DEFORMATION BEHAVIOR OF A CIRCULAR TUNNEL IN LAYERED SOIL USING FLAC 3D

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ABSTRACT

In nature, soils with the same characteristics are hardly seen. Most of the time, layered soil profiles are observed. Sometimes, it is necessary to construct tunnels within this layered soil. So, it is essential to understand the tunnel behaviour in layered soil to ensure its safety. This study investigates the response of tunnel deformation behaviour under a strip surcharge load applied across the tunnel and along the tunnel at the top of the model in layered soils. Within this study, the numerical model of circular shaped tunnel is developed using FLAC 3D, where three different soil layers with different physical characteristics have been considered. The Mohr- Coulomb model is adopted as a material model. During this study, the effect of pore water pressure is also considered. A strip surcharge load is applied on the top face at various locations of the numerical model, with pore water pressure and without pore water pressure. In both cases, the thickness of these three soil layers is kept the same. Finally, the result is analysed, and the findings are reported. This study helps to understand the impact of surcharge and pore water pressure on tunnel deformation in layered soil.

Keywords: *Multi-layered soil, Circular Tunnel, Surcharge Load, FLAC3D*

1. INTRODUCTION

In the age of urbanization, tunnels are one of the most important infrastructure that has improved transport systems and made utility facilities more accessible and more convenient. Tunnels are constructed within both soil and rock strata. Although tunnels are constructed in both shallow depth and deep depth, construction of tunnel in shallow depth has significantly increased in recent times. Inside the soil, the tunnel experiences adverse conditions such as surcharge load, water pressure, and earth pressure which is threatening for tunnel stability. Research on tunnel behaviour plays a vital role in increasing the stability and durability of tunnel structures. For this purpose, numerical studies make it possible to do indoor experiments more precisely and accurately where researchers can consider different physical conditions to understand tunnel response.

Previous tunnel accidents caused by an applied surcharge on the ground surface and pore water pressure in the soil, have inspired researchers to research tunnel stability and tunnel response to its physical characteristics that reveals from previous studies(H. W. Huang and Zhang 2016; Z. Huang et al. 2020; Tan et al. 2020; Wang et al. 2016; Yan et al. 2018; Zhang et al. 2018). The study about the face stability of the circular tunnel, while driven underneath the water table using a kinematical approach of limit analysis, was conducted by Mašín et al. (2006). While researching the impact of pore water pressure on tunnel support, Bobet (2003) considered both dynamic and seismic loads. Another study was carried out by Z. Huang et al. (2020), where the authors considered seven different soil profiles to evaluate the deformational response of dual circular tunnels induced by surcharge loading. Yamamoto et al. (2011a, 2011b) conducted two different studies to evaluate the stability of both a circular and a square tunnel in cohesive-frictional soil due to surcharge loading. Similar study for dual circular tunnel was also conducted by Yamamoto et al. (2013). Zou and Qian (2018) investigates the influence of coupled flow deformation on the stability of tunnels constructed under the water table. They carried out this by utilizing a well-integrated strategy that integrates the kinematic principles of limit analysis theory with numerical simulations, as comprehensively documented in their work. Besides the study conducted by F. Huang and Yang (2011) to investigate the influence of pore water pressure on the shape of a collapsing block in a circular tunnel. They concluded that the rock parameters and tunnel radius have a significant effect on the collapsing shape of circular tunnels, and increasing the pore pressure coefficient reduces the width and height of the collapsing block in circular tunnels. Ghotbi Ravandi and Rahmannejad (2013) adopted numerical modelling to forecast the elastic and plastic wall displacements of circular, D-shaped, and modified horseshoe-shaped tunnels under stress fields that are not influenced by hydrostatic pressure. Yan et al. (2018) researched the dynamic behaviour of shield tunnels while subjected to an impact load caused by a derailed train.

The objective of this study is to examine the displacement behaviour of a circular tunnel constructed in a multi-layered soil profile under surcharge load. A 10 m wide surcharge strip is considered that applied on the top surface of the circular shaped tunnel. The model is constructed with three different types of soil, and the surcharge strip may represent a railway track or roadway. In this study, the displacement at the crest of the tunnel model is analysed in the presence of a water table at different positions and in the absence of a water table. This study aims to reveal the deformational behaviour of the tunnel due to the applied surcharge, both in the presence and absence of a water table.

2. METHODOLOGY

All the steps required for the successful completion of this study are described in the following section.

3. Problem Overview

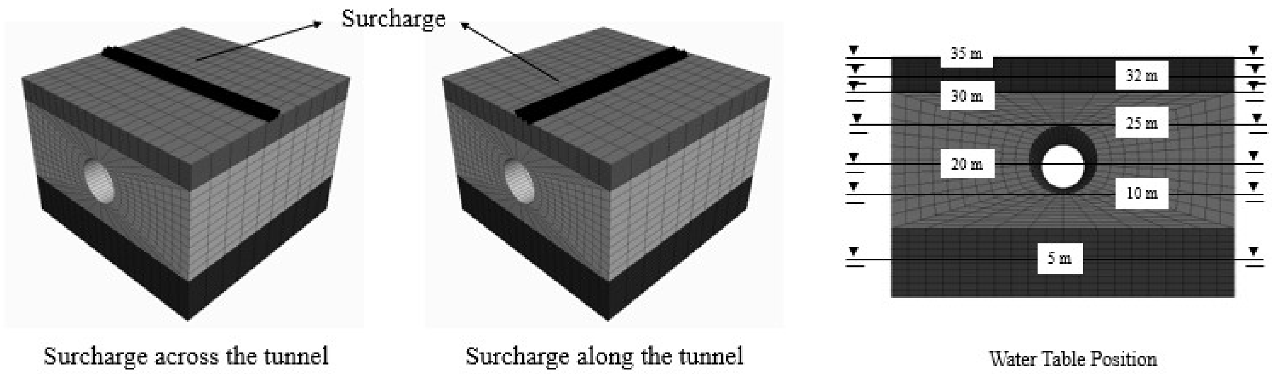


Figure 1: Graphical presentation of problem overview

A strip surcharge of 1 MPa with a width of 10 m, which may represent a railway track or roadway load, is applied along and across the tunnel model, consisting of three types of soil. The water table at different positions is also considered in this study. The displacement at the crest of the tunnel is analysed due to the applied surcharge, both in the presence of the water table at different locations and in the absence of the water table. The graphical presentation of the problem outline is illustrated below as shown in Figure 1.

4. Creation of Geometry

For this study, a model is constructed by using FLAC3D having a length of 50 m and width of 50 m and a total height of 35 m, and the model includes a tunnel with a diameter of 10 meters. Three types of soil layers are considered, each with a height of 10 m, 20 m, and 5 m, respectively. As this study focuses on analysing the displacement behaviour at the crest level of the tunnel, displacement is observed at the midpoint at the crest along the tunnel length. Details are illustrated in Figure 2.

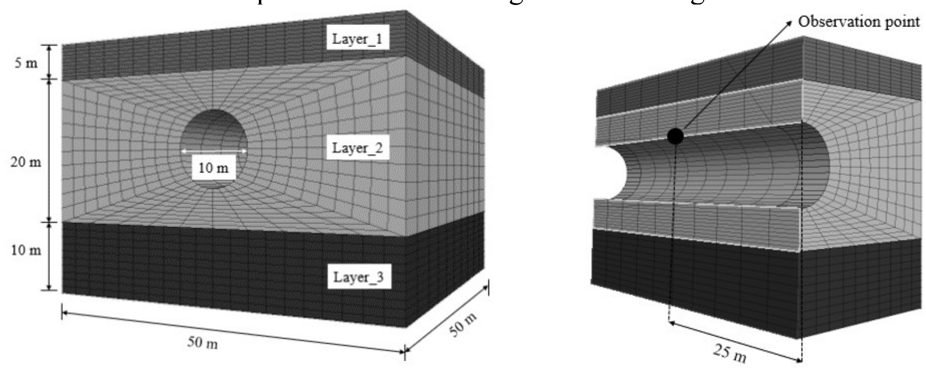


Figure 2: Circular tunnel model constructed using FLAC3D

5. Material Properties

In this study, Mohr-Coulomb is considered as a material model and a model is constructed using three types of soil profiles and water is considered as a fluid material. The properties of soil and fluid are presented in Table 1 and Table 2, respectively(Itasca Consulting Group 2017).

Table 1: Soil Properties

Soil Type	**Thickness** m	**Bulk Modulus** MPa	**Shear Modulus** MPa	**Cohesion** MPa	**Friction angle** (Degrees)	**Dilation angle** (Degrees)	**Dry density** kg/m^3
Clay	5	25.0	11.6	0.025	26	0	1830
Sandy Slit	20	81.9	37.8	0	34	2	2000
Sandy Clay	10	147.4	68	0	38	5	2050

Table 2: Fluid Properties

Fluid Type	**Fluid bulk Modulus** Pa	**Density** kg/m^3
Water	2×10^9	1000

6. Boundary Conditions

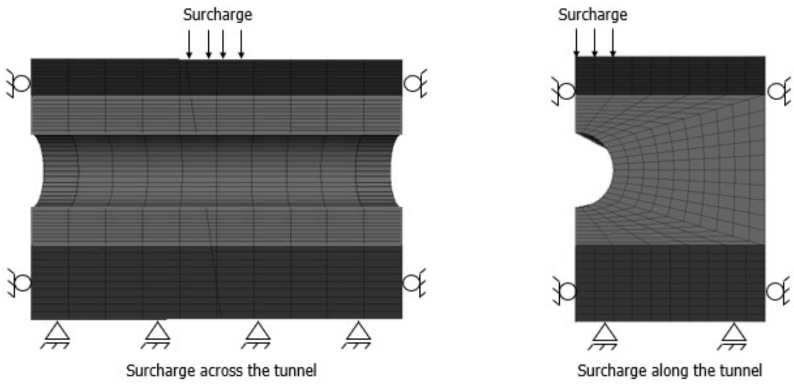


Figure 3: Illustration of boundary conditions used in this analysis

The bottom face of the model is considered fixed that prevent both vertical and horizontal displacement. Conversely, all faces except the top surface are considered roller boundaries that allow only vertical displacement and restricting horizontal displacement. The top surface is kept free, and a surcharge strip is applied both across the tunnel and along the tunnel. A graphical presentation of applied boundary conditions is presented in Figure 3.

7. RESULT AND DISCUSSION

Applied surcharge is considered both across the tunnel and along the tunnel that are presented in the following sections.

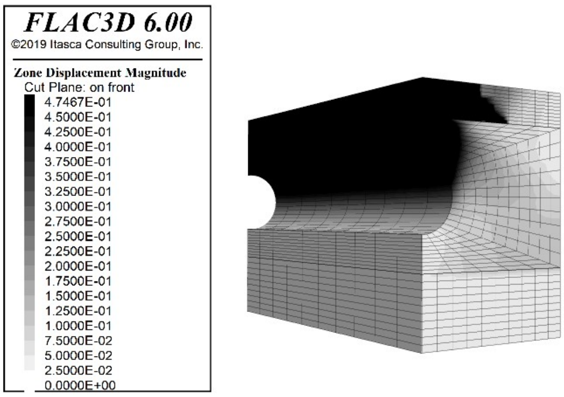


Figure 4: Absence of Water Table

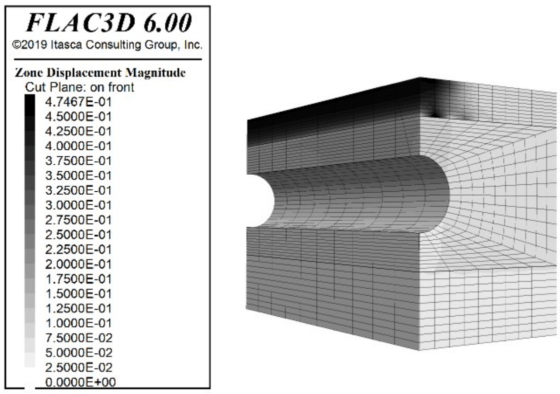


Figure 5: Water Table at 5 m from bottom

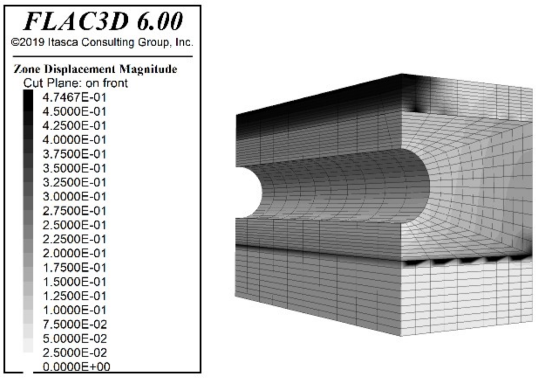


Figure 6: Water Table at 15 m from bottom

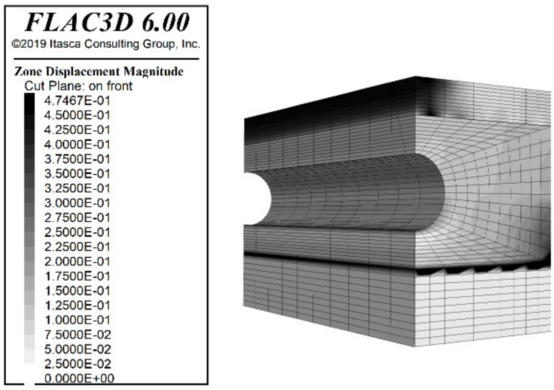


Figure 7: Water Table at 20 m from bottom

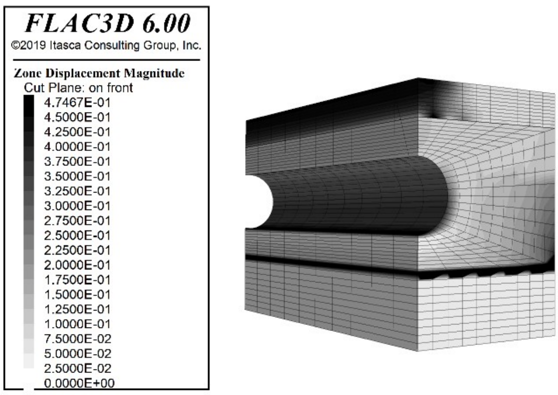


Figure 8: Water Table at 25 m from bottom

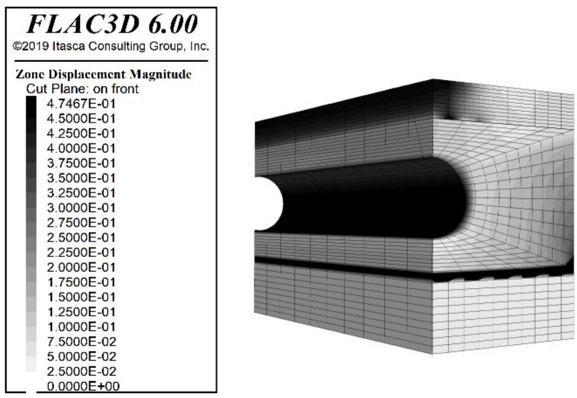


Figure 9: Water Table at 30 m from bottom

8. Surcharge is Applied Along the Tunnel

The darkest zone at the crest of the zone displacemer
the tunnel's crest experiences a more significant impac
water table maximum displacement is observed from
applied surcharge at the crest level of the tunnel is
considered, as shown in the contour map in Figure
buoyancy property of water. As the water table is grac
significantly minimized by the water table, as shown
up to 25 m, the lower crest of the tunnel becomes
before, shown in Figure 4-7. As the water table contii

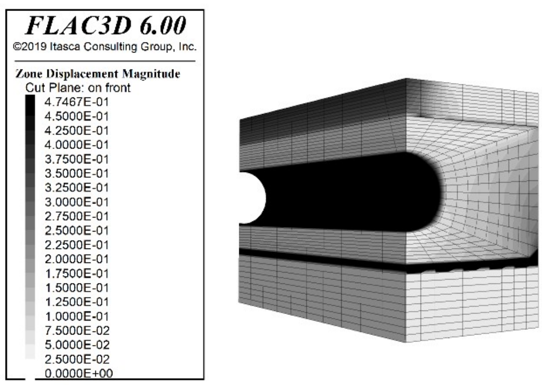


Figure 10: Water Table at 32 m from bottom

Figure 11: Water Table at 35 m from bottom

observed that the tunnel boundary experiences a significant impact from water pressure, and its colour darkens along the tunnel boundary, as shown in Figure 9-11. As the water table increased from the upper crest to the top surface of the model, though the effect of surcharge significantly decreased, water pressure gradually increased, exerting force on the tunnel boundary; as a result, displacement at the upper crest of the tunnel is gradually increased, illustrated in the graph, shown in figure 12.

9. Surcharge is Applied Along the Tunnel

Figure 12: Stepwise displacement profile corresponding to water table position when surcharge is applied along the tunnel

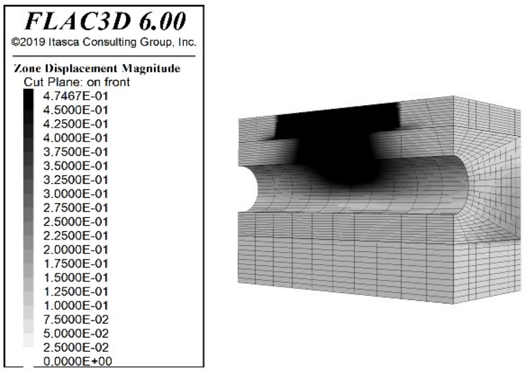


Figure 13: Absence of Water Table

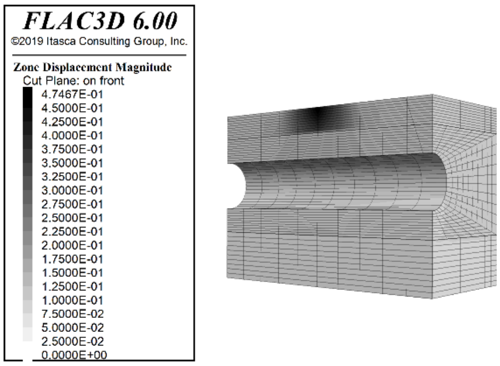


Figure 14: Water Table at 5 m from bottom

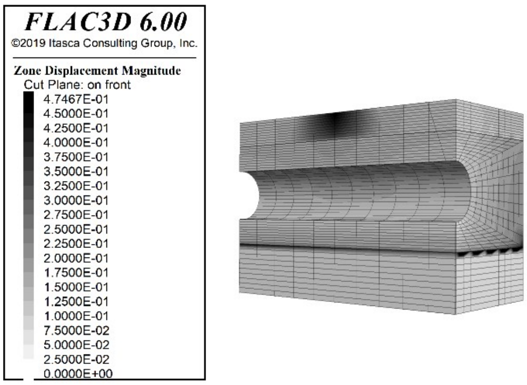


Figure 15: Water Table at 15 m from bottom

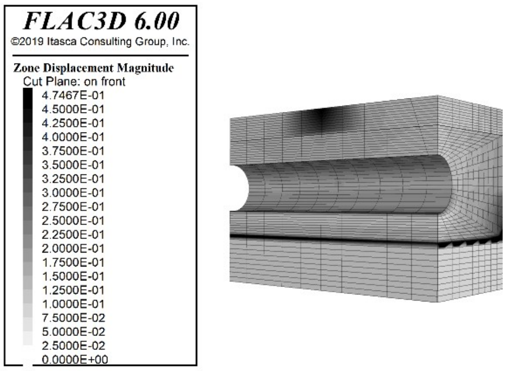


Figure 16: Water Table at 20 m from bottom

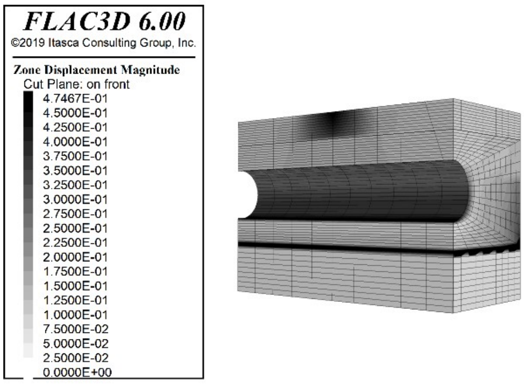


Figure 17: Water Table at 25 m from bottom

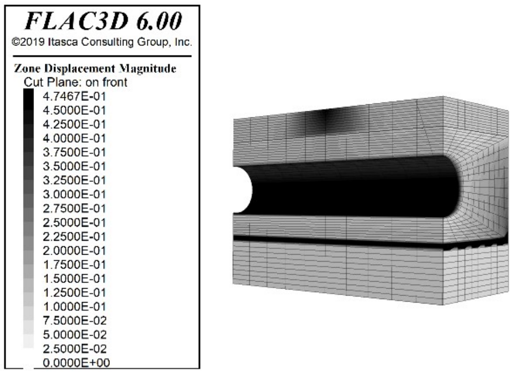


Figure 18: Water Table at 30 m from bottom

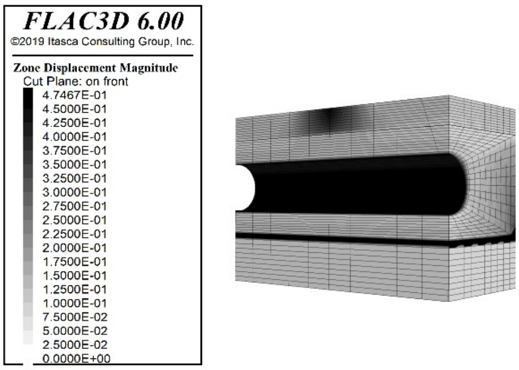


Figure 19: Water Table at 32 m from bottom

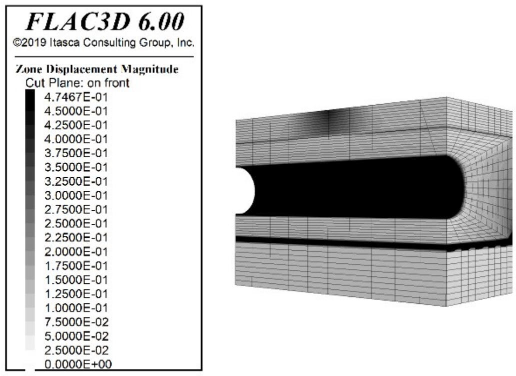


Figure 20: Water Table at 35 m from bottom

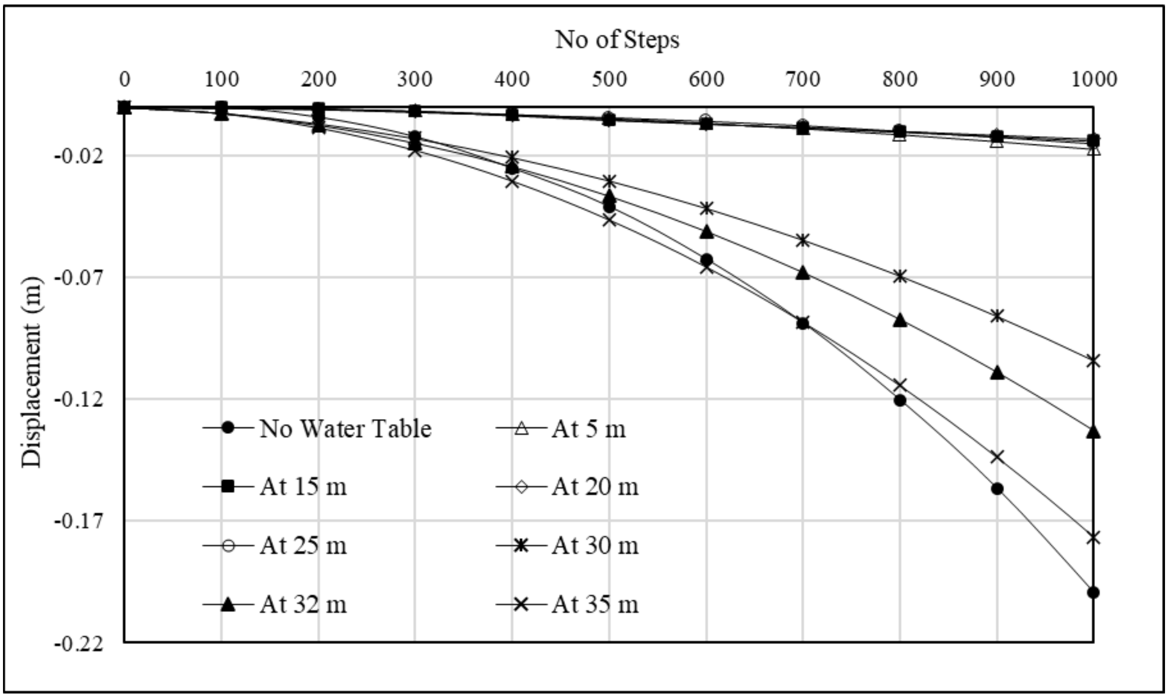


Figure 21: Stepwise displacement profile corresponding to water table position when surcharge is applied across the tunnel

The illustrated contour maps shown in Figure 13 – Figure 20 depict the impact of the surcharge applied across the tunnel, both in the presence and absence of a water table. In the absence of a water table, the maximum displacement effect is observed, and the area is coloured dark, particularly where the surcharge is applied, as shown in Figure 13. Here, the graph presented in Figure 21 illustrates the effect of water on displacement. Without a water table, the applied surcharge results in maximum displacement. However, when the water table is considered to extend from the bottom of the tunnel up to the lower crest, the displacement is significantly reduced due to the buoyant effect of the water. Further increasing the water table, the effect of water pressure along the tunnel wall boundary is increased; as a result, displacement at the tunnel crest is gradually increased again, illustrated in the graph shown in Figure 21.

10. Comparison of Induced Displacement

By using graphs, this section illustrates the comparison of the deformation at the crest of the tunnel caused by the application of surcharge on top of the tunnel model, both along the tunnel and across the tunnel. Figure 22 shows that in the absence of the water table, the deformation caused by the surcharge applied along the tunnel is higher compared to the surcharge applied across the tunnel.

Furthermore, in the presence of the water table, it is observed that though displacement is reduced both along the tunnel and across the tunnel due to surcharge applications, in all cases, the displacement is relatively lower across the tunnel compared to along the tunnel, as illustrated in Figure 23- Figure 26. When the water table is considered from the upper crest of the tunnel to the top surface of the model, due to the water pressure effect that act along the tunnel wall boundary, it is noticed that despite of applying a surcharge either along the tunnel or across the tunnel, the displacement at the tunnel crest remains the same, as presented in Figure27- Figure 29.

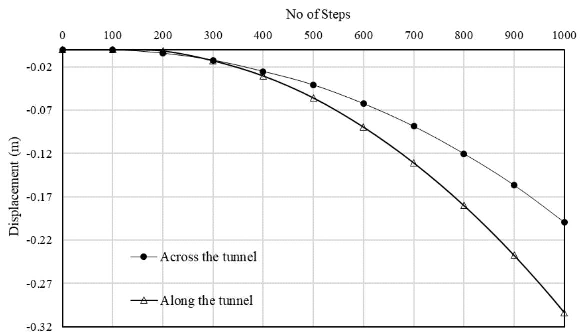


Figure 22: Comparison of induced displacement due to applied surchage in absence of the water table

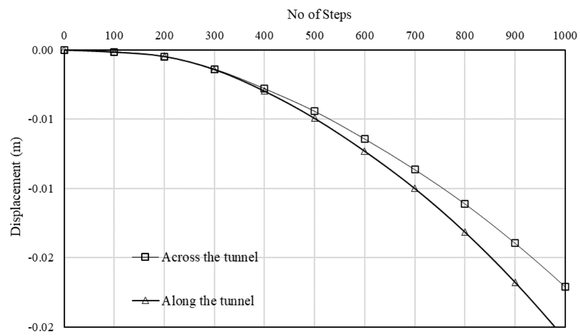


Figure 23: Comparison of induced displacement due to applied surchage when the water table is at 5m

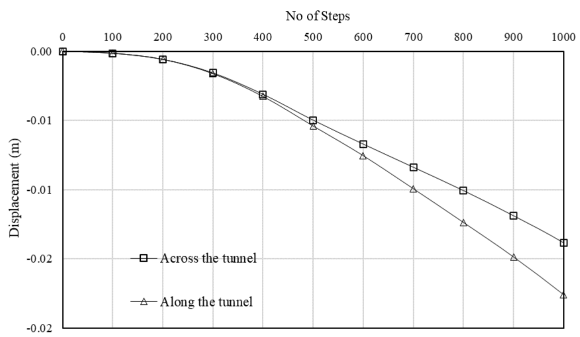


Figure 24: Comparison of induced displacement due to applied surchage when the water table is at 15m

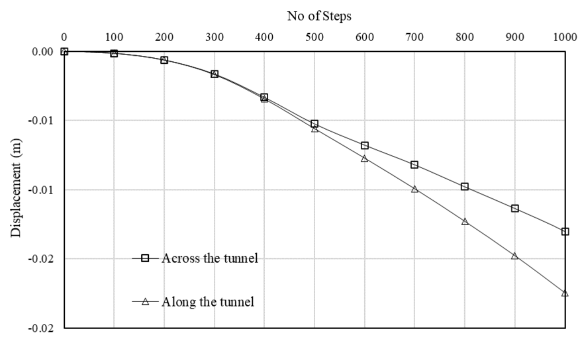
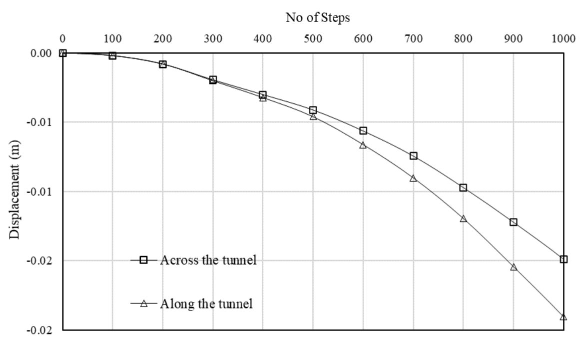
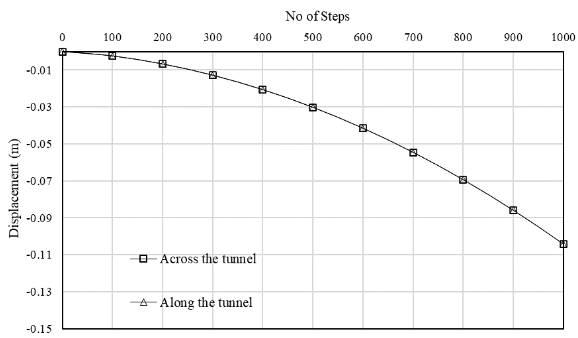


Figure 25: Comparison of induced displacement due to applied surchage when the water table is at 20m





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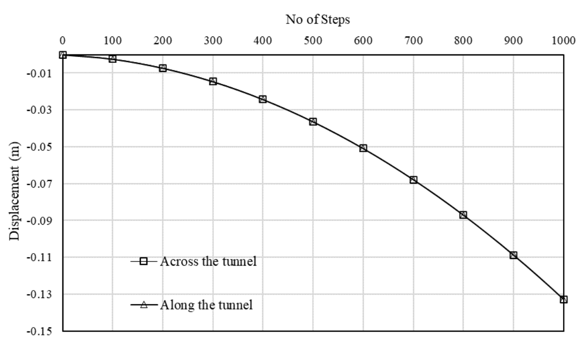

Figure 28: Comparison of induced displacement due to applied surchage when the water table is at 32m

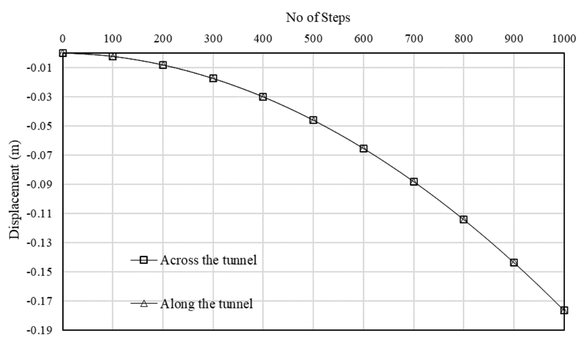

Figure 29: Comparison of induced displacement due to applied surchage when the water table is at 35m

11. CONCLUSION

To ensure the structural safety of the tunnel, it is important for us to understand the tunnel behaviour corresponding to different physical parameters. This paper has investigated the deformational behaviour of a circular tunnel due to the application of surcharge load both along the tunnel and across the tunnel in the presence of a water table at different positions. The model has been constructed in a multilayer soil profile by using FLAC3D. Here, a surcharge strip has been considered on the top surface of the model, both the tunnel and across the tunnel on the top of the model, and the deformational response due to applying the surcharge in these two directions has been compared. The analysis shows that the tunnel crest experiences significant deformational response when a surcharge is applied along the tunnel. Water table plays a vital role in reducing the effect of surcharge on the displacement behaviour. It is noticed that up to the lower crest of the tunnel model, displacement is significantly reduced by the water table. When the water table gradually rises, water pressure acts uniformly along the tunnel. As a result, displacement is noticeably gradually increased and when water table is located over upper crest of the tunnel it is noticed that displacement remains the same due to the application of surcharge both along the tunnel and across the tunnel. Here displacement curve due to application of surcharge is similar to the previous studies conducted by different researchers (Du, Dias, and Do 2020; Gao, X. Wang and Jiang 2021; Z. Huang et al. 2020).

Finally, it can be concluded that the application of surcharge along the tunnel is more severe than applying it across the tunnel. For future studies, horseshoe-shaped tunnels can be considered for similar studies.

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