# A numerical study on the effect of basement excavation and fibre reinforced concrete as tunnel lining material

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**Keywords:** Tunnel, Tunnel Lining, Basement Excavation, Finite Element Modelling (FEM), Fibre Reinforced Concrete (FRC)

**Abstract.** Metros are one of the important transportation systems in urban areas. Due to rapid development in urban areas, there is huge commercial demand resulting in the development of underground spaces are rapid. Some of the developments may have deep excavations for basements in close proximity to existing tunnels. If the induced tunnel deformation and internal forces exceed the capacity of the tunnel structures then damages such as segmental cracking, leakage and longitudinal distortion of the tracks occur and it threatens the safety of the passengers and hence is a major concern. A parametric study on the effect of basement excavation on the underground metro in soil gives an idea about the influence of various factors like lining material and lining thickness. The crown and right spring line undergo more displacements in both the excavation and loading stage. From the study it was observed that, providing FRC as tunnel lining material has significant effect on reducing foundation settlement.

## Introduction

Infrastructure is rapidly evolving, leading to the development of additional buildings in major cities and urban areas. Due to the scarcity of space in urban areas, especially metropolitan cities, the use of underground space for transit as metros or multiple levels of basements in buildings becomes a necessity. The ground movement towards the excavation will certainly occur during the construction of such subterranean metro tubes, resulting in ground surface settlement. This ground settlement is likely to have an impact on nearby structures and constitute a risk to the environment. Construction of the basement inevitably causes stress changes in the ground leading to soil movements which may cause potential damage to adjacent tunnels. Thus, it is essential for designers and engineers to assess excavation-induced movements occurring in the tunnel as well as nearby structures. Ground movements that occur during the construction of metro tunnels result in ground settlements and these settlements induce high risk to the nearby existing structures. There are also a number of numerical studies that explored the influence of tunnelling on foundations, in addition to studies on green-field settlement prediction and control owing to tunnelling.

Gang, (2008) studied the response of existing tunnel due to overlying excavation using 2D FEM. The study concluded that this deformation is mainly due to the uneven changes in ground contact pressure on tunnel linings. Also, as the tunnel embedded depth beneath the excavation increased the vertical and horizontal displacement of the tunnel decreased. Shi et al., (2013,2015) conducted a three-dimensional numerical parametric study to investigate the influence of excavation geometry, sand density, tunnel stiffness and joint stiffness on tunnel responses by overlying basement excavation. The heave and tensile strain induced in the tunnel reduced rapidly as the tunnel stiffness increased. Stiffening a tunnel can be an effective way to reduce the adverse effects on the tunnel due to basement excavation. Huang et al., (2014) investigated the effect of deep excavation above an existing tunnel by conducting a series of centrifuge model tests. When the tunnel cross-section was 1.5 times the excavation depth away from the center of the excavation, the additional moments decreased rapidly to negligible. Mahajan et al., (2016, 2019) carried out a numerical analysis to examine the effect of basement raft loading on the existing tunnel in sand using PLAXIS 3D. The results indicated that the displacement and moment at the crown, invert, springing lines and deformations are significantly affected by various stages of construction of the raft and loading. The variation in the total displacement is more when excavation is closer to tunnel location, i.e., X/D ratio is zero. This study concluded that the critical distance between the tunnel edge and the basement foundation is about 2.5 times the tunnel diameter to avoid the detrimental effects on tunnel lining.

Marara et al. (2011) studied the toughness of normal strength steel fibre reinforced concrete (NSSFRC). Concrete cylinders reinforced with three different aspect ratios of hooked-end steel fibres 60, 75, and 83 and six different percentages of steel fibres L/D (length/diameter of fibre) = 0.5, 1.0, 1.25, 1.5, 1.75, and 2.0% were tested. And a compressive strength of 83 MPa was obtained for the ratio of L/D=1 and 83% fibre volume fraction.

Although there have been a few studies on the impact of pile loading on existing tunnels, there hasn't been enough focus on understanding the interplay of basements and tunnels. Also, very few studies have been carried out regarding the use of fibre-reinforced concrete (FRP) as tunnel lining material for reducing the deformation in tunnels and foundations. The scopes of the present study are to conduct a numerical analysis on the influence of basement excavation near existing tunnels and understand the deformations of the foundation and basement. In this study, the tunnel is considered to be constructed before the basement excavation, and the excavation takes place at close proximity to the tunnel i.e., at X/D=0 (where X is the clear distance between the foundation and tunnel and D is the diameter of the tunnel). In a later stage parametric studies were conducted to study the influence of different lining materials (PCC and FRC) for different tunnel lining thicknesses on the tunnel and foundation. Foundation settlement and tunnel deformations mainly in the crown, invert, left and right spring lines are studied in detail.

## Effect of basement excavation on tunnel

In this numerical study, the effect of a three-floor basement excavation and foundation loading on an existing underground metro tunnel at X/D=0 is analysed using PLAXIS 2D. A parametric study is then conducted to understand the effect of different tunnel lining thicknesses (0.25 m,0.3 m, 0.35 m, 0.4 m) on tunnel deformation mainly at the crown, invert, left and right spring line. The effect on foundation settlement with existing structures are also considered. Similarly for different tunnel lining materials Reinforced cement concrete (RCC) and fibre reinforced concrete (FRC) and their effect on tunnel deformation and foundation settlement is also studied.

In this proposed problem there exists a tunnel with a diameter of 6 m considered similar to that of the Delhi Metro Tunnel. In this study, the pressure simulated is 270 kPa, which corresponds to a 15-storey and three basement structure. The tunnel crown is located 18 m below the ground level. Soil properties are taken as that of Delhi Yamuna sand. The basement foundation of 15m width is considered to be made of reinforced cement concrete (RCC) and is designed for 15-storey loading and 3 basement floors. Retaining wall up to the height of 11 m i.e., 9 m height of three basements and 2 m thick foundation. Counterforts with high stiffness have been provided to control the deflection at the top of the retaining wall.

The properties of the soil, tunnel, basement foundation and retaining wall are provided in Tables 1 and 2 [21]. Temporary sheet pile walls and struts are provided to stabilize the soil before excavation and to limit sheet pile deflection as well as the embedment depth respectively. The total length of sheet piles is taken as 15 m. The sheet piles and retaining walls are kept at a clear distance of 0.5 m in the numerical model to avoid numerical discrepancies. Struts with normal stiffness EA $=2 \times 10^6$ kN as elastic members with an out-of-plane spacing of 5 m. The property of temporary sheet pile walls is provided in Table 2. In PLAXIS 2D, the staged excavation and foundation loading can be numerically simulated as it occurs in the field. This study tries to understand the most critical case where the deformations are expected to be maximum. The schematic diagram of the model is presented in Fig. 1. The numerical model schematic diagram is given in Fig. 2, which is considered for all the presented in Fig. 1.

*Table 1. Soil Properties [21]*

| Property | Soil (Yamuna sand) |
|---|---|
| Dry unit weight | 15 [kN/m$^3$] |
| Young’s modulus | 25000 [kPa] |
| Poisson’s ratio | 0.3 |
| Friction angle | 34$^o$ |
| Cohesion | 1 [kPa] |

**Numerical Modelling PLAXIS 2D – Basement Excavation and Foundation Loading**

The plane strain model with 15-noded elements was used for the numerical modelling. Mohr-Coulomb model was considered for modelling the soil. Tunnel lining was modelled using plate elements as an elastic material. Model geometry was considered as 220 m x 50 m, where the sides were laterally restrained, and the bottom is fixed. Fig 2 shows the numerical model created and Fig 3 shows the finite element mesh generated. The meshing adopted is very fine and had a total of 1564 elements. The total number of nodes are 12919 and the average element size is 2.67m. The initial stresses are generated using $K_o$ procedure ($K_o$=1) and the initial effective principal stress generated is -748.29 kN/m$^2$. In the calculation stage total of 9 phases are defined. These are defined in such

*Table 2. Material properties [21]*

| Parameter | Tunnel Lining (D=6.0m) | Basement Foundation | Retaining wall | Sheet Pile |
|---|---|---|---|---|
| Material (model behaviour) | Concrete<br>(Linear elastic) | Concrete<br>(Linear elastic) | Concrete<br>(Linear elastic) | Steel<br>(Linear elastic) |
| Equivalent thickness (m) | 0.25 | 2.0 | 1.5 | 0.25 |
| Flexural rigidity (EI) kNm2/m | 3.2x10$^4$ | 1.7x10$^7$ | 7.03x10$^6$ | 2.6x10$^6$ |
| Normal stiffness (EA) kN/m | 6.25x10$^6$ | 5x10$^7$ | 3.75x10$^7$ | 5x10$^7$ |
| Poisson’s ratio | 0.15 | 0.15 | 0.15 | 0.2 |
| Weight (kN/m/m) | 6.0 | 48 | 36 | 19.7 |

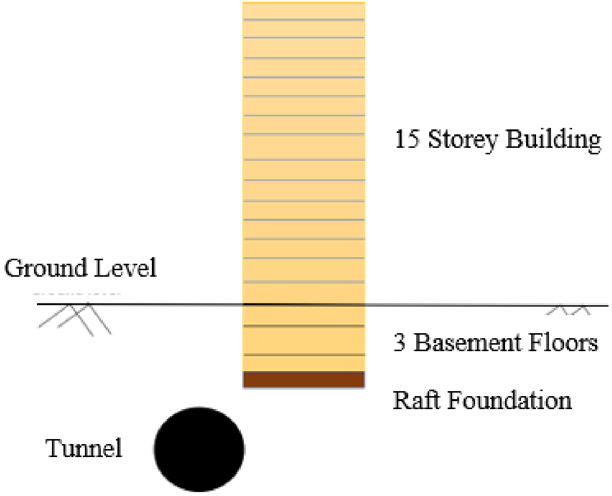

*Fig 1. Schematic diagram – Storeys + Basements + Tunnel*

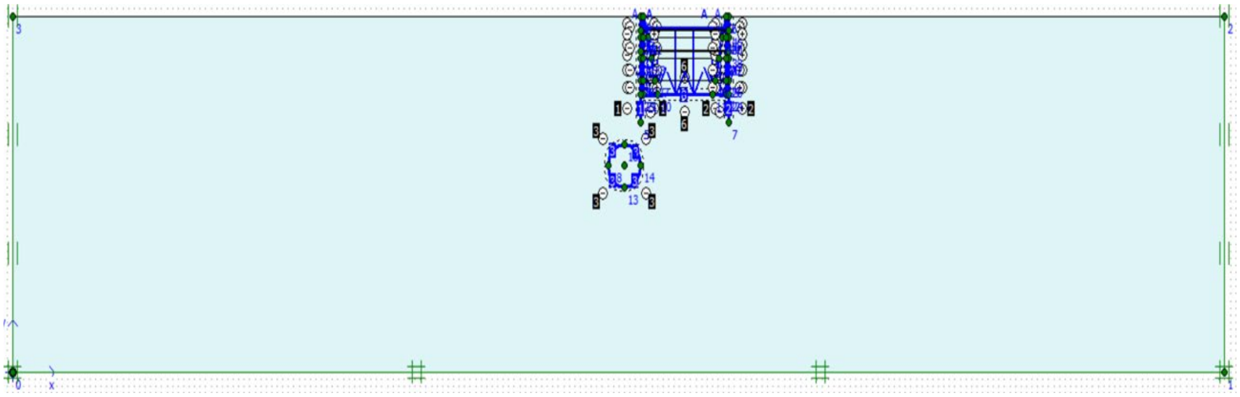

*Fig 2. PLAXIS 2D Numerical model*

These are defined in such a way that it represents how the construction is stimulated in the field. In the first stage, the tunnel was excavated up to a cover depth of 18 m from the ground level. In phase 2, temporary sheet pile walls were driven. The first phase of excavation and struts were provided in phase 3. Similarly, the second and the third phase of excavations are defined in phases 4 and 5. In phase 6, after removing the struts, foundation was being constructed. In phase 7, retaining wall and counterfort walls were numerically stimulated.
In phase 8 the sheet pile walls were removed and finally,
in phase 9 the loading was provided. In this first study, the analysis is carried out for three cases:
1. Effect on tunnel points after excavation
2. Effect on tunnel points after loading
3. Effect on foundation settlement

The effect on tunnel lining due to the three-floor basement excavation is represented by the deformed mesh in Fig 4 and tunnel deformation in Fig 5. Due to the basement excavation, stress relief is induced at the base of the excavation pit which results the tunnel lining to move upwards, i.e., towards the excavation. Table 4 shows the deformations at different tunnel points after excavation.

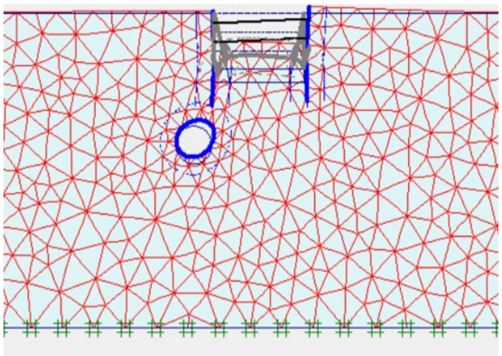

*Fig 4. Deformed mesh- After excavation*

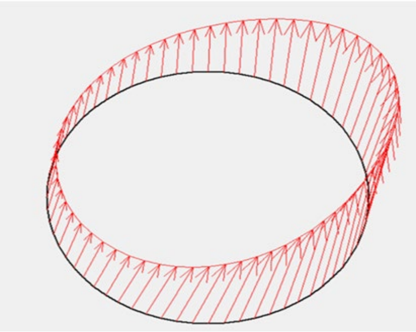

*Fig 5. Tunnel lining deformation-After Excavation*

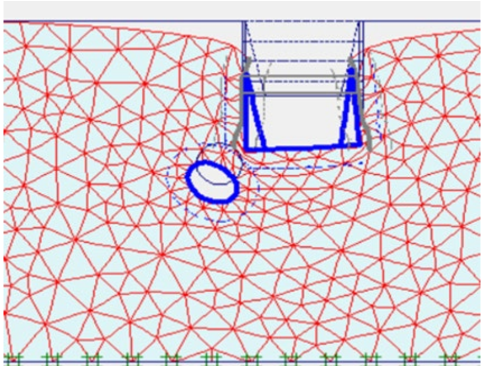

*Fig 6. Deformed mesh- After loading*

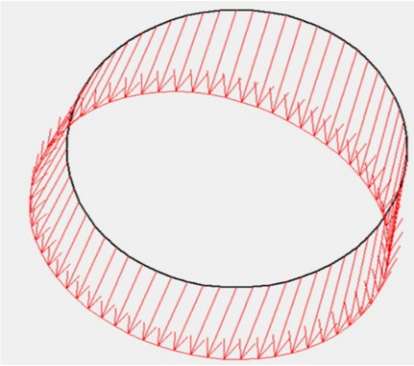

*Fig 7. Tunnel lining deformation-After Loading*

**Effect on Tunnel Points and Foundation after Loading**

The effect on tunnel lining due to the three-floor basement loading is represented by the deformed mesh in Fig 6 and tunnel deformation in Fig 7. Due to the basement foundation loading the tunnel lining moves away from the pit this is represented by displacement of tunnel lining in the opposite direction as shown in Fig 7. The total displacements at tunnel points after loading are represented in Table 4. For the given problem, the maximum displacement of the foundation after loading was found to be 158.41 mm. From Table 4, it can be analysed that the crown and right spring line undergoes more displacement in both the excavation and loading stages compared to invert and left spring line. Among them the right spring line undergoes maximum displacement because it is in close vicinity to the basement excavation compared to other tunnel points.

*Table 4. Tunnel deformations – After Loading*

| Stage | Crown [mm] | Invert [mm] | Right spring line [mm] | Left spring line [mm] |
|---|---|---|---|---|
| After excavation | 14.084 | 21.349 | 27.446 | 10.519 |
| After loading | 61.986 | 53.110 | 65.934 | 50.097 |

The tunnel crown is affected more by foundation loading than excavation of basement and foundation compared to other tunnel positions. After loading the total displacement at the crown increased by about 48 mm. Allowable limit of total displacement (in any direction) of underground, transition and subaqueous rapid transit system structures is specified as 15 mm by Land Development Authority [15] and 20 mm by Buildings Department [4].

The maximum displacement of the foundation after loading was found to be 158.41 mm. As per IS 1904, the maximum settlement for the RCC/Steel framed buildings over a raft foundation resting on sandy soil is 75 mm and can be increased to 100 mm for the structure like water towers and silos the maximum settlement under a raft foundation of RCC building and towers/water tanks/silos can go up to 125 mm. In some cases, maximum settlement can be allowed up to 150 mm without affecting serviceability of the building [11]. Hence, there is a need to limit the total settlement to 150 mm.

**Effect of tunnel lining material and tunnel lining thickness**

For this study, two types of tunnel lining materials were considered: Plain cement concrete (PCC) and Fibre reinforced concrete (FRC). The properties of PCC lining material are given in Table 5. The 28-day compressive strength of fibre reinforced concrete cylinder sample is higher than plain concrete. The properties of fibre-reinforced concrete are given in Table 5 [24].

*Table 5. Fibre concrete material properties[24]*

| $f_c$ [MPa] | EA [kN/m] | EI [kNm$^2$/m] | T[mm] | ν |
|---|---|---|---|---|
| 83 | $9.2\times10^6$ | $6.2\times10^4$ | 300 | 0.2 |

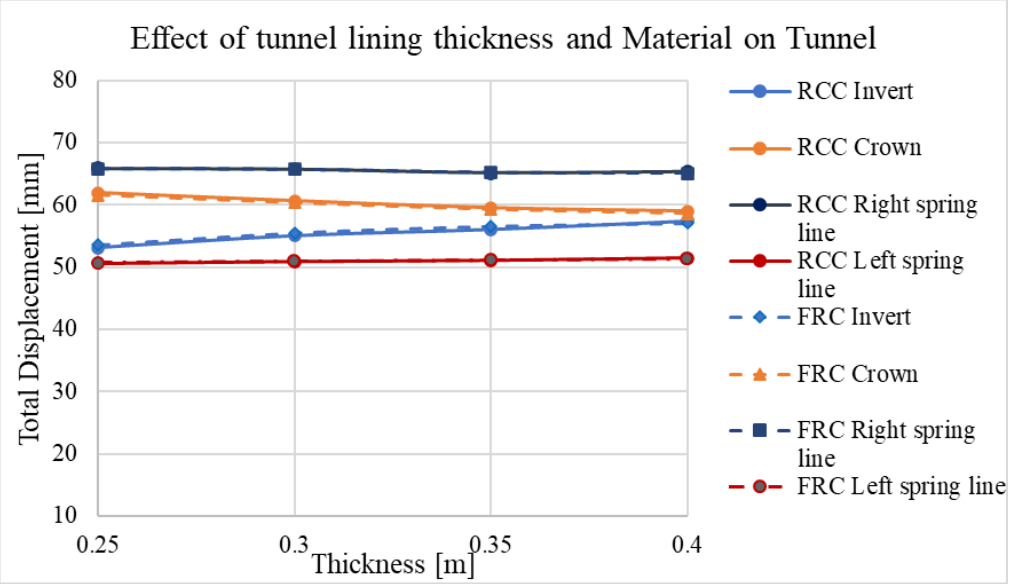

*Fig 8. Effect of tunnel lining thickness for PCC and FRC on tunnel positions*

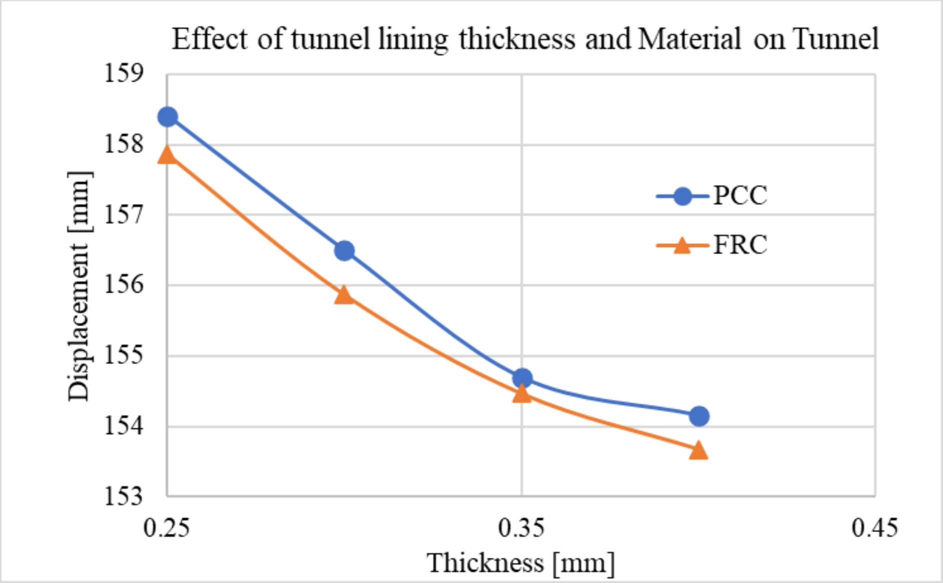

*Fig 9. Effect of tunnel lining thickness for PCC and FRC on foundation settlement*

The total displacements of tunnel crown, invert, left and right spring line for PCC as tunnel lining for different tunnel lining thicknesses (0.25 m, 0.3 m, 0.35 m, 0.4 m) and total displacements for FRC as lining material for different tunnel lining thicknesses are plotted in Fig 8. The foundation settlement shows a similar pattern (Fig. 9). From the results obtained it can be observed the effect of using FRC instead of PCC as a tunnel lining material in reducing tunnel deformations is very small. Both PCC and FRC show similar behaviour. However, the total displacement increases at the invert compared to the crown and either of the two spring levels. This may be due to the fact that as the tunnel lining thickness increases the total unit weight of concrete concentrating at the invert position which leads to an increase in the total displacement.

Unlike tunnels, the effect of using FRC in reducing foundation settlement is significant. By using FRC as tunnel lining material and with a tunnel lining thickness of 0.4 m the foundation settlement is reduced from 158.41 mm to 153.68 mm.

## Conclusion

Construction of any structure (pile, super-structure) or any excavation activity near an existing tunnel gives rise to a complicated and sensitive condition in terms of deformations and stresses generated. Tunnelling near pile foundations results in an increase in the lateral displacement of the pile when the lateral distance between the pile and tunnel is minimum.

1. The crown and right spring line undergo more displacement in both the excavation and loading stage compared to the invert and left spring line. Among them, the right spring line undergoes maximum displacement because it is in close vicinity to the basement excavation compared to other tunnel points. The tunnel crown is affected more by building loading than the basement excavation than other tunnel positions.
2. Both PCC and FRC show similar behaviour. From the results obtained it can be observed the effect of using FRC instead of PCC as tunnel lining material in reducing tunnel deformations is very small. Unlike tunnel, the effect of using FRC in reducing foundation settlement is significant. Foundation settlement was reduced from 158.41 mm to 153.68 mm by using FRC as tunnel lining material with 0.4m thickness.

From the results obtained from this study, the total displacements at the tunnel positions were not reduced to the permissible limit as per Land Development Authority [15] and Buildings Department [4]. However, the foundation settlement was considerably reduced to within the permissible limit. Since the tunnel deformations were not reduced within the permissible limit in this study where X/D =0, more studies are required to determine the best way to reduce the tunnel deformations more effectively.

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