Paper ID: CE 0363

Effect of Tunnel Shape on the Deformation Behavior of a Tunnel Using FLAC3D

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Abstract

The shape of a tunnel plays a vital role in the deformation behavior around a tunnel. This paper focuses on the effect of tunnel shape on the deformation behavior around a tunnel subjected to a surcharge load. In this study, horseshoe shape and circular shape tunnels in homogeneous rock are considered and analyzed under surcharge load. The diameter of the circular shape tunnel and the base of the horseshoe shape tunnel is kept identical. An equal amount of distribution load is applied to the two tunnels. The surcharge is applied on the top surface of the numerical model of the tunnel. The finite element method is employed for the study. This study analyzes and discusses the effect of tunnel shape for different height to diameter (H/D) ratios on the displacement around the tunnels using FLAC3D. The strain-softening model is used as a material model in FLAC3D. This study depicts that tunnel shape has a substantial effect on the deformation behavior around the tunnel. The effect of the H/D ratio on the displacement for the above stated tunnels is discussed. It is noted that displacement contour is a function of the H/D ratio subjected to the surcharge load regardless of the tunnel shape.

Keywords: *Tunnel shape; Displacement; Surcharge Load, FLAC3D.*

1 Introduction

The tunnel is a passage constructed underground or underwater through excavating soil or rock. Tunnels allow people a range of facilities to fulfill various needs like more efficient and convenient transportation, utilities, mining, military, and storage. Usually, tunnels are constructed in different shapes depending on their intended uses and the geological formation of the surrounding soil or rock. Circular shape and horseshoe shape tunnels are the common type of tunnels and they are constructed at shallow depths to reduce project costs. As this type of tunnel is close to the ground surface, the effect of surcharge on the ground surface for these types of tunnel can be significant. Such surcharge load can come from the construction of a new building, dumping of soil or vehicles and traffic load over the tunnel. From an engineering aspect, it is essential to understand the tunnel behavior due to the surcharge effect. Because several accidents have already occurred due to induce extreme surcharge that has emerged from previous studies (Huang and Zhang, 2016; Huang *et al.*, 2020). Surcharge loading often causes ground movement, which affects the tunnel and it develops cracks in the tunnel. Already, many researchers have investigated deformation-induced tunnel problems in various methods.

For example, Huang *et al.* (2020) conducted an indoor model experiment using FLAC3D simulation to observe the ground settlement, vault settlement, and tunnel structure deformation under different surcharge applications and discussed the effectiveness of control measures to prevent such issues, which was also validated using a case study (Huang *et al.* 2017). The authors used simplifications such as a homogeneous soil mass, non-layered foundation, and isotropic semi-infinite space elastic body to calculate the longitudinal deformation of a shield tunnel caused by surface surcharge loading but did not consider soil creep, drainage consolidation, and time-varying loads. They recommended taking into consideration various factors such as soil properties and surface and tunnel settlement limits to determine maximum stacking height and suggested further research on effective methods for controlling ground settlement and improving the use of space above subway tunnels. Yamamoto *et al.*, (2011a) utilized finite element limit analysis methods based on previous formulations (Sloan, 1988; Sloan and Kleeman, 1995; Lyamin and Sloan, 2002; Krabbenhoft *et al.*, 2005) to investigate the stability of a circular tunnel in cohesive-frictional soil under continuous loading, with varying interface conditions, tunnel diameter to depth ratios and material properties, and presented results as dimensionless stability charts. To verify the accuracy, upper-bound rigid-block mechanisms were also developed and compared to the finite element results. Here, drain loading conditions were considered by the authors. Gao et al. (2021) have provided an analytical solution to calculate the displacement and stress for shallow depth lined tunnels under surcharge load, with simplifications such as homogeneous and elastic ground surfaces and neglect the lining deformation and later verified the solution using the finite element method and compared the results. Du et al. (2020) used the hyperstatic reaction method (HRM) to calculate normal force, bending moment, and radial displacements of tunnel lining under surface loading and pore water pressure, and compared their results to numerical simulation. They found that both surcharge and groundwater level significantly influence the normal forces, bending moments, and radial displacements of tunnel linings, with normal forces greatly affected by the surcharge when the tunnel burial depth is approximately four times its height, while increasing groundwater levels cause decreasing normal force along the entire tunnel and affect the bending moment at the sidewall of the tunnel. Similar to the previous study, Yamamoto *et al.*, (2011a) have conducted three more studies on the stability of single square (Yamamoto *et al.*, 2011b), dual circular (Yamamoto *et al.*, 2013), and dual square (Yamamoto *et al.*, 2014) tunnels in cohesive frictional soil. According to the authors, the center to center distance has a significant impact on the behavior of dual square and circular tunnels compared to their respective single tunnel cases. Zhang *et al.*, (2019) investigated the stability of dual tunnels in a rock mass when subjected to surcharge loading and found that having small H/D values stability number N varies differently with changing L/D values.

This paper analyzes the effect of tunnel shape for different height to diameter ratios (H/D) on the displacement around the stated tunnels. Because of the significant advantages of numerical analysis, the numerical method is adopted for this study. At first, two numerical models for circular shape and horseshoe shape were constructed by FLAC3D with the same dimension where the diameter of circular tunnel and the base of horseshoe shaped tunnel were kept identical. Here, homogeneous rock is considered for the analysis. An equally distributed surcharge load is applied on the top surface of both tunnels. Finally, the result is observed with the change in the tunnel's height. This study aims to provide insights into the structural behavior of these tunnels.

2 Geometric model

In this study, FLAC3D (Itasca Consulting Group, 2017), a three dimensional numerical analyzing software is used. Here, the diameter of the circular shape tunnel and the base of horseshoe shape tunnel is kept identical (10 m). The bottom of the model is pin supported and the other four sides are roller supported. The model dimension is 50 m in the x-direction, 30 m in the y-direction and 50 m in the z-direction. The geometric model is illustrated in Figures 1 and 2.

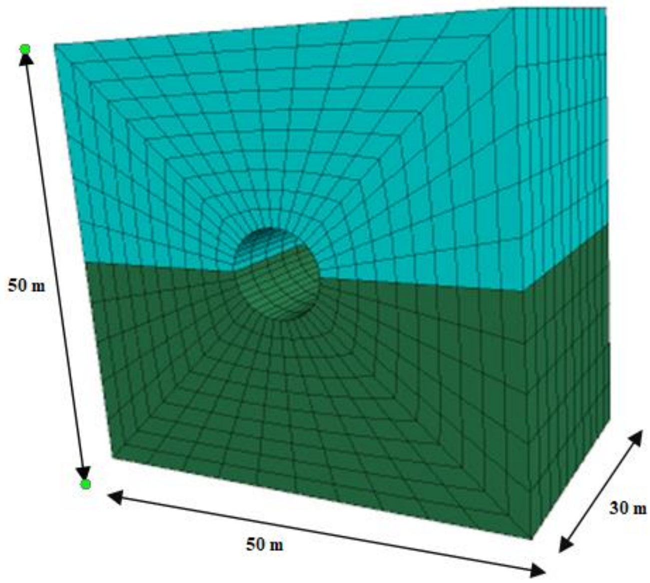

Figure 1. Geometric model of the circular shape tunnel

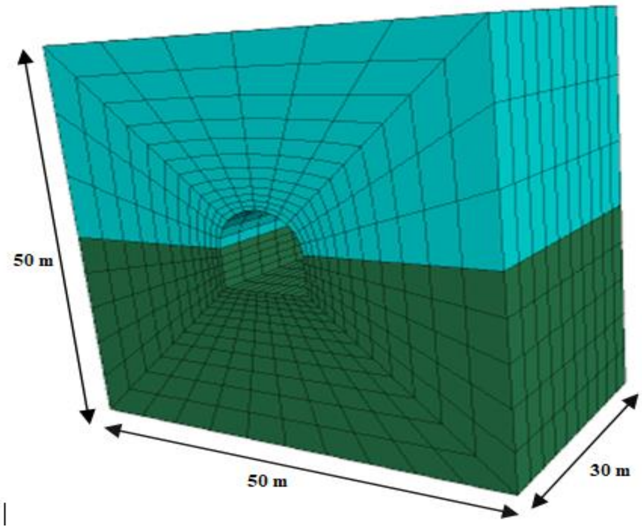

Figure 2. Geometric model of the horseshoe shape tunnel

3 Material Properties

For this study, the strain-softening model has been used as a material model in FLAC3D. The properties of the material such as shear modulus, bulk modulus, friction angle, cohesion and tensile strength is shown in Table 1 (Itasca Consulting Group, 2017).

Table 2: Properties of material used in this study

Material Type	Bulk Modulus (Pa)	Shear Modulus (Pa)	Cohesion (Pa)	Friction Angle (Degree)	Tensile Strength (Pa)	Dilation Angle (Degree)
Rock	14.1×10^9	8.87×10^9	4×10^6	35	5×10^5	5

4 Results and Discussion:

The effect of tunnel shape on the deformation characteristics is discussed in this section. The effect of tunnel shape on the deformation characteristics is depicted in Figures 3 to 6 for different H/D ratios (1 to 5). According to this study, it is observed that horseshoe and circular shaped tunnel behaves differently due to the uniformly distributed loading. It is also noticed that the displacement depends on the H/D ratio where D is fixed but H is variable. From the contour obtained from FLAC3D, it is observed that when H/D=1 (Figure 3), highest displacement occurs at crest for circular shape tunnel. Similar behavior is also observed for the horseshoe shape tunnel (the displacement at the crest is also maximum). When H/D=2 (Figure 4), the displacement at the crest is less than the displacement at crest for H/D=1 for both shape of tunnels. This is clearly evident in Figures 8 and 9. When H/D=3 (Figure 5), the displacement is very little at the crest for the two shape of tunnels. When H/D=4 (Figure 6), the displacement at the crest is minimum for both the shape of tunnels. When H/D=5 (Figure 7), the displacement is also minimum at the crest for both the shape of tunnels. So, from the study, it can be concluded that when the H/D ratio increases, the displacement on the tunnel at crest decreases. A larger value of H causes less displacement at the crest of the two tunnels. So, the tunnel at the deeper height is more convenient for the safety of the tunnel. It also makes the tunnel more stable. The magnitude of displacement at the crest for the two shape of tunnels is not the same which indicates that tunnel shape has the influence in the deformation behavior around the tunnel although the surcharge is the same for the two tunnels. Lastly from Figure 9, it can be concluded that horseshoe shaped tunnel is more stable than circular shaped tunnel as its displacement is less. Circular shaped tunnel shows more displacement than horseshoe shaped tunnel which means horseshoe shaped tunnel is safer.

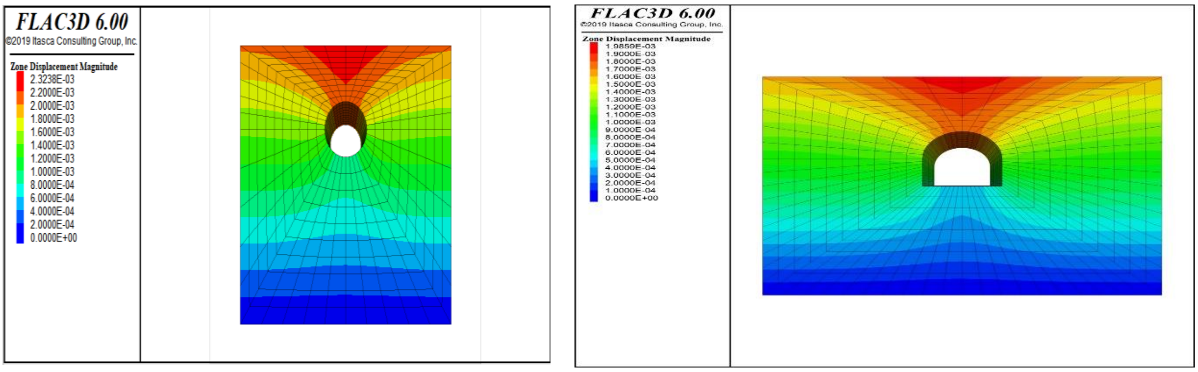

Figure 3. Displacement contour for H/D=1

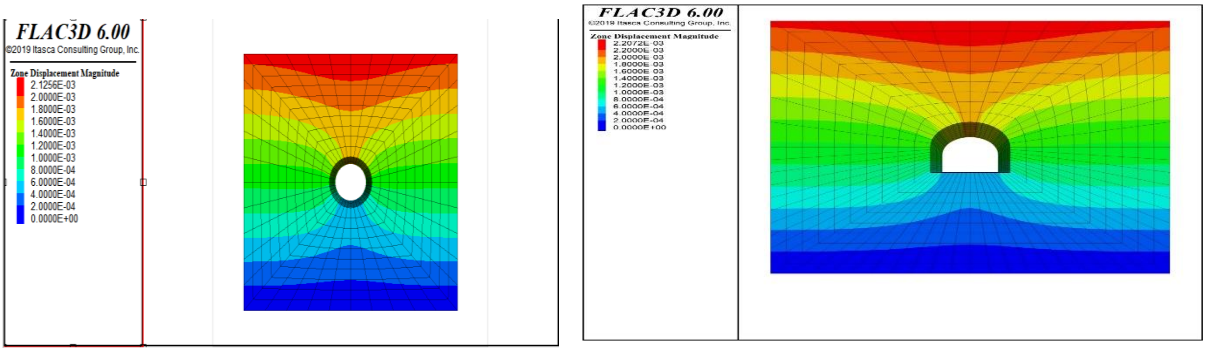

Figure 4. Displacement contour for H/D=2

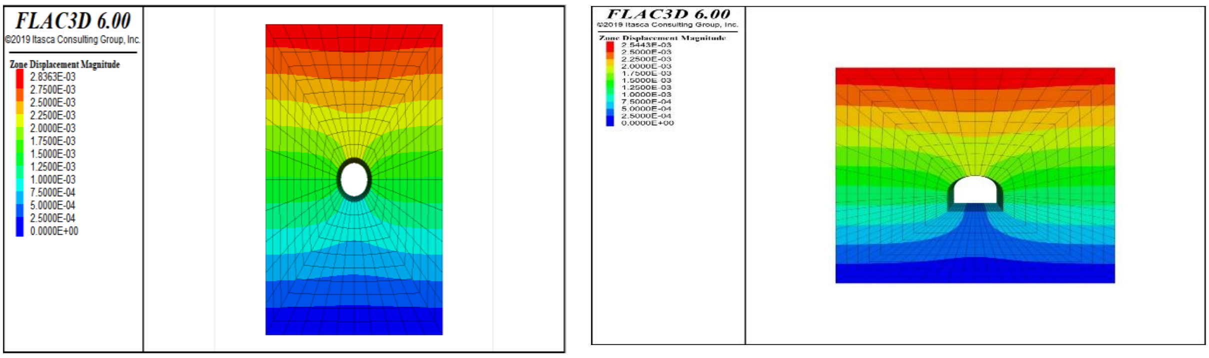

Figure 5. Displacement contour for H/D=3

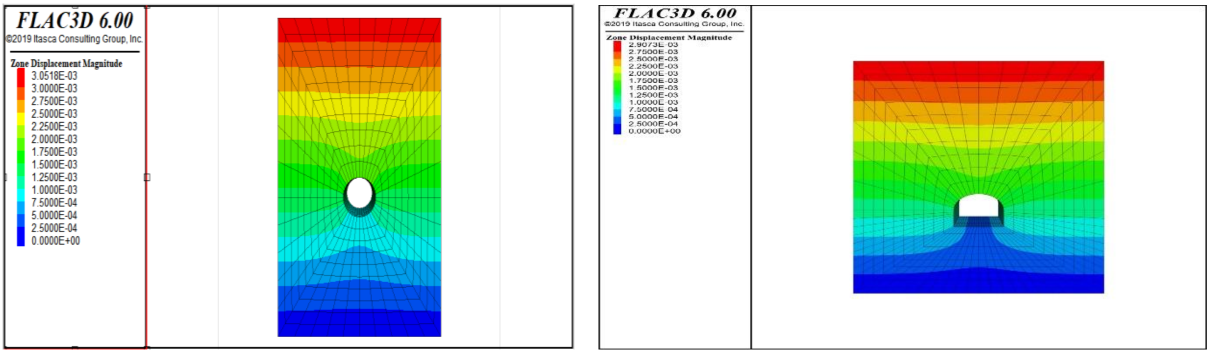

Figure 6. Displacement contour for H/D=4

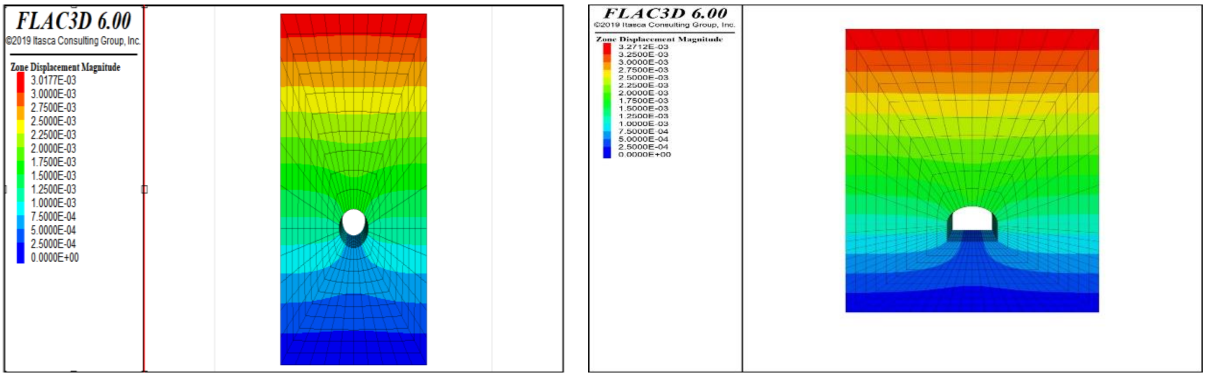

Figure 7. Displacement contour for H/D=5

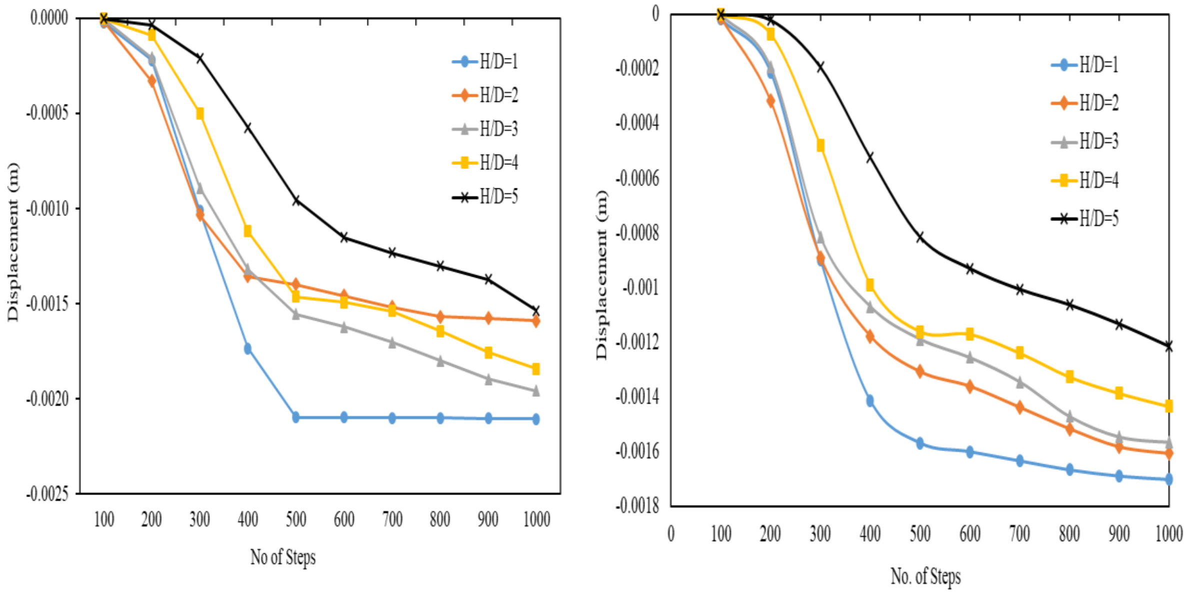

Figure 8. Relationship between displacement at crest and no of steps for circular shaped tunnel (left) and horseshoe shaped tunnel (Right)

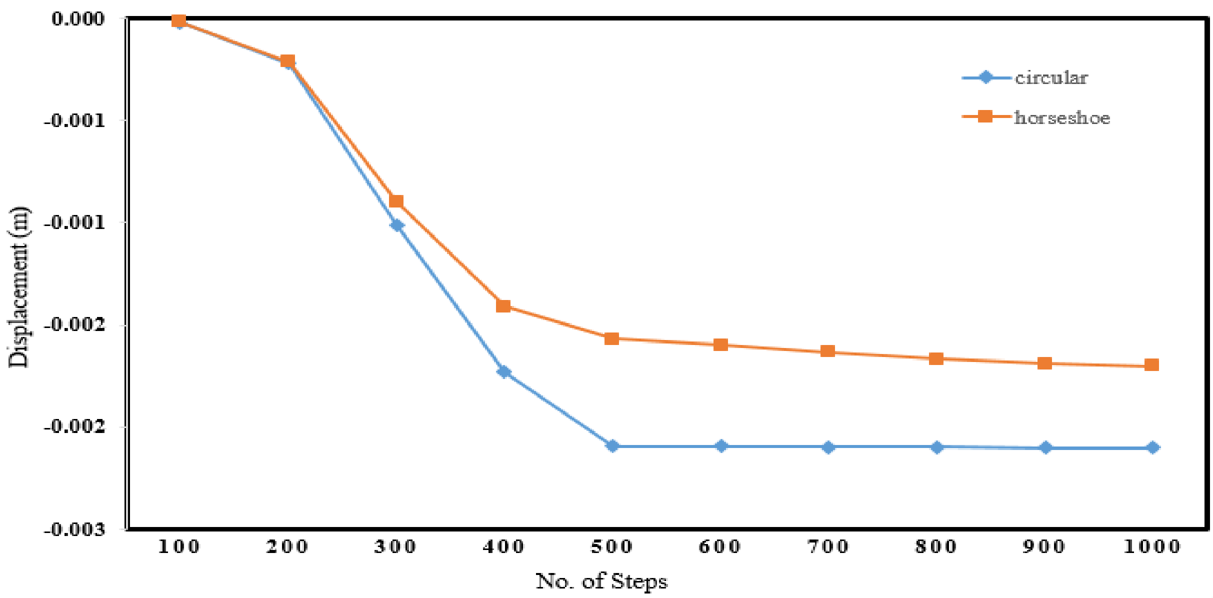

Figure 9. Displacement for H/D=1 for both tunnel

5 Conclusions:

In this study, the effect of the shape of the tunnel on the deformation characteristics around a tunnel subjected to a surcharge load is studied using FLAC3D. Two types of shapes, namely, horseshoe shape and circular shape tunnels in homogeneous rock are considered and analyzed under surcharge load. The diameter of the circular shape tunnel and the base of the horseshoe shape tunnel is kept identical. An equal amount of surcharge load is applied on the top surface of the numerical models for both cases. The finite element method is used for the study. The strain-softening model is employed as a material model. This study depicts that tunnel shape has a substantial effect on the deformation behavior around a tunnel. The displacement contour depicts the clear differences in the deformation behavior for the different shapes of the tunnel. The displacement is influenced by the H/D ratio as well. Thus the displacement behavior is a function of the H/D ratio subjected to surcharge loads regardless of the shape of the tunnel.

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