

# Effect of Piled Structures on the Tunnel Stability for Different Pile-Tunnel Configurations



M. Wasif Naqvi and Mohd. Ahmadullah Farooqi

**Abstract** In view of the rapid pace of urbanization, the demand to enhance the capacity of existing transportation infrastructure and construction of alternative modes of transport is escalating. In the recent pursuit of metro trains in India, the focus toward the construction of underground tunnels has substantially increased. The construction of infrastructure on the ground surface is still growing and may potentially influence the stability of tunnel passing underneath it. The situation may become worse when the structure is to be constructed on deep foundation like piles or wells. In terms of sustainable development, it is of paramount importance to understand the influence of piled structures on the tunnel lining in terms of location and load of pile and pile-tunnel configuration in different subsoil profiles. The present study aims to investigate the effect of the piled structure on stability of the tunnel and the surrounding soil. The 2D multiplier elastoplastic analysis has been carried out using the popular Mohr-Coulomb material model on the commercial finite element-based software OptumG2. The stresses on tunnel lining and the surrounding soil mass have been analyzed under different pile-tunnel configurations under varying load and pile eccentricity with respect to the axis of tunnel. Also, a parametric study has been done to evaluate the displacement and stress distribution of surrounding soils and tunnel lining under increasing pile load, length, and different pile-tunnel placements.

**Keywords** Pile-Tunnel interaction · Numerical modeling · Limit analysis · OptumG2

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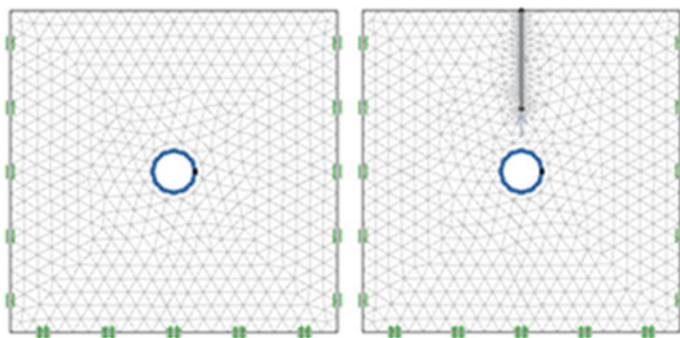
## 1 Introduction

In the recent economic development in India, urban zones are expanding swiftly over the adjacent rural areas and it is expected that this expansion would reach 60–70% by 2050 (World Urbanization Prospects 2014). On the other hand, in search of jobs, rural population is fast inverting to the nearby metropolitan cities; hence, increasing demand on the already saturated infrastructural capacity. Road traffic congestions and elevated environmental pollution levels are among the worst affected sectors. In Delhi, to slow down this economic exodus, National Capital Region Planning Board has identified national capital regions (NCR), with a view to develop them into regional economic hubs and connect them with the national capital territory (NCT) through peripheral expressways and orbital rail corridors (“National Capital Region Planning Board,” n.d.). The metro rail facility through a network of tunnels is an extensively adopted and sustainable solution to regulate elevated traffic volume and to reduce pollution challenges. In urban development scenario, it is relatively more important to investigate the effect of tunneling on existing structures. Significant research has already been done ranging from field studies (Vorster et al. 2005; Li et al. 2014; Selemetas et al. 2006; Kaalberg et al. 2005), experimental work (Loganathan et al. 2000; Chen et al. 1999; Bezuijen and Van der Schrier 1994; Chapman et al. 2001; Pang et al. 2006; Yao et al. 2008; Meguid and Mattar 2009), analytical modeling (Kitiyodom et al. 2005; Lee and Ng 2005; Cheng et al. 2007; Marshall 2012; Marshall and Haji 2015), 2D numerical modeling (Huang et al. 2009; Zhang et al. 2012; Giardina et al. 2015), and 3D numerical modeling (Arunkumar and Ayothiraman 2010; Kitiyodom et al. 2005; Mroueh and Shahrour 2002; Mroueh and Shahrour 2003; Franza et al. 2017; Yao et al. 2012; Zidan and Ramadan 2015) to study the effect of tunneling. However, in an effort to connect remote regional economic areas with sparse developments through metro tunnels, it is of paramount importance to consider the alignment and depth of tunnels and strength and stability of tunnel lining to account for potential future surface infrastructural development.

On account of the prospective future construction of new structures or reconstruction of the old ones, this study aims to explore the effect of construction of piled structures on the lining of existing tunnel. A numerical model has been developed to investigate the effect of piles on tunnel lining by increasing pile load, on four different pile locations, with three different pile-tunnel configurations.

## 2 Numerical Model

The whole 2D model is modeled using newly developed finite element software OptumG2 (“OptumG2” 2013). Figure 1 shows the typical meshed models of soil with and without pile. The outer dimensions of tunnel of 6 m is taken from the study conducted by Basile (Basile 2014). The thickness of concrete lining used for the modeling is kept 28 cm (Singh et al. 2017). The tunnel concrete lining is made using



**Fig. 1** Discretized domain of problem with and without pile

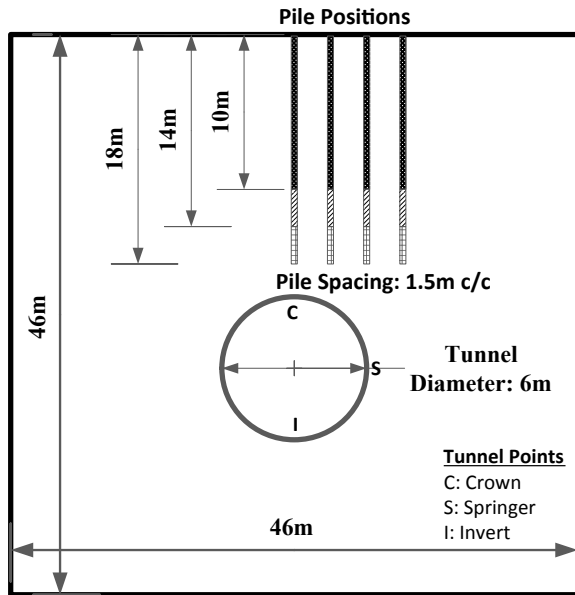
**Table 1** Physical properties of materials

<i>Delhi silty sand</i>	
Unit weight	15 kN/m <sup>3</sup>
Young modulus	25,000 kPa
Poisson ratio	0.3
Friction angle	37.5
Cohesion	0.5 kPa
<i>Concrete liner</i>	
Density	25 kN/m <sup>3</sup>
Young modulus	23.48 GPa
Poisson ratio	0.2

P800 plate structural element having the properties as shown in Table 1 (Mahajan et al. 2016). The elastoplastic model of the soil is provided using the famous Mohr-Coulomb theory. The dimensions of the soil model are kept  $46 \text{ m} \times 46 \text{ m}$  with tunnel at its center having diameter of 6 m. All the dimensions are kept such that all the faces are at a distance of  $3d$ , where  $d$  is the diameter of tunnels, from the center of the tunnel. This is done because the stress contour is significant up to this distance and the effect is trivial beyond this distance (Jose and Shounak 2015). The soil is considered as Delhi silty sand with properties given in Table 1 (Mahajan et al. 2016). The bottom is provided with a fixed support while the two sides of the soil model are provided with roller support with movement allowed in the vertical direction (Fig. 2).

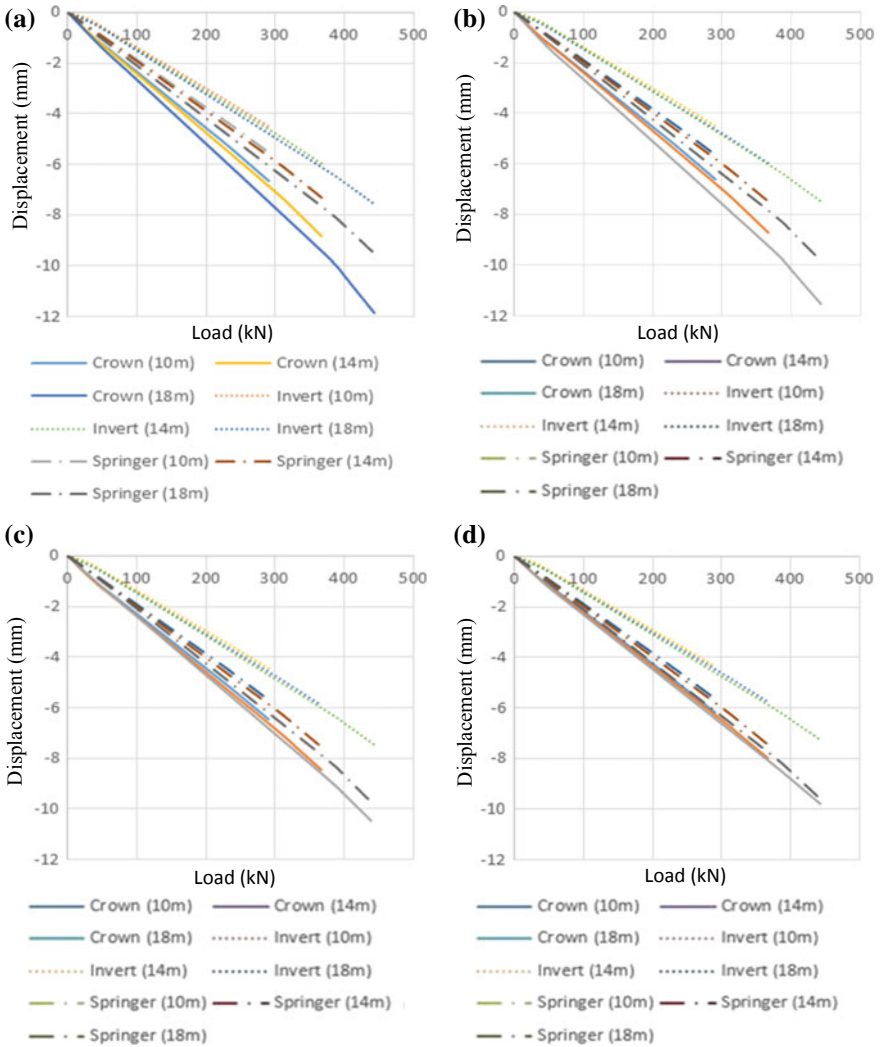
Piles of varying length are provided at different locations in the soil model. The massive circular concrete piles are modeled using standard beam elements in OptumG2. The diameter of the pile is kept 0.5 m having length varying as 10, 14, and 18 m. the properties of the pile are given in Table 1. The element type used for modelling is 6-node Gaussian elements.

**Fig. 2** Geometry of the modeled problem. Pile positions start with eccentricity value of 0 m, at the centerline of tunnel to 4.5 m at a spacing of 1.5 m. Three different depth values are taken: 10, 14, and 18 m. The tunnel crown is located at 20 m from surface



## 2.1 Stages of Analysis

The analysis is carried out in four sequential stages to simulate the real ground scenario. Initially, the green field analysis is done in which only soil is modeled and the stresses induced due to self-weight are calculated using initial stress analysis of OptumG2. In the second stage, the tunnel is excavated and the tunnel perimeter is provided with full support and elastoplastic analysis is carried out. In this step, a relaxation factor,  $\lambda$ , of 0.5 is specified to consider convergence–confinement method. In the next stage, the perimeter support of tunnel is replaced with a plate element to model the lining and the elastoplastic analysis is carried out to determine the deformation and stress in the model. In the final stage, the pile is inserted at zero eccentricity to simulate the complete problem. The final stage is varied to consider different locations and depths of piles. The analysis carried out in this stage is termed as multiplier elastoplastic analysis which is a combination of limit analysis and elastoplastic analysis. In this type of analysis, the pile is incrementally loaded to a certain value of limiting load and resulting deformations are simultaneously recorded, as shown in Fig. 3. An axial load is applied at pile top to determine the ultimate load-bearing capacity of pile and subsequently, the stresses induced and displacement caused due to varying load is analyzed. The initial displacement is set to zero before this analysis to only observe the effect of gradual loading on piles.



**Fig. 3** Critical displacement values against incremental load at the crown, springer, and invert points on tunnel lining. The values in bracket represent eccentricity of pile away from the center line of tunnel

### 3 Results and Discussions

The vertical displacement induced at crucial tunnel points, namely crown, invert, and springer, subjected to varying loads, are calculated for different depths and eccentricities of pile. The contours of normal force, shear force, and bending moment at maximum loads are simultaneously studied. Finally, the stresses and vertical displacements induced in the surrounding soil are also observed.

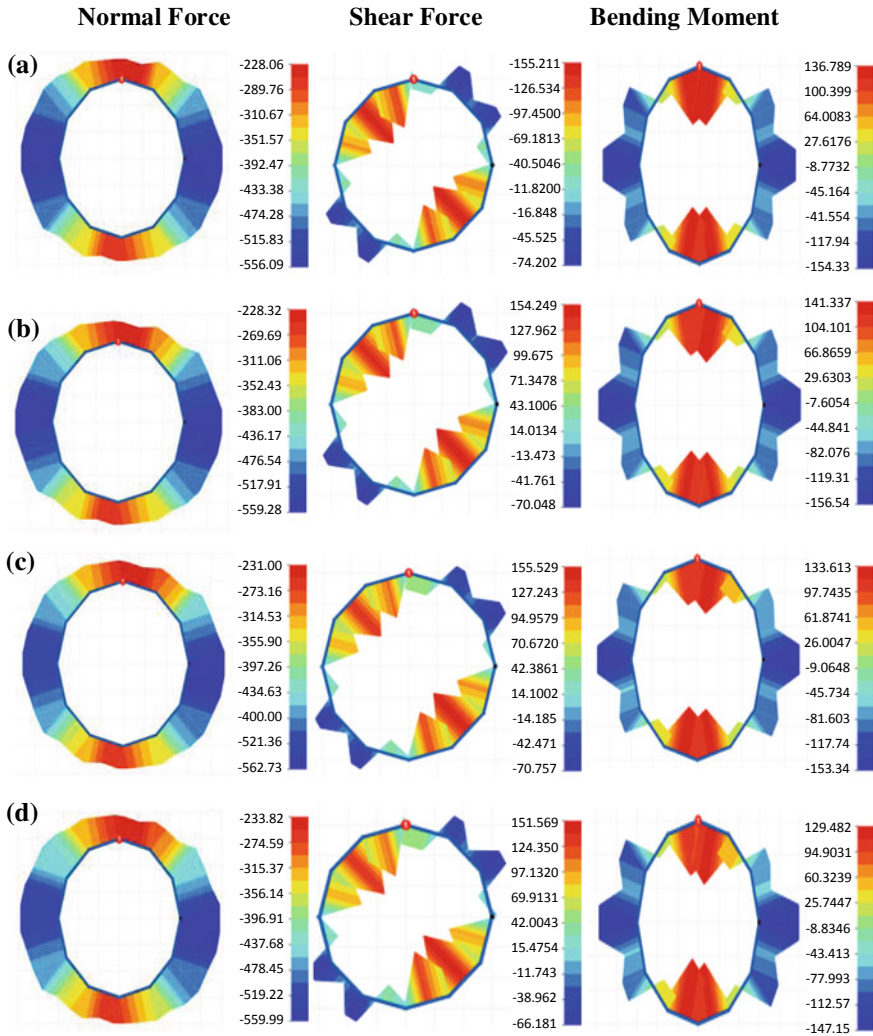
#### 3.1 Vertical Displacement of Crucial Tunnel Points

Vertical displacement of crown is found to be the maximum in all cases with a maximum vertical displacement of 11.85 mm in the loading case when the pile is above the crown. The displacement of all crucial tunnel points tends to decrease with the increase in eccentricity with minimum vertical displacement of 4.36 mm is found at invert point in the case of maximum eccentricity of 4.5 m from tunnel axis. The values of maximum displacement at crown, invert, and springer points are found to be 11.85, 4.51 and 9.60 mm at no-eccentricity, no eccentricity and 4.5 m eccentricity cases, respectively. The tunnel point that is most affected by the increase in the depth of pile is the crown with a maximum variation of 5.19 mm in no-eccentric loading case while the least affected point is invert. Crown remained the most affected point under eccentric loading, with variation of up to 2 mm from no-eccentricity to maximum eccentricity case.

#### 3.2 Forces and Moments in Tunnel Lining

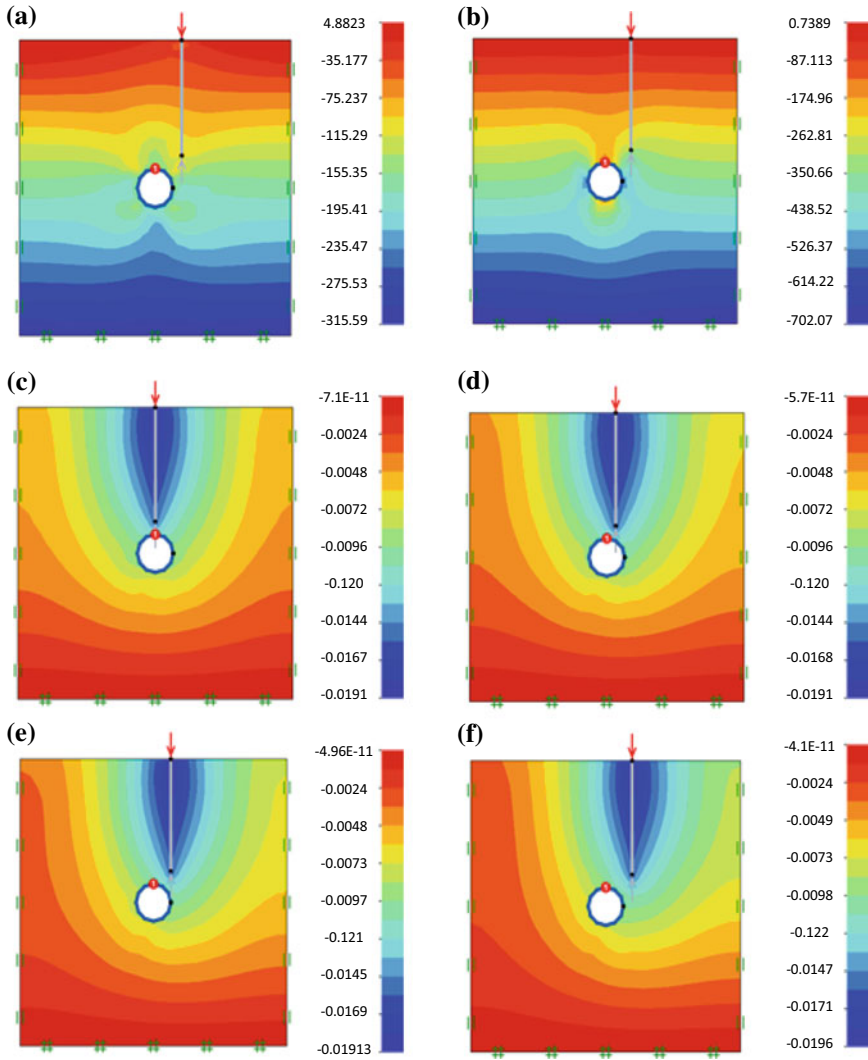
The contours of normal forces are as shown in Fig. 4. The normal forces at crown and invert show the usual positive trend while the negative normal forces can be seen at the springer point in all the cases. The maximum magnitude of normal force is at crown and invert points in all cases. The normal forces tend to increase with increase in depth of pile while the change in eccentricity of load has no significant variation in the magnitude of normal force. The minimum and maximum normal forces are  $-522$  and  $-562$  kN in the case of no-eccentricity and at 3 m eccentricity case, respectively.

The contours of shear forces in tunnel lining are also shown in Fig. 4. The shear force is not much influenced with the eccentric loading and is only slightly affected with the increase in depth of the pile. The maximum shear force on tunnel lining is found at 1.5 m eccentric loading case, with magnitude of 156 kN. The contours of bending moment in tunnel lining are shown in Fig. 4; the bending moment is not influenced by the eccentricity significantly but the effect of depth of pile has a significant effect in the bending moment on tunnel lining. The maximum bending



**Fig. 4** Contours showing distribution of normal force, shear force, and bending moment along the tunnel lining for **a** eccentricity: 0.0, **b** eccentricity: 1.5, **c** eccentricity: 3.0, and **d** eccentricity: 4.5 meters away from the centerline of the tunnel

moment is found to be 156.5 kNm in the 1.5 m eccentric loading when the pile is at a depth of 18 m while the minimum bending moment of 136 kNm in the tunnel lining is in the 4.5 m eccentric loading case having depth of pile as 10 m.



**Fig. 5** Stress and displacement distribution in soil mass: principal stresses in soil **a** vertical direction and in **b** horizontal direction. Vertical displacement in soil mass for **c** eccentricity: 0.0 m, **d** eccentricity: 1.5 m, **e** eccentricity: 3.0 m, and **f** eccentricity: 4.5 m

### 3.3 Stresses and Displacement in Soil

The maximum principal stresses of soil in  $x$ - and  $y$ -directions are shown in Fig. 5. There is no significant variation of stresses in the soil with change in configuration of pile with respect to tunnel. The maximum principal stresses in  $x$ - and  $y$ -directions are found to be 316 and 702 kN/m, respectively. The displacements in soil mass in the case



of 18 m depth pile at various eccentricity values are shown in Fig. 5. The maximum displacement in soil occurs at pile top with a maximum downward displacement of 19.6 mm in the case of 4.5 m eccentric loading having pile at 18 m depth. The displacement as expected is influenced with the pile depth and not significantly affected with eccentricity.

## 4 Conclusions

The present study aims to investigate the effects of construction of piled structure on the stability of existing tunnel. A 2D plain strain model has been developed in OptumG2, and multiplier elastoplastic analysis has been carried out using popular Mohr-Coulomb material model. The displacement and stresses on the tunnel lining and the surrounding soil mass have been studied by increasing pile load and decreasing pile-tip-tunnel distance and increasing pile eccentricity with respect to the axis of tunnel. A parametric study has been done to evaluate the displacement and stress distributions. It has been found that the critical condition for tunnel lining occurs when pile-tip-tunnel distance is reduced and pile is located between crown and springer points. The 18 m long pile challenged the stability of tunnel significantly more than their 10 or 14 m counterparts. In case of surrounding soil, eccentricity played the most challenging role and the worst case scenario existed at 4.5 m eccentricity in terms of both stresses and displacements.

It can be conveniently concluded that heavily loaded long piles located between crown and springer points of tunnel are critical for tunnel lining while those with eccentricity beyond the springer point are critical for surrounding soils.

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