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Numerical analysis of the effect of bilateral excavation and superstructure loading on existing metro twin tunnels

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ABSTRACT: The construction of a superstructure with a basement near the existing underground structure will redistribute the stresses around it. This paper aims to study the response of existing twin tunnels due to bilateral excavation and loading on either side of the tunnels. A parametric study was conducted numerically using the hardening soil model. The effects of the construction sequence of both the structures, symmetrical and unsymmetrical loading, foundation depth, number of floors, depth of the existing tunnel, and horizontal offset distance were analyzed. Uplift deformation was observed during the excavation, while the opposite behavior was observed during the loading phase. During the excavation stage, the displacement at the spring levels is greater than the displacement at the crown, whereas, during the loading stage, the crown is more displaced than the spring levels. These displacements may lead to cracking and spalling of the lining and water seepage. The symmetry of the construction sequence was observed to impact the tunnel's distortion significantly. The horizontal offset distance of the foundation has a significant impact on the relative displacement of the tunnel.

Keywords: Underground structure; parametric; hardening soil model; crown; spring level.

1 INTRODUCTION

The underground metro system is becoming the preferred choice of the major urban transport system. The advantage of the underground metro system is that it provides additional space on the ground surface. With the growing population in urban areas, the spaces in and around the good transport system have become hot spots for new infrastructure developments. These construction activities lead to stress redistribution on the ground. These stresses may be compressive or tensile in nature and may damage the existing underground structure. Many researchers have attempted to study the effect of basement excavation, raft loading, and tunnel construction near the current system. There are case histories where tunnel lining is damaged adjacent construction activities. Burford (1988) was the first to report an uplift of the surface of the London subway tunnel due to foundation pit excavation. Chang et al., 2001 reported damage to the Taipei Rapid Transit system due to excavation adjacent to the tunnel. There was a catastrophic failure of Shanghai Metro Line 4 in 2003 due to the undermining of the cross passage (Tan et al., 2020). Many studies have been carried out to investigate the effect of excavation on the existing underground facility. Studies involving various methods, including numerical studies (Ng et al., 2015; Sun et al., 2019; Xu et al., 2021), analytical studies (Liang et al., 2017; Liao et al., 2008; Shi et al., 2017; Wei et al., 2022) experimental testing, and field measurement (Li et al., 2017; Ng et al., 2013; Sharma et al., 2001; Tan et al., 2019) are available.

Most of the studies focus on excavation's effect on the existing tunnel. A detailed parametric analysis of the impact of basement excavation and raft loading was performed by Mahajan et al., 2019. Zakhem and El Naggar, 2020 studied the effect of a newly constructed building on the existing tunnel using PLAXIS 3D. However, few studies are available involving construction on both sides of the tunnel, which is very limited.

This study focuses on the parameters that can affect the existing tunnel due to bilateral excavation and superstructure loading using PLAXIS 2D. For this study, the actual field conditions of the Delhi metro are adopted. In this study, we have conducted an analysis of the displacement of tunnel linings of the existing tunnels. The Tunnel linings are constructed with concrete, and the concrete properties are independent of site conditions. The results were compared with respect to the maximum allowable displacement limits for the concrete elements, given in the LTA Code of Practice for railway protection (2000), Singapore, and Building Department, Hong Kong Special Administrative Region (HKSAR) APP-24 (2009). The decision to adopt these limits is based on the available studies, including those by Ng et al., 2013 and Mahajan et al., 2019, which are on the response of the existing tunnel to basement excavation and loading on the single-side of the tunnel in different site conditions.

2 DETAILS OF NUMERICAL ANALYSIS

There are various metro systems across the world in different soil conditions. This study involves multiple parametric variations of the foundations, such as the foundation's width (*B*), the foundations' horizontal offset distance from the existing tunnel (*X*), and the loading symmetry shown in Figure 1. The left and right tunnels are named Tunnels 1 and 2, respectively.

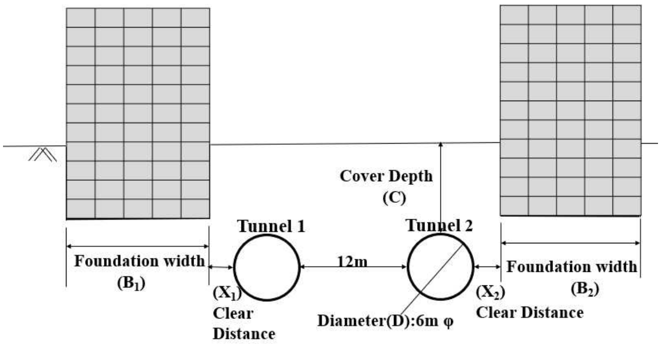


Figure 1. Schematic figure of the model

This study focuses mainly on the tunnels in dry cohesionless soil; therefore, the site conditions of the Delhi metro are chosen for the study. The numerical study does not model the water table level for simulating the dry conditions. The soil profile is taken from the thesis work of Mahajan et al., 2020. The geotechnical bore log data includes four different layers of soil. Layer one ranges from 0-4.5 m; layer two ranges from 4.5-15 m; layer three ranges from 15-35 m; layer four ranges from 35-50 m. The soil is modelled as a Hardening soil model (HSS) as from the previous study; it is found that the HSS model is more realistic. The details of the geotechnical properties of the soil of each layer are given in Table 1.

Table 1. Soil properties for Hardening soil analysis

Description	Layer 1	Layer 2	Layer3	Layer4
γ (kN/m^3)	15	17	17	17
E_{50}^{ref} (kPa)	20000	16000	15000	16000
E_{oed}^{ref} (kPa)	16000	13000	12000	13000
E_{ur}^{ref} (kPa)	59000	49000	46000	49000
m	0.8	0.8	0.8	0.8
ν_{ur}	0.2	0.2	0.2	0.2
P^{ref} (kPa)	100	100	100	100
∅°	26°	30°	30°	34°
Ψ°	0	1	3	3
c_{ref} (kPa)	22	15	15	5

The diameter of the Delhi metro tunnel is 6 m (Mahajan et al., 2019). Generally, the urban metro tunnel cover-to-diameter (*C/D*) ratio varies between 3-5. The tunnel at greater depth will have less impact due to changes over the ground surface; therefore, a *C/D* of 3 is adopted. The horizontal distance is varied in terms of horizontal distance-to-diameter *(X/D)*. Foundations are placed at *X/D* of 0 and 0.5. The bearing capacity and settlement analysis of soil suggests that the superstructure of 3 basements with a width of 15 and 30 m with 15 floors can be successfully constructed. The model size is a critical factor for the numerical study. It should be sufficiently large so there is no boundary effect; therefore, the boundary size is 50 m deep and 220 m wide. For the boundary conditions, the bottom of the model is taken as a fixed condition, whereas the sides of the model are restrained for lateral movement, and the top of the model is assumed to be free. Figure 2 shows the numerical model. Other structural elements include tunnel lining, raft foundation, retaining wall, and sheet pile wall. The sheet pile wall is modelled as a steel linear elastic element, while others are concrete. The details are given in Table 2.

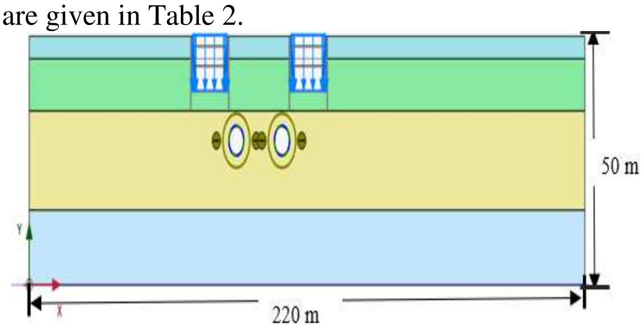


Figure 2. PLAXIS model

Table 2. Material properties of structural elements

Description	Tunnel lining	Raft	Retaining wall	Sheet pile
Equivalent Thickness (m)	0.25	2	1.5	0.25
Normal Stiffness (E.A.) (kN/m)	6.25 E^6	5.00 E^7	3.75 E^7	5.0 E^7
Flexural rigidity (E.I.) (kNm^2/m)	3.20 E^4	1.70 E^7	7.03 E^6	2.6 E^6
Poisson's ratio	0.15	0.15	0.15	0.2
Weight (kN/m/m)	6	48	36	19.7

3 MODELLING STEPS

PlAXIS 2D is a finite element program. It involves mainly five steps: model size and borehole definition-creating structural elements (modelling tunnel, sheet pile wall, support system, and raft foundation)- meshing the model-calculation. The tunnel was modelled using the tunnel designer tool, which includes modelling all the tunnelling steps as given in the PLAXIS 2D Tutorial. A c_{ref} of 0.5% was taken, which corresponds to a volume loss of 0.5% of the tunnel volume. With the excavation of the tunnel, there will be stress initialization. This stress field will change with each construction stage. In this study, the focus is on the displacement of the tunnel lining. No provision is available in PLAXIS to reset these stresses to zero; however, the reset displacement zero option is available. With this option, displacement can be reset to zero at the beginning of any phase. This means that any displacement in the model due to changes, e.g., load changes, structural elements being activated, soil activated/deactivated, can still occur in this phase: the phase just starts with zero displacements (PLAXIS reference manual). There are several stages involved in the construction stage, but considering the study's objective: the impact of basement excavation and loading on the existing tunnel, only the results of essential steps are discussed in this study which is shown in Table 3. The option to reset displacement to zero is applied after the tunnel excavation stage, which helps in getting the displacement of the tunnel lining due to the basement excavation and raft loading only. Therefore, the results section at the initial stage also represents the existing tunnel and other construction activities after this, and the displacement value at this stage is zero.

Table 3. Stages considered for the discussion of the results

Stages	Stage details	Symbol
Initial	Existing tunnel	Initial
1	Foundation + basement loading	Fdn
2	Foundation + basement loading + 8 floors	Fdn+8 floors
3	Foundation + basement loading + 12 floors	Fdn+12 floors
4	Foundation + basement loading + 15 floors	Fdn+15 floors

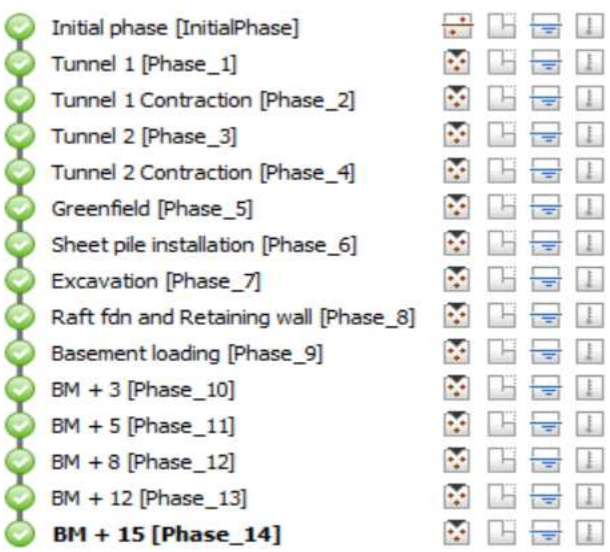


Figure 3. Details of the construction stages.

The details of the construction stages adopted for the result analysis are given in Figure 3. The calculation stage is further divided into different construction stages. These construction stages should be such that it replicates the construction sequence followed on-site. The study aims to see the impact of the basement excavation and loading on the existing tunnel; therefore, the first tunnel construction phases were considered (Phases 1 to 5). The sheet piles were activated in Phase 6. In Phase 7, the excavation was carried out, and the struts were activated. In Phase 8 raft foundation with a retaining wall was constructed, and the sheet piles were deactivated. Phase 9 is the beginning stage of the loading. The load is applied in increments according to the number of floors in each stage. From the available literature (Mahajan et al., 2019), the load applied per floor is 10 kPa; therefore, in each loading stage, the load is applied at increments of 10 kPa per floor in that construction stage.

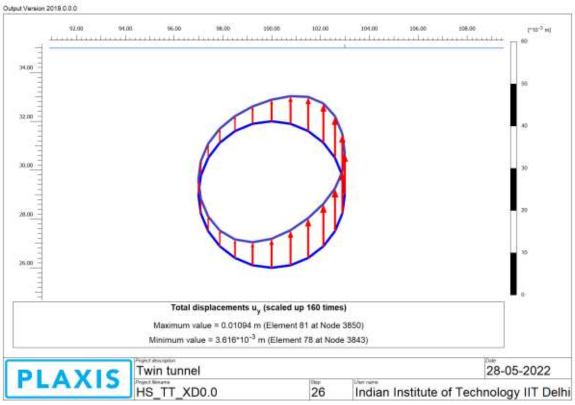
4 RESULTS AND DISCUSSIONS

This study aims to see the effect of basement excavation and construction on the existing tunnels. Therefore, the initial stage is considered as the existing tunnel; hence the displacement at this stage is taken as zero, and relative displacement to this initial stage is reported. Land transport authority (LTA) Code of Practice for railway protection (2000), Singapore and Building Department, Hong Kong Special Administrative Region (HKSAR) APP-24 (2009) has given specifications on the maximum allowable displacement of the concrete element as 15 mm and 20 mm, respectively. Although the site conditions of the Delhi metro are adopted in this study, the tunnel linings are concrete. Therefore, the damage analysis is done based on these provisions. The deformation is measured at four locations crown, invert, right spring level (RSL), and left spring level (LSL). The left tunnel will be referred to as Tunnel 1 and the right tunnel as Tunnel 2, as shown in Figure 1, for discussing the results.

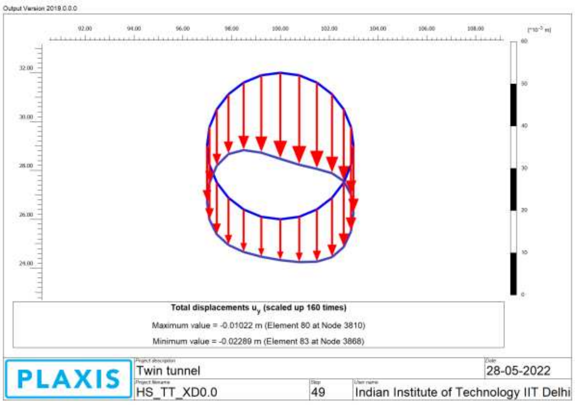
4.1 Single-side excavation and loading

Figures 4 and 5 show the tunnel displacement closer to the building in vertical and horizontal directions, respectively, at different stages of construction when the construction is done on one side (single side) of the tunnel (both tunnels already exist). Although the total displacement is always positive, in Figure 6, the total displacement of the tunnel (closer to the building) values is both negative and positive. These are given to indicate the direction of tunnel movement towards (−ve) or away (+ve) from the excavation.

Figures 4 and 5 show that the deformation in tunnel lining is the opposite in excavation and superstructure loading cases. While the excavation causes the tunnel to inflate in the vertical direction and suppress in the horizontal direction, the deformation pattern reverses as the raft is loaded with building weight. The critical condition is reached at the highest building load. It can be inferred from Figure 6 that although the soil can carry more load, the number of floors should be restricted as the tunnel deformation exceeds the allowable limit.

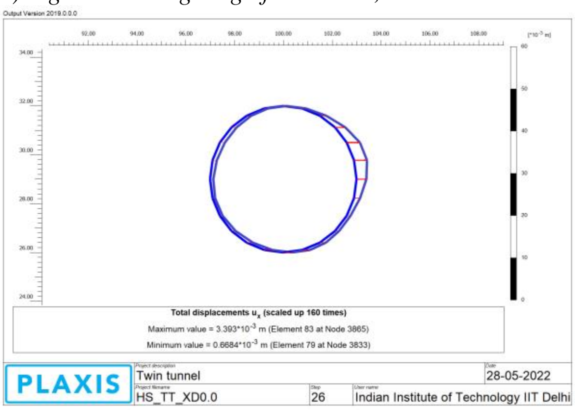


(a)



(b)

Figure 4. Tunnel vertical displacement (a) excavation stage (b) highest loading stage for X/D=0, and B=15 m



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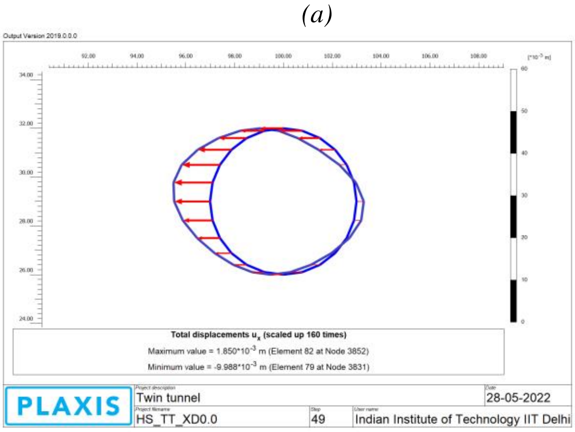


(b)

Figure 5. Tunnel horizontal displacement (a) excavation stage (b) highest loading stage for X/D=0, and B=15 m

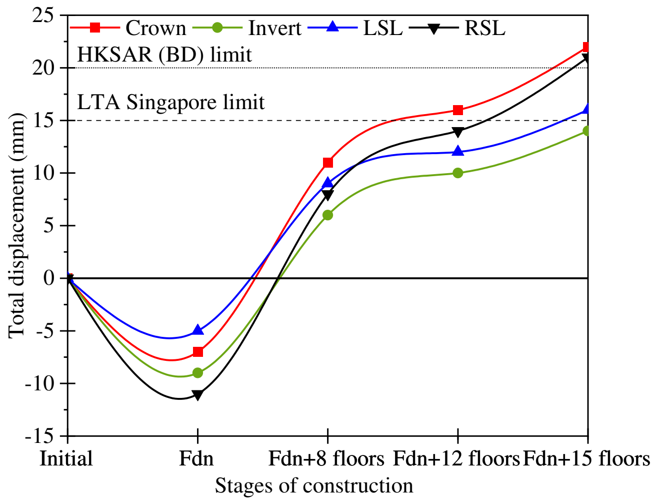
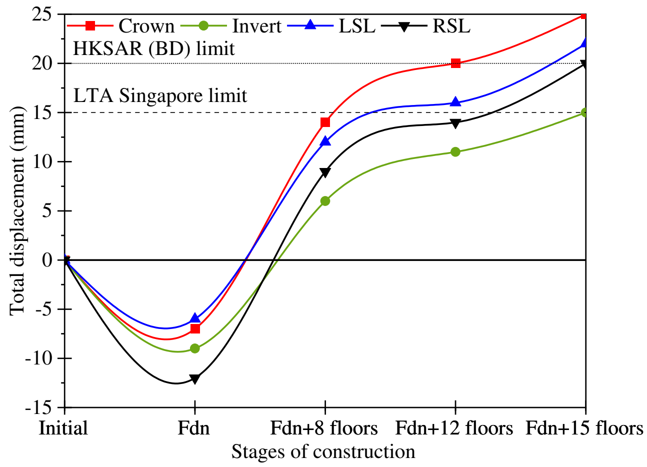


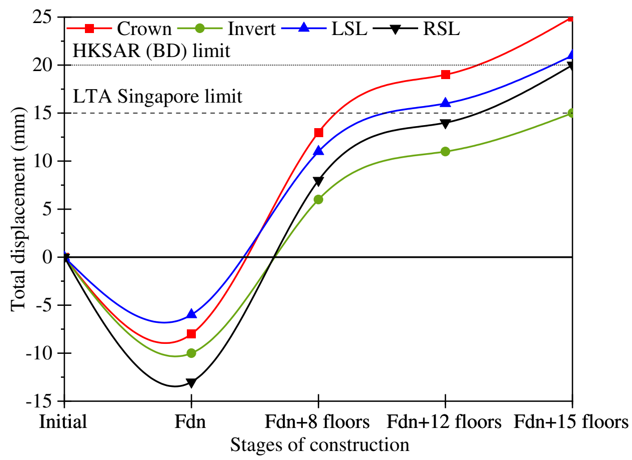
Figure 6. Tunnel lining deformation at different construction stages for X/D=0, and foundation width 15 m

4.2 Bilateral excavation and loading

The primary objective of the study is to simulate the effect of excavation and loading on either side (bilateral) of the tunnel. Accordingly, the parametric analysis is carried out, and some typical results are discussed herein.



(a)



(b)

Figure 7 Tunnel lining deformation at different construction stages for X/D=0, B1=B2= 15 m (a) Tunnel 1, (b) Tunnel 2

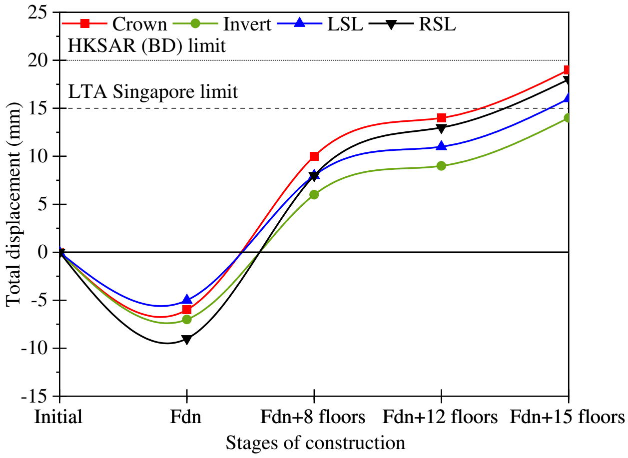
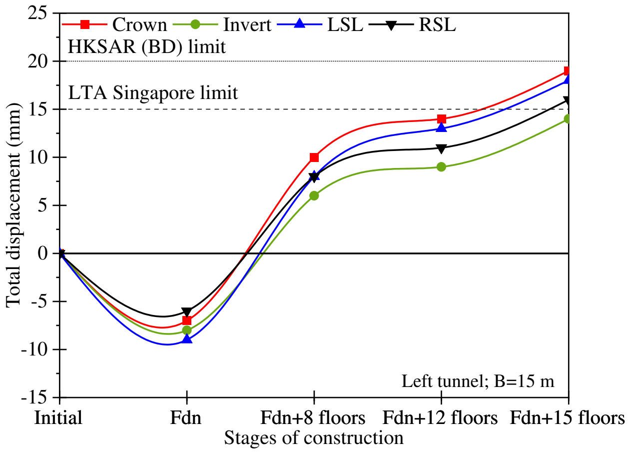
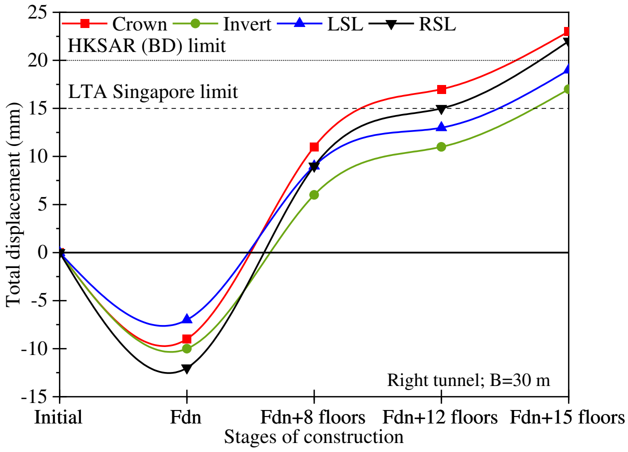


Figure 8 Tunnel 1 lining deformation at different construction stages for X/D=0.5, B1=B2= 15 m



(a)



(b)

Figure 9 Tunnel lining deformation at different construction stages for X/D=0.5, B1=15 m, and B2=30 m (a) Tunnel 1, (b) Tunnel 2

Figure 7 shows the response of tunnels in which both the foundations are 15 m in width and placed at *X/D* of 0. It can be seen from Figure 7 that both the tunnels have almost undergone the same displacement in all the stages. It can also be inferred that though the soil conditions permit the construction of 15 floors, the number of floors may have to be limited to 12, considering the safety of the existing metro tunnel (for the conditions analysed). This indicates that rigorous parametric study is needed to develop general guidelines for restricting the new construction activities near the existing tunnel. Figure 8 shows the displacement of different locations on the tunnel lining for the foundation width of 15 m located at an *X/D* of 0.5. However, both tunnel undergoes almost the same displacement; therefore, Figure 8 shows the displacement of only tunnel 1.

Figures 7 and 8 show that with the increase in the distance between the tunnel and the raft, displacement decreases significantly, reaching the values below the limit specified by HKSAR (B.D.). However, the value at some locations still exceeds the limit set by LTA Singapore. Figures 6,7,8 and 9 also show that during the excavation stage, the tunnel's spring levels undergo more displacement, whereas, at the highest loading stage, the crown undergoes more displacement. In all the figures, it can also be seen that maximum negative displacement occurs before the foundation (Stage 1). This may be because of the foundation loading after the excavation.

In this study, the unsymmetrical loading is only considered by considering the different sizes of the foundation. The same loads were applied at the same construction phase on both sides. Figure 9 shows the condition of unsymmetrical loading, where both the foundations are at *X/D* of 0.5, but the foundation width near tunnel two is 30 m. It is observed that the tunnel closer to the larger foundation width deforms more. The displacement in the tunnel lining closer to the foundation width of 30 m exceeds both the limits before 15 floors. In contrast, from Figures 8 and 9 b, it can be seen that the far-away tunnel shows a negligible effect as compared to the symmetrical loading.

5 CONCLUSIONS

Based on the current study following conclusions can be withdrawn:

The foundation design in the presence of an existing underground structure depends not only on the bearing capacity of the soil and settlement but also on the safety of the existing underground structures like tunnels.

Excavation and loading have different effects depending on the geometrical arrangements of the tunnel and foundations. From Figure 9, it can be inferred that during the excavation stage, the spring level closer to the excavation is more critical. Whereas from Figures 6,7,8, and 9, it can be seen that during the loading stages, the maximum displacement is observed at the crown level of the tunnel lining irrespective of the loading conditions. Hence, it becomes a critical condition for determining the maximum permissible loading near the tunnel.

The tunnel lining undergoes lesser deformation for symmetrical loading compared to unsymmetrical loading.

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