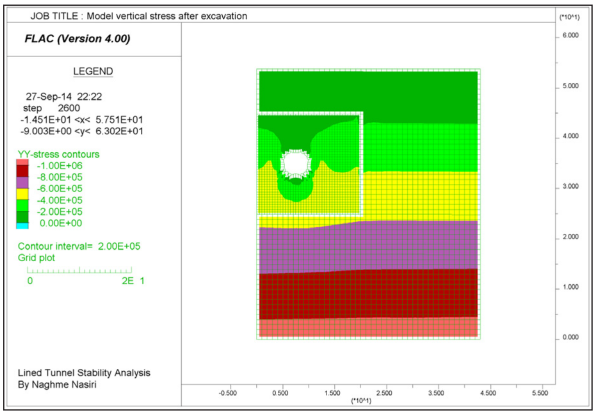

Figure 5. Vertical stress contours after the drilling stage without segmental lining

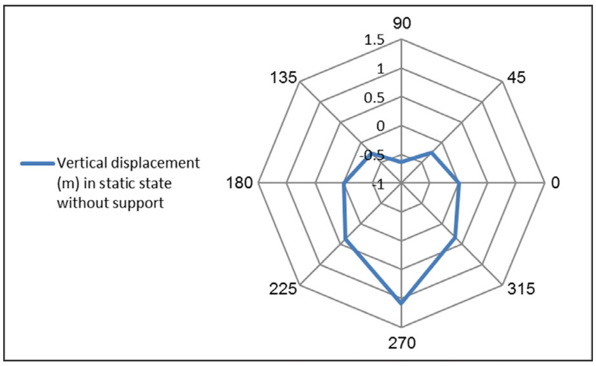

Figure 6. Vertical displacement in static state without support.

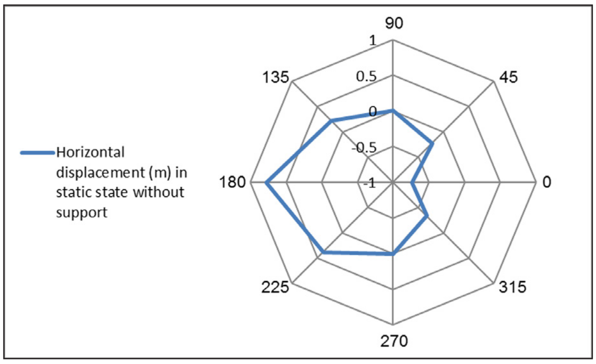

Figure 7. Horizontal displacement in static state without support.

3.2 Modeling with Support Lining

In the next step, drilling was done, having the support system in a static state. As mentioned before, the drilling and lining installation steps were done simultaneously. Figure 8 shows the history of unbalanced forces after drilling. Accordingly, there is a lack of balance of forces after drilling, and finally, equilibrium is established in the model.

Figure 9 shows the vertical displacement contours after drilling with a segmental lining. In this case, the vertical displacement in the tunnel ceiling is between 5-10 mm as subsidence, and the vertical displacement in the form of tunnel floor heave is between 1.5-2 cm. The amount of surface subsidence, in this case, is about 5 mm. Figures 10 and 11 show the values of the displacements in the vertical and horizontal directions on the diagram. It is evident that the displacement is much less than it is in the previous case, and it can be, therefore, said that the tunnel is stable. Figure 12 compares the displacements in the vertical direction in the above two states. According to the diagram, the displacement in the static state with the support lining is much less than the state without the support lining system, and the use of the lining in this tunnel is necessary.

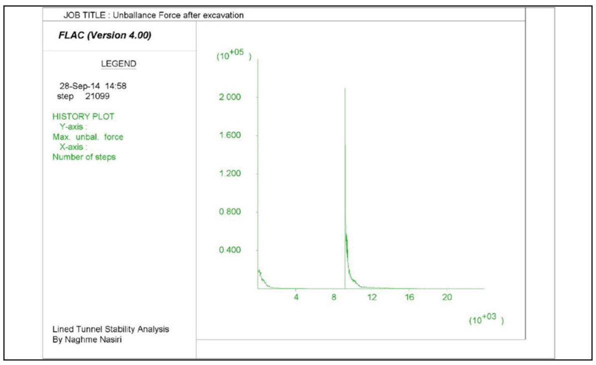

Figure 8. History of unbalanced forces after the drilling stage with a support lining.

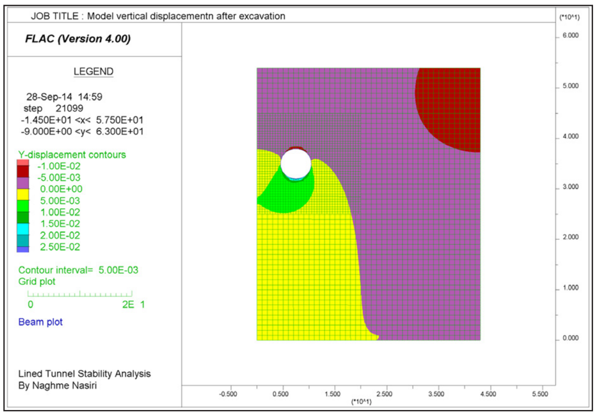

Figure 9. Vertical stress contours after the drilling stage with a support lining.

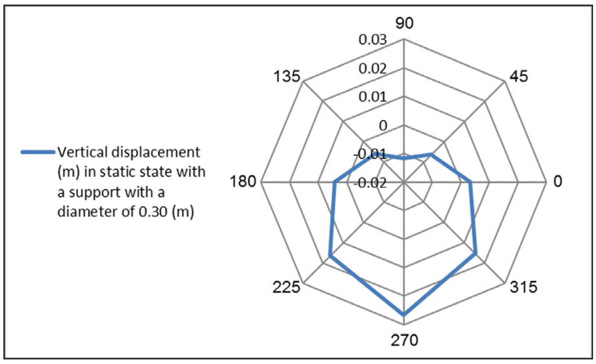

Figure 10. Vertical displacement in static state with a support lining.

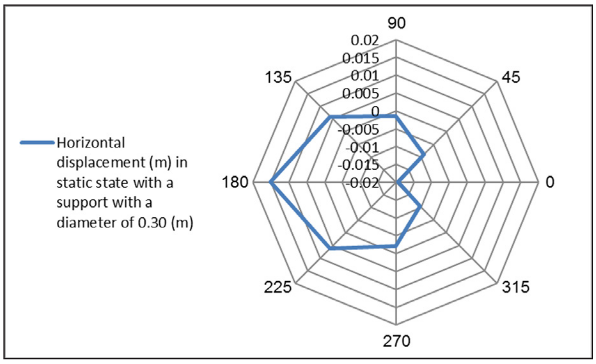

Figure 11. Horizontal displacement in static state with a support lining.

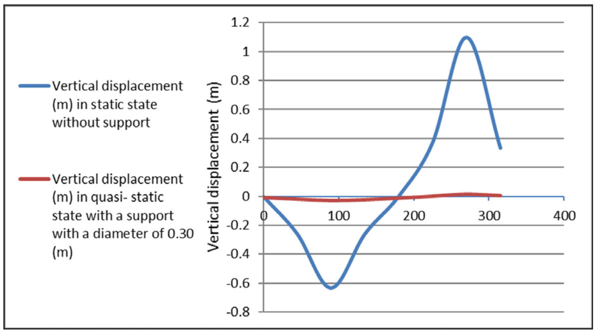

Figure 12. Comparison of displacements in the vertical direction in static state with and without lining.

For modeling in quasi-static analysis, the procedure is similar to the previous steps. The only difference is that the earthquake horizontal acceleration in the area is considered 0.3 g according to the 2800 code of practice, an Iranian code of practice for seismic resistant design of buildings (Road, Housing and Urban Development Research Center, 2014). As shown in Figure 13, the model has also reached equilibrium after the drilling stage in this case. Figure 14 shows the vertical displacement after the drilling stage in the quasi-static state, indicating an increase in the displacement compared to the static state. The surface subsidence also reaches 2 cm.

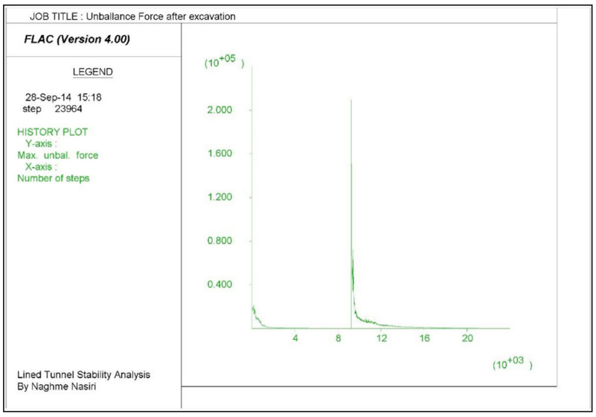

Figure 13. History of unbalanced forces in quasi-static state with support lining.

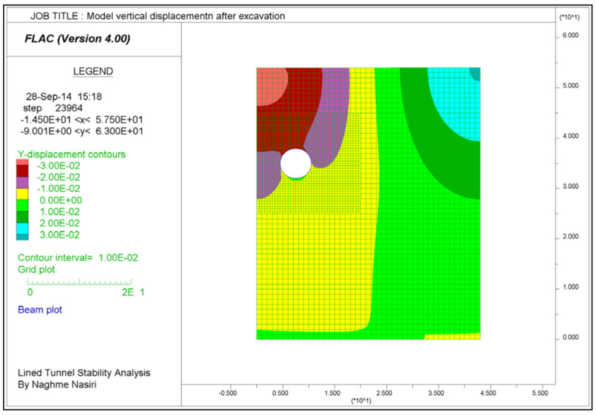

Figure 14. Vertical displacement contours after the drilling stage in quasi-static state with support lining.

According to Figures 15 and 16, the displacement in both vertical and horizontal directions has increased in the quasi-static, compared to the static state, and the tunnel is still stable.

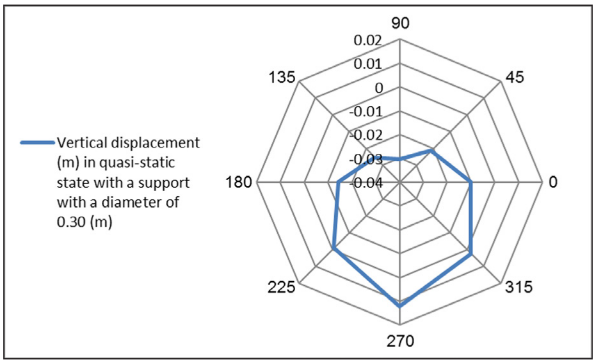

Figure 15. Vertical displacement in a quasi-static state with support lining.

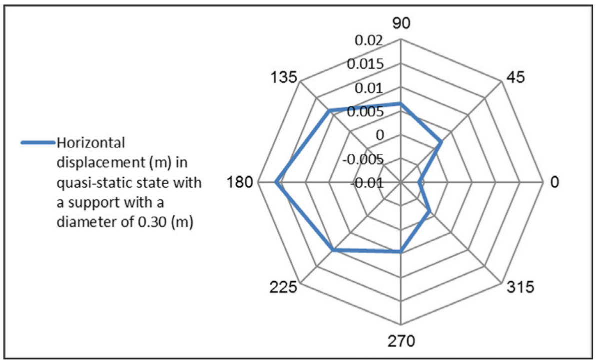

Figure 16. Horizontal displacement in a quasi-static state with support lining.

3.3 Investigation of Displacements by Changing the Lining Thickness During Quasi-Static Analysis

The displacement values were obtained for linings with a thickness of 0.25, 0.20, 0.15, and 0.10 meters in the vertical and horizontal directions. It should be noted that as the thickness of the lining changes, the properties of the lining also change.According to the diagrams in Figures 17 and 18, the displacement increases with decreasing the lining thickness. Accordingly, the lining with a thickness of 0.3 m has less displacement than the others. Thus, it is the most suitable case for use as a support lining in the relevant tunnel among the studied thicknesses.

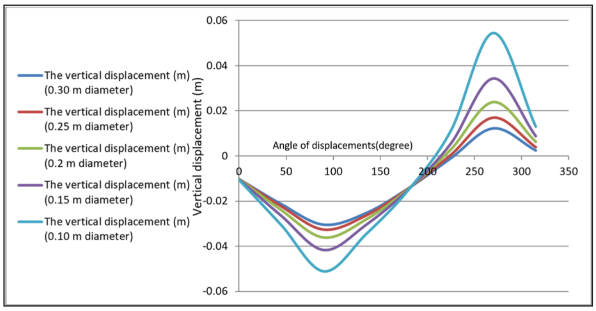

Figure 17. Comparison of vertical displacement in quasi-static state with different thicknesses of support lining.

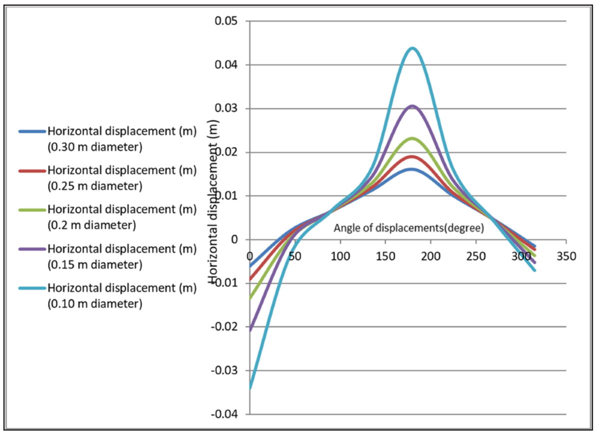

Figure 18. Comparison of horizontal displacement in quasi-static state with different thicknesses of support lining.

4. Discussion:

The study's findings underscore the pivotal role of support lining in ensuring the stability and integrity of tunnels during and after drilling processes. The absence of support lining led to notable instabilities, marked by high displacements and the inability to reach equilibrium, resulting in the collapse of the tunnel model. This result aligns with established research emphasizing the importance of support systems in underground constructions (Zhang et al., 2017).

Simultaneous application of support lining during drilling proved instrumental in establishing equilibrium and mitigating displacements. This strategy resonates with previous studies emphasizing the real-time implementation of support systems during excavation to counteract unbalanced forces and maintain stability (Qin et al., 2022). The analysis showcased that the support lining effectively reduced both vertical and horizontal displacements, promoting stability and structural integrity.

Moreover, the investigation into different lining thicknesses yielded valuable insights. The varying displacements, corresponding to different thicknesses, highlighted those thinner linings and resulted in higher displacements. They emphasize the critical role of proper lining thickness selection. This finding corroborates with the body of research, focusing on the relationship between lining properties and tunnel stability (Xu et al., 2021; Chen et al., 2019).

The study's implications extend to practical applications in tunnel construction and engineering practices. Engineers and construction teams can utilize these findings to make informed decisions regarding the implementation of support lining strategies. Optimal thickness selection, such as the identified 0.3-meter thickness, emerges as a crucial consideration to minimize displacements and ensure stability during tunnel construction. However, further research could explore additional variables, impacting support lining effectiveness, such as material properties, installation methods, and geological conditions. Additionally, conducting field studies to validate these findings in real-world tunnel construction scenarios would strengthen the practical applicability of the results.

This study emphasizes the indispensability of support lining systems in maintaining tunnel stability during and after drilling processes. The insights into simultaneous application and optimal thickness selection serve as a foundation for enhancing tunnel engineering practices, contributing to safer and more resilient underground infrastructure.

5. Conclusions

The metro route, primarily clay with low plasticity and occasional silt and sand, necessitates sealed prefabricated concrete parts due to soil permeability. Analysis affirms tunnel instability without support lining, evident in unbalanced force diagrams and displacement contours. However, appropriately designed linings, detailed in Table 1, stabilize the tunnel, limiting maximum vertical displacement to 20 mm. Both static and quasi-static analyses confirm tunnel stability with designed support linings, with the only discrepancy being increased displacement due to seismic factors in the latter case. Reducing lining thickness exacerbates displacement, as depicted in relevant diagrams.

Conflicts of interest

The authors declare no conflict of interest

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