NUMERICAL ANALYSIS ON EFFECT OF BASEMENT RAFT LOADING ON EXISTING URBAN TUNNEL IN SOIL

Sumeet Mahajan[1]
Shabin Asaf [2]
Ramanathan Ayothiraman[3]
Krishan Gopal Sharma[4]
Gunturi Venkata Ramana[5]
[1]Research Scholar, [2]Former M tech student, [3]Associate Professor, [4]Professor, [5]Professor, Dept. of Civil Engineering, IIT Delhi.
E-mail ID: [1]sumeetmahajan2@gmail.com, [2]shabinasaf@gmail.com, araman@civil.iitd.ac.in, [4]kgsharma@civil.iitd.ac.in, [5]ramana@civil.iitd.ac.in

ABSTRACT: The tunnelling induced ground settlement is the major problem in tunnelling activities in urban areas. These settlements can damage the overlying structures and it should be reduced to an acceptable value. On the other hand, the impacts of surface construction and excavation to the existing tunnels have not yet been examined sufficiently. The construction of foundation and its loading in urban area may inevitably induce stress changes in the nearby tunnel. An attempt is made to carry out a numerical analysis to examine the effect of basement raft loading on existing tunnel in sand using PLAXIS 3D. Results indicate that the displacement and moment at crown, invert, springing lines and deformations are significantly affected by various stages of construction of raft and loading.
Keywords: Tunnel, Basement Raft, Tunnel lining

1 INTRODUCTION

Tunnels are the vital elements for the everyday life of the people especially in heavily crowded urban areas. In an urban environment, due to lack of space, a lot of underground constructions such as metro tunnel and building with 2 to 3 basements are increasing. The tunnelling induced ground settlement is the major problem in tunnelling activities in urban areas. These settlements can damage the overlying structures and should be reduced to an acceptable value. Peck (1969) developed a method to determine surface settlement and lining stresses induced by tunnelling based on field measurements and empirical data. Analytical and empirical solutions of similar problems were also developed by several researchers to calculate the surface settlements and lining stresses. As of today well established design guidelines are available to evaluate the displacement of adjacent structures/foundations due to tunnel excavation, which are typically verified using proper monitoring system in practice.

On the other hand, the impacts of deep excavation, foundation construction and foundation loading on existing tunnels have not yet been examined sufficiently. Influence of pile foundation construction and loading on existing tunnel was studied by few researchers (Benton and Phillips, 1991; Higgins et al., 1999; Calabrese and Monaco, 2001; Schroeder, 2002, 2003 and 2004; Arunkumar and Ayothiraman, 2010; Ayothiraman and Arunkumar, 2011; Singh, 2011, and Sharma, 2013). Although there are few studies reported on influence of pile loading on exiting tunnels, not enough attention have been given to understand the interaction of basement raft foundation with the existing urban tunnels (Sesharao, 2014). There exists a great gap, thus giving scope to focus the research on this problem. This paper presents the results of 3D FE analyses on effect of raft excavation and loading on existing tunnel. Before the analyses, the proposed numerical modelling procedure was verified by comparing the reported case studies as discussed below.

2 VALIDATION PROBLEMS

Validations of numerical analysis have been carried out using PLAXIS (2D and 3D) software in two parts. First validating the basic problems i.e the effect of tunnelling on the subsurface settlement was carried out in the PLAXIS 2D and second the effect of tunnelling on existing foundation was carried out in PLAXIS 3D.

2.1 Settlement Trough due to Tunnelling

Settlement trough due to tunnelling has been validated using PLAXIS 2D for the Barcelona subway Network Extension Tunnel, Barcelona case (Ledesma and Romero, 1997). Soil was predominately red and brown clay with sand and gravel (C_u=30-150 kPa). The depth of tunnel axis is 10.0 m and diameter of the tunnel was 8.0 m with percentage volume loss of 0.8%. The predicted and measured settlement trough is given in Figure 1. It was found that the surface settlement profile obtained from the finite element was shallow and wide compared to the measured data and the closed form analytical solution given by Loganathan and Poulos (1998) shown in Figure 1. Maximum settlement of the trough ranges from 21.4 mm to 25.6 mm, which are comparable.

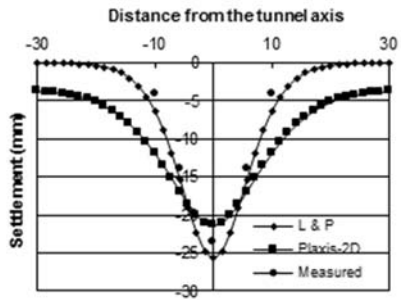


Fig. 1.0 Predicted and observed settlement trough.

2.2 Foundation Movement due to Tunnelling

Foundation movement due to tunnelling has been validated using PLAXIS-3D for the construction of a tunnel for the Angel Underground Station in London (Chen et al. 1999). The tunnel was driven between pile foundations supporting a seven-story building with a two-story basement, the tunnel axis line being approximately 5.7 m from the centerline of the nearest piles. The tunnel was excavated using hand tools in two stages, the first a pilot tunnel of 4.5 m diameter and the second an enlargement of 8.25 m diameter. Measured ground loss ratios were approximately 1.5% for the pilot tunnel and 0.5% for the tunnel enlargement. The piles were driven through 28 m London clay. The total lateral deflection predicted by the FE model is compared with the lateral deflection predicted by Chen et al. (1999) and measured value as shown in Figure 2. Figure 2 shows an acceptable comparison.

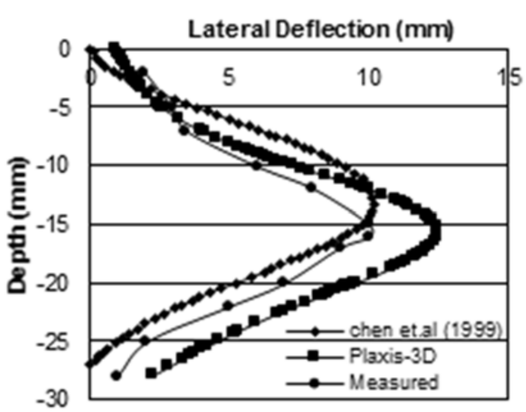
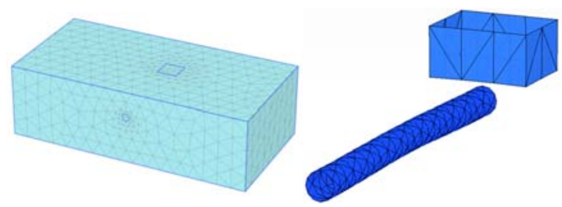


Fig. 3.0 Measured and predicted pile lateral deflection

3 RAFT LOADING ON EXISTING TUNNEL: MODELLING

3.1 Soil

The soil was modelled using 10-noded tetrahedral elements in 3 D analysis. The size of the soil model was taken 200 m × 100 m and 60 m depth. Bottom of the model was treated as fixed boundary conditions and sides of the model were assigned with roller supports. The elasto-plastic behaviour of the soil was modelled using the Mohr-Coulomb model. Medium mesh density is used for the soil, but close to tunnel, fineness of mesh is increased. Figure 3 shows the details of a typical FE mesh. The input properties of soil used in the analysis are presented in Table 1.



(a) (b)

Fig. 4: Typical FE mesh (a) meshed ground (b) meshed lining and raft-retaining wall

Table 1: Input Properties used in FE Analysis

Material	Property	Value
Yamuna sand	Unit weight (kN/m^3)	15
	Young's modulus (kPa)	25000
	Poisson's ratio	0.3
	Friction angle (°)	37.5
	Cohesion (kPa)	0.5
Tunnel Liner	Unit weight (kN/m^3)	25
	Young's Modulus (GPa)	23.48
	Poisson's ratio	0.2
Raft and Retaining Wall	Unit weight (kN/m^3)	25
	Young's Modulus (GPa)	29.5
	Poisson's ratio	0.2

3.2 Tunnel

A prototype dimension of tunnel constructed by Delhi Metro Rail Corporation (DMRC) was considered. The inner and outer diameter of running tunnels for Qutab Minar Line and airport metro line adopted by DMRC are 5.6 and 6.35 m (Hsiung et al. 2010). In the present study, prototype tunnel diameter of 6.0 m is considered for modelling. Thickness of the tunnel lining was considered 0.28 m thick. Tunnel is modeled as 6 noded triangular plate elements having elastic behaviour. The input properties of elastic tunnel lining considered in the model are presented in Table 1. It is assumed that tunnel liner is installed immediately after excavation of each stage and simulating the volume loss of 1.0 %.

3.3 Basement Raft-Retaining Wall

The basement raft (thickness 0.6 m) and retaining wall (thickness 0.5 m) are assumed to behave as elastic material. After excavation of the tunnel, raft excavation (16 m x 16 m) upto 3rd basement was carried out at a clear distance of 0.5 *D* from the face of the tunnel. Then, basement raft and retaining wall were installed simultaneously. The properties of basement raft and retaining wall is assumed as per the values given in Table 1.

3.4 Construction Stages

In PLAXIS -3D model, construction stages were defined in such a way that the stages are simulated as per the field conditions. Based on the problem statement seven stages of construction are created. The load increment on the raft is considered as 10kN/m^2 for each floor.

4 DISCUSSION OF RESULTS

The results predicted by the FE analysis are presented and discussed herein.

Figures 5 and 6 shows the displacement contours of the whole model at the central cross-section corresponding to the final stage, '3B+20F', as well as tunnel alone respectively.

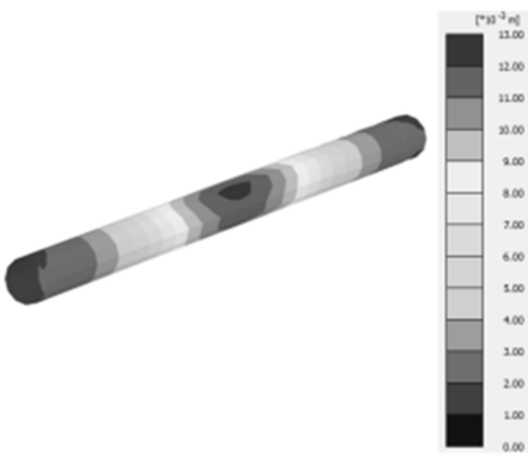


Fig. 5: Predicted displacement contour of complete FE mesh

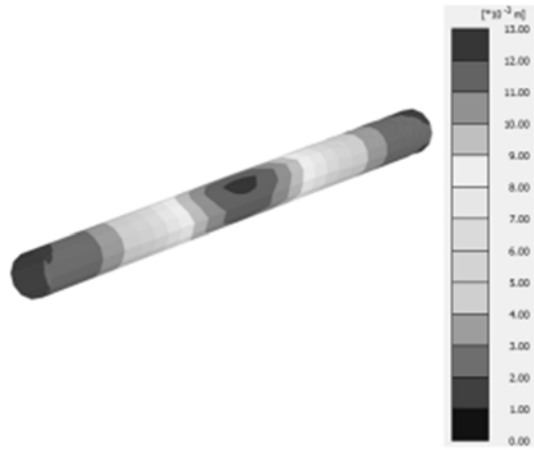
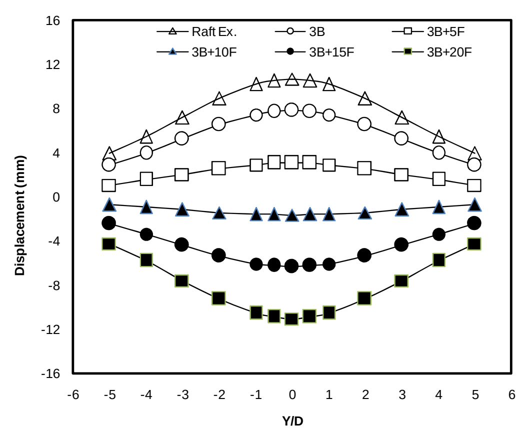


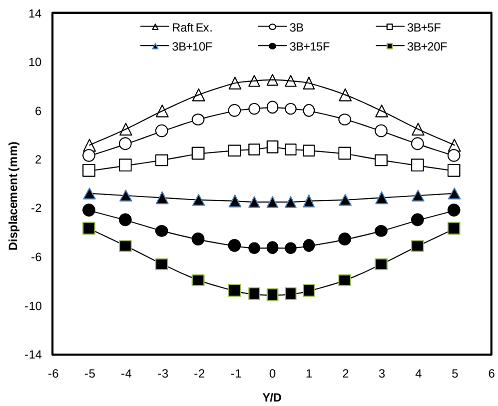
Fig. 6: Predicted displacement contour of tunnel lining.

It is observed from Figures. 5 and 6 that the maximum displacement occurs near to the shoulder position of the tunnel due to raft excavation. When further load due to floors is applied, displacement reduces towards zero, subsequently increases further in the opposite direction with an increase of floor loads.

Figure 7 shows the typical variation of vertical displacement at crown and left springing along the length of tunnel. In this figure, the displacement were interpreted along the crown of tunnel at different lengths with reference to centre line of the raft (Y-coordinate = 50 m), which is normalized to the diameter of tunnel (*Y*/*D*). Results are obtained for different stages of the analysis as shown Figure 7.



(a)



(b)

Fig. 7: Vertical displacement along the length of the tunnel: (a) Crown and (b) Left springing.

Similar procedure was adopted to plot the displacement variation with normalized tunnel length for invert and springing lines. It is seen from Figure 7 that………… Value of displacement are observed maximum at the center of the raft and goes on decreasing as we move away from the center of the raft. The graphs are normalised by dividing with the value of diameter of the tunnel for general comparison purposes

5 Summary and Conclusions

Based on the results obtained, it is concluded that the variation of displacement is significant with respect to various stages of construction. It is observed that vertical displacement of tunnel is more prominent compared to its horizontal movement. The tunnel liner is found to move towards the raft foundation while excavation and then away from it as a result of loading. This is due to the heaving effect of soil as a result of release of stress as excavation is made. Further due to loading of raft foundation, the opposite effect is made.

REFERENCES

Arunkumar, S. Ayothiraman, R. (2010). Effect of Vertically Loaded Pile on Existing Urban Tunnel in Clay, *Indian Geotechnical Conference, Bombay*, 751 – 754.

Ayothiraman, R. and Arunkumar, S. (2011). Influence of vertical pile loading on existing tunnel lining in soft clay, *14th Australasian Tunnelling Conference, Auckland, New Zealand*, 1-13.

Benton, L.J. and Phillips, A. (1991). The behaviour of two tunnels beneath a building on build foundation. Deformation of Soils and Displacements of Structures. *X ECSMFE, Florence*, 2: 665-668.

Calabrese, M. and Monaco, P. (2001). Analysis of stresses induced in an old deep tunnel by pile driving from the surface. *FLAC and Numerical Modeling in Geomechanics*, 199-204, France.

Chen, L.T., Poulos, H.G. and Loganathan, N. (1999). Pile responses caused by tunnelling. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 125(3): 207-215.

Coutts, D. R. and Wang, J. (2000). Monitoring of reinforced concrete piles under horizontal and vertical loads due to tunnelling, *Tunnels and Underground Structures* (eds. J. Zhao *et al*.), Balkema, 541-546.

Higgins, K.G., Chudleigh, I., St. John, H.D. and Potts, D.M. (1999). An example of pile tunnel interaction problems. *Proc. Int. Symp. on Geotechnical Aspects of Underground Construction in Soft Ground*, IS-Tokyo ’99 (eds. O. Kusakabe, K. Fujita and Y. Miyazaki), Balkema, 99-103.

Loganathan, N., Poulos, H.G., (1998). Analytical prediction for tunnelling-induced ground movement in clays, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, ASCE, 124 (9): 846–856.

Peck, R. B. (1969). Deep excavations and tunnelling in soft ground, *Proc. of the 7th int. Conference on Soil Mechanics and Foundation Engineering*. State of the art volume. Societal Mexican de Mechanical de Solos, A. C. 225-290.

Schroeder, F.C., Addenbrooke, T.I. & Potts, D.M. (2002). A numerical investigation into the impact of pile group loading on tunnels. *Proc. 2 nd Int. Conf. on Soil Structure Interaction in Urban Civil Engineering*, 205-212

Schroeder, F. C. (2003). *The influence of bored piles on existing tunnels,* Ph.D. thesis, Imperial College, University of London.

Schroeder, F.C., Potts, D.M. &Addenbrooke, T.I. (2004). The influence of pile group loading on existing tunnels. *Géotechnique*, 54(6): 351-362

Schedule of Dimensions issued by Delhi Metro Rail Corporation Limited for Airport Metro Express Line 2010.

Singh P. (2011). *The influence of pile loading on existing tunnel,* M. Tech Thesis, Indian Institute of Technology, Delhi, India

Sharma, A. (2013). *Influence of Pile Loading on Existing Tunnels***,** M. Tech Thesis, Indian Institute of Technology, Delhi, India

Sesharao, P. (2014). *Influence of Basement Raft Loading on Existing Tunnels*, M. Tech Thesis, Indian Institute of Technology, Delhi, India.