Numerical Analysis on Interaction of Single Pile Tunnel System

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Abstract. In past few years, the number of tunnels construction in several populous cities significantly increases for better infrastructure development. In many situations, tunnel alignment must be laid below the high rise buildings, bridges or important civil engineering structures. In such condition, the chances of possible damage to the foundations of these structures are very high. Hence, it is vital to study the tunnel-pile interaction behaviour for the safety and serviceability of the both tunnel and the foundation of the existing structures. In view of this series of numerical analysis are carried out on tunnel-pile interaction behaviour. It is observed that the maximum surface settlement takes place at the centre of tunnel and it decreases with horizontal distance from tunnel centre at Greenfield condition. In tunnel pile condition, different pile behaviour is observed for varying tunnel position with respect to pile. Maximum pile head settlement is found when tunnel is placed just beneath the pile toe position. Reduction in pile capacity is found to be 3.07% and 6.98% when tunnel is placed near the centre of pile length and near the pile toe consequently. This is because of maximum end bearing resistance reduced when tunnel placed near the pile toe.

Keywords: Tunnel, Surface Settlement, Pile load carrying capacity.

1 Introduction

With rapid urbanization and economical development, heavy traffic congestions have become a problem for city planners and administrators. Due to scarcity of land, expansions of roads are also not possible for most of the urban areas. Underground rapid transport system came as a solution of above-mentioned problem. In rapid transit system, alignment of a proper tunnel path is a complex work. To avoid the interaction of foundation of several civil engineering structures, alignment of tunnel path is done through major roads, but problem arises when roads take a 90-degree sharp bend. Tunnel alignment has to take a curve turn towards a new road. At that time tunnel is bound to interact with pile foundation of high-rise building. Due to tunneling operation, ground movement takes place. Pile transfers its load to soil and presence of tunnel may disturb the load carrying mechanism of pile leading to the failure of structures. For these reasons, the position of tunnel with respect to pile is an important aspect which needs to be considered by practicing engineers for the better safety and serviceability of the structures.

In this regard, several researches have been carried out to get a better understanding on tunnel induced ground settlement and tunnel induced pile behaviour. Based on several experimental and numerical studies, it is found that maximum induced surface settlement occurred at the centre of tunnel and it decreases with increase in horizontal distance from tunnel centre (Peck, 1969; Mair and Taylor, 1977a, b; O'Reilly and New, 1982; Mair et al., 1993; Loganathan et al., 1999; Somraoo et al., 2017). It is also observed that single tunnel induced ground settlement can be represented by Gaussian distribution curve. Tunnel excavation also causes pile head settlement or reduction in pile load carrying capacity like surface settlement in Greenfield condition. Bezuijen and Schrier (1994) conclude from their studies that pile head settlement can be significant when tunnel pile distance is less than the tunnel diameter. It is also found that tunnel induced pile behaviour depends on tunnel position with respect to pile (Loganathan et al., 1999, Jacobsz et al., 2004; Ng et al., 2013; Somraoo et al., 2017). Therefore, extensive study is required to investigate the insight behaviour of pile due to the construction of single tunnel for various tunnel pile configuration.

In view of this, present study aims to investigate the change in induced pile behaviour for different positions of single tunnel respect to pile through a series of numerical analysis in sand. The influence of several parameters such as single tunnel induced surface settlement at Greenfield condition, tunnel induced pile behaviour for different position of the tunnel on the overall behaviour of pile tunnel system are reported and discussed in this study.

2 Methodology

2.1 Numerical studies

The objective of present study was achieved by performing numerical analysis using FLAC 2D software package. This is two-dimensional explicit finite difference program used to solve various complex geotechnical problem and complex boundary condition. Highly nonlinear and irreversible response of soil and rock can be analyzed with the help of several constitutive models which are default in FLAC. A typical layout of FLAC 2D model with the details of loading and the boundary conditions are shown in Fig. 1, where L_P is the length of pile and Z_T is the depth of tunnel from soil surface. S is denoting the horizontal spacing in between pile toe and centre of tunnel.

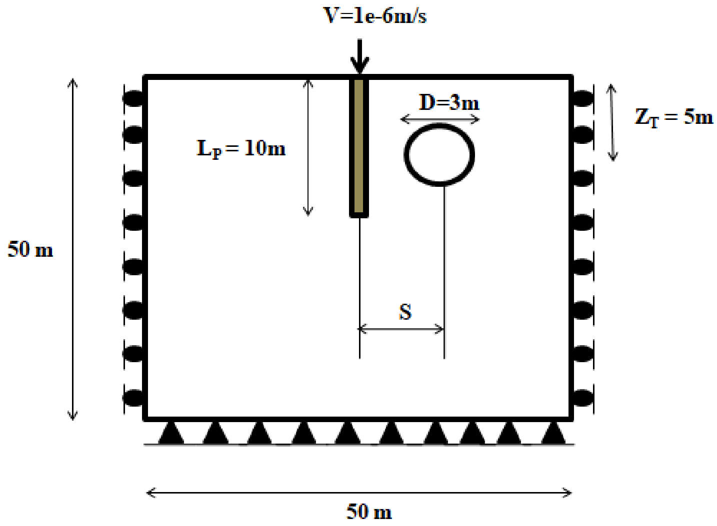

Fig. 1. Configuration of typical numerical model for case of Z_T/L_P = 0.5 (elevation view)

2.2 Finite element mesh and boundary condition

The finite difference model for tunnel pile system used in this study is presented in Fig. 2. The dimensions of model used in this study were sufficiently large to minimize boundary effects in the numerical simulation. Besides, it is also observed that increase in number of grids beyond 50×50 did not influence computed results. For applying, boundary condition on the model, roller and pin supports were installed along the vertical sides and bottom sides of the mesh. So that, the horizontal movement for vertical boundaries and both horizontal as well as vertical movements for bottom boundaries were restrained. The elastic perfectly plastic Mohr-Coulomb model is used to model soil profile. Predefined structural elements, pile and liner are used to simulate pile and tunnel lining behaviour in this study. Pile has installed just middle of the model. The interaction between pile and soil has been controlled by shear and normal coupling spring of pile elements which were already designed in FLAC 2D software package. At a specified distance from pile, tunnel of 3m diameter is simulated by excavating grids of initial model. This excavation is done using null commands. Liner elements are installed to simulate adequate tunnel support system. Tunnel is placed at 5m depth from the top of the surface. As per requirement of study, tunnel position has varied vertically with respect to pile. As per requirement of study, tunnel has positioned at centre level of pipe and at the bottom of the pile consequently. Parameters used in present study are summarized in Table 1.

Mair and Taylor (1977) reported typical volume loss up to 1% for sand when earth pressure balance shield is used for tunnel excavation. Based on this recommendation, tunnel volume loss of 1% is considered for present study.

Total five numerical models are simulated to represent Greenfield condition and various tunnel pile configurations as per requirement of present study. Single tunnel induced ground movement is investigated using Greenfield numerical model. Two different tunnel positions with respect to pile are simulated in tunnel pile system and represented by Z_T/L_P ratio (i.e. Z_T/L_P - 0.5, 1). Tunnel induced pile behaviour is analyzed for every Z_T/L_P ratio.

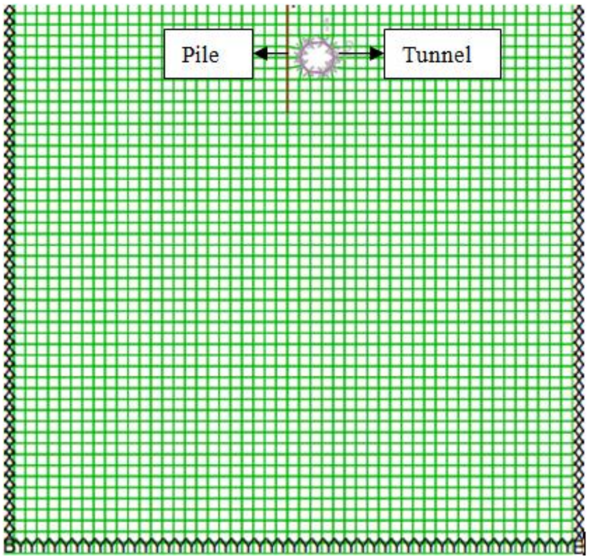

Fig. 2. Finite difference grids and boundary conditions of numerical model of Z_T/L_P = 0.5

Table 1. Parameters used in present study

Sl No.	Properties	Value
1	Sand bulk modulus (Pa)	74e6
2	Sand shear modulus (Pa)	24.6e6
3	Friction angle (degree)	25°
4	Density(Kg/m^3)	1541
5	Stiffness of pile material (Pa)	2e11
6	Stiffness of liner material (Pa)	4e10

3 Results and Discussions

3.1 Validation of numerical model

Initially, it is necessary to compare computed numerical results with experimental results to verify the accuracy of the proposed numerical model. For this, load displacement response of single pile reported by Malhotra et al. (2019) has been considered. The model dimensions and the properties of the material were adopted same as the experimental model. The comparison between load displacement response of pile obtained from present numerical model and experimental results reported by Malhotra et al. (2019) is presented in Fig. 3. In general, it has been observed that a numerical results holds good agreement with experimental results. However, a little discrepancy between two results exits. This is probably due to the small error occurred while obtaining the soil properties in laboratory. Hence it can be said that the present numerical model can be used to simulate the pile behaviour in sandy soil conveniently. Subsequently, this model has been extended to study the tunnel pile interaction behavior in details, which is presented in the following section.

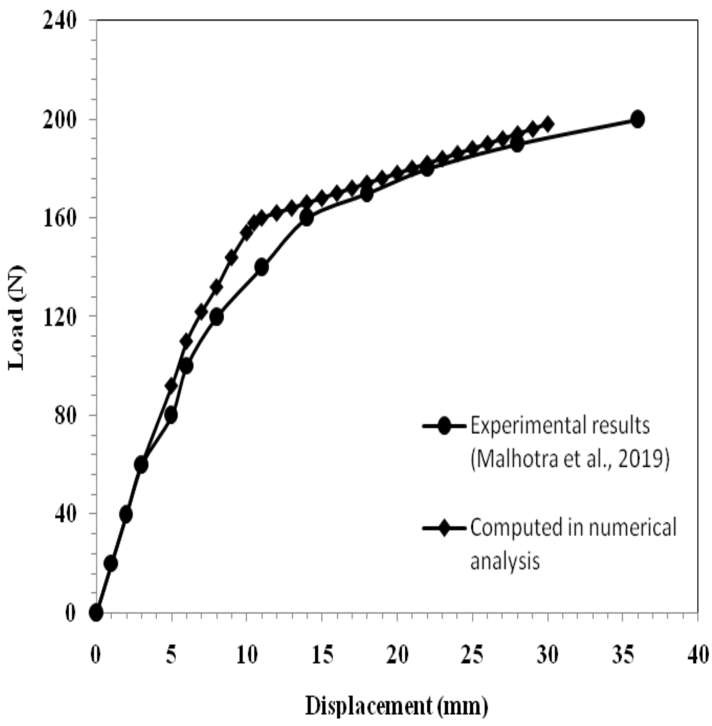

Fig. 3. Comparisons between experimental and numerical results

3.2 Ground surface settlement due to tunneling in Greenfield condition

Tunnel excavation causes stress relaxation around a tunnel which leads to ground movement or surface settlement. Surface settlement profile due to single tunnel excavation is investigated in present study and presented in the Fig. 4. It is seen that the maximum surface settlement of 0.58% of *D* (i.e., 17 mm) occurred at the centerline of the tunnel for *C/D* ratio of 1.2. Lu et al. (2019) has reported similar behaviour through experimental analysis as well. The maximum settlement observed from centrifuge test for *C/D* ratio of 1.5) at centre line of the tunnel is about 0.5% of *D* (Lu et al. (2019). Thus surface settlement data observed from present numerical analysis holds good agreement with experimental results as reported by Lu et al. (2019). Besides, the surface settlement curve due to tunnelling at Greenfield condition can be represented by Gaussian distribution curve. This curve was proposed by Peck (1969). Ground surface settlement *S* according to Peck (1969) can be obtained using following equation.

$$S(x) = S_{max} \exp(-x^2/2i^2)$$

Where, S_{max} represents the maximum ground surface settlement and *i* represent distance between tunnel centreline to point of inflexion point. The value of *i* for present case is 2.25 m. Accordingly O'Reilly and New (1982), i can be represented by KZ_T, where Z_T represents depth of tunnel centre. The value of Z_T in present case is 5m. Besides, width parameter K value can be obtained using following equation.

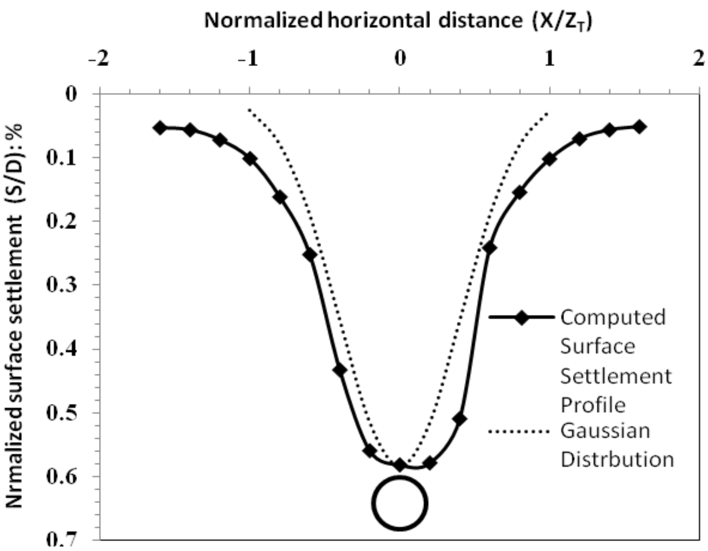

Fig. 4. Ground Surface settlement due to single tunnel excavation at Greenfield condition

$K = i/Z_T$ or $K = 2.25/5 = 0.45$

According Mair and Taylor (1977), the typical value of K should be in between 0.25 to 0.45. Hence, the obtained K value for the present case is found to be 0.45, which is in the range.

3.3 Reduction in ultimate load bearing capacity of pile due to tunnel

Fig. 5 shows load displacement curves of pile before and after tunnelling when tunnel placed near the centre depth of pile (i.e. Z_T/L_P ratio 0.5). The ultimate load of pile is obtained from load displacement response using double tangent method before and after tunnel excavations. Change in ultimate load bearing capacity of 3.07% is found at Z_T/L_P ratio 0.5. Similar observation on change in ultimate bearing capacity (i.e., change in bearing capacity =4% at Z_T/L_P ratio 0.5) is also reported from by Malhotra et al. (2019).This is because the tunnel excavation causes stress reduction near the centre of the pile when tunnel placed at Z_T/L_P ratio 0.5.
Vertical displacement contour of pile before and after tunnel excavation is shown in Fig. 6 and Fig. 7. The pattern of displacement contour without tunnel found to be similar in both side of pile (Fig. 6). However, the pattern of vertical displacement contour of pile after tunnel excavation found to be distorted on the right side of pile due to the tunnel excavation. Similar type of vertical displacement pattern has been reported by Malhotra et al. (2019).

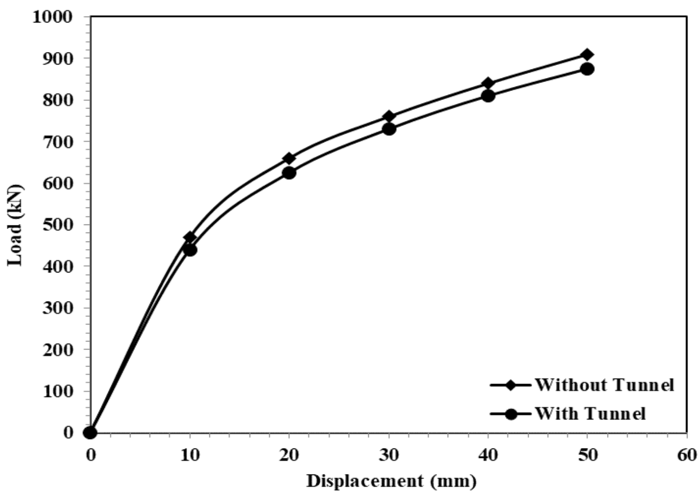

Fig. 5. Load displacement curve of pile: Z_T/L_P= 0.5

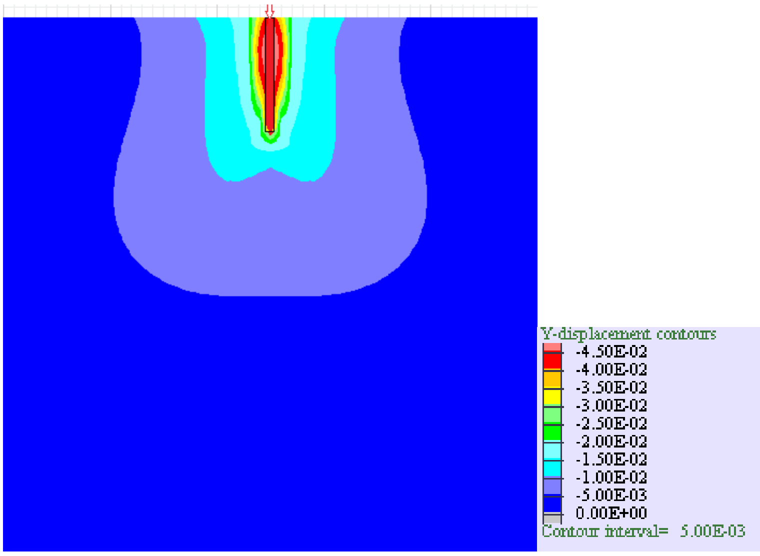

Fig. 6. Vertical Displacement contour of pile without tunnel

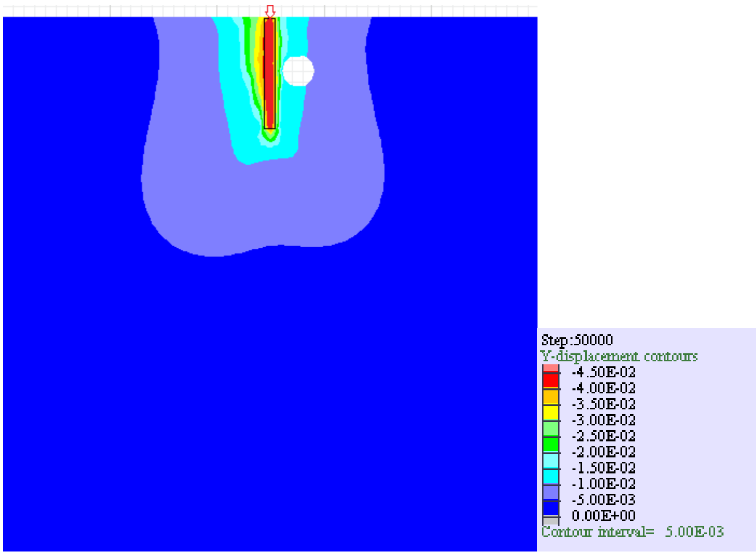

Fig. 7. Vertical Displacement contour of pile with tunnel: $Z_T/L_P = 0.5$

It is seen that higher load reduction of 6.92% is observed at Z_T/L_P ratio 1 which is presented in Fig. 8. This is because the tunnel excavation causes reduction in shaft resistance at lower portion of pile. Extra load due to decrement in shaft resistance transfers to the pile toe. To support this extra load, the end bearing resistance gets mobilized (Ng et al., 2012). Consequently, a clear increment in vertical displacement near pile toe is found in vertical displacement contour of tunnel pile system (shown in Fig 9). Change in vertical displacement contour is also found to be minimum at upper portion of pile which signifies lesser effect on upper portion of pile.

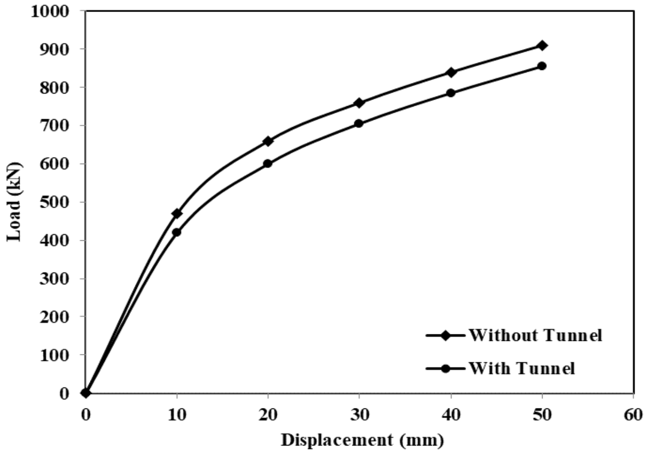

Fig. 8. Load displacement curve of pile: Z_T/L_P= 1.0

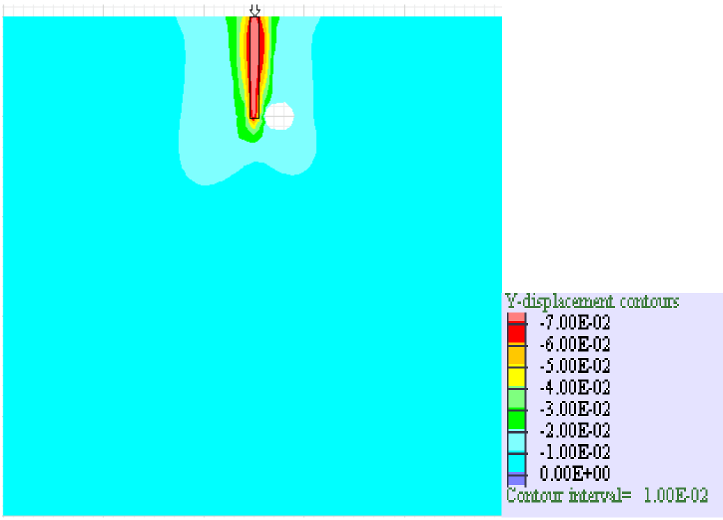

Fig. 9. Vertical Displacement contour of pile with tunnel: Z_T/L_P =1

3.4 Parametric study

Parametric study has been carried out to investigate the influence of sand stiffness and friction angle on the overall behaviour of pile-tunnel system. Fig. 10 shows the reduction in load bearing capacity of pile for decreasing value of sand stiffness for every tunnel position when friction angle kept fixed at 25°. The change in load bearing capacity is calculated for two different sand stiffness values for every tunnel pile configuration (i.e. Z_T/L_P= 0.5, 1). Sand stiffness has been varied in terms of E_P/E_S ratio (i.e., E_P/E_S = 3000, 6000, 9000). Where, E_p represents the elastic modulus of pile material, E_S represents the elastic modulus of sand. It is observed from Fig. 10 that the reduction of load carrying capacity increases with increasing E_P/E_S ratio. This is because of more stress reduction around a tunnel due to decrease in sand stiffness which leads to more detrimental effect for low stiffness sand. For this reason, maximum reduction of load carrying capacity is found to be 7.2% when E_P/E_S ratio is 9000. The similar type analysis is also performed for friction angle 30°, 35° and 40°. The relation in between pile behavior and sand stiffness is found to be same for all given values of friction angle which is presented in Fig. 10. It can be seen that the reduction in load bearing capacity due to tunnel excavation decreases with increase in friction angle of soil. This indicates that the stability of tunnel-pile system higher for greater friction angle of soil mass.

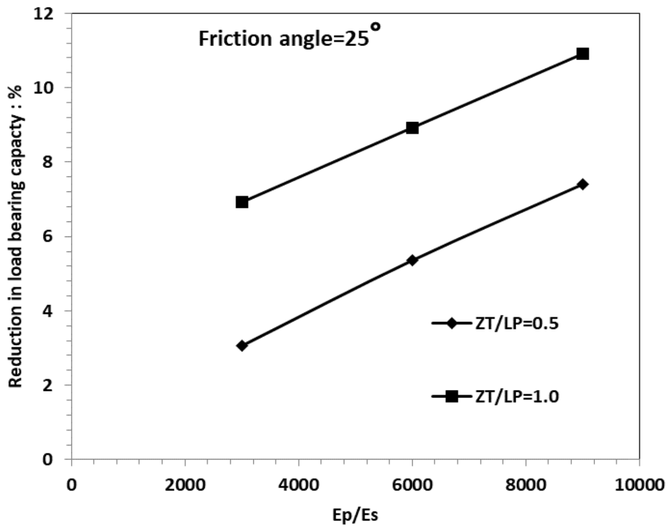

Fig. 10. Reduction in pile capacity with increasing Ep/Es ratio: friction angle=25°

4 Conclusions

1. Surface settlement ground and load bearing capacity of pile is greatly influenced by the excavation of tunnel all around the pile.
2. Tunnelling induced surface settlement trough can be represented by Gaussian distribution curve. After single tunnel excavation, maximum surface settlement of 0.56% (i.e., 17mm) is occurred at the centreline of the tunnel and it decreases with the horizontal distance from tunnel centre.
3. Reduction in bearing capacity due to single tunnel excavation is maximum when tunnel placed at the adjacent to the pile toe (i.e., Z_T/L_P = 1). This re-

duction is found to be about 3.07% for Z_T/L_P=0.5 and 6.92% for Z_T/L_P ratio 1.

4. Influence of sand stiffness and friction angle on tunnel induced behaviours of pile is analysed in this study. It is observed that reduction of load carrying capacity increases with decreasing vales of sand stiffness at a given friction angle of sand. Reduction in load carrying capacity increases from 3.07% to 7.41% with decrease in sand stiffness from 6.66MPa to 2.22 MPa at Z_T/L_P ratio 0.5 for friction angle of 25°. This observation indicates more detrimental effect for low stiffness sand. This is a result of more stress reduction around a tunnel due to decrease in sand stiffness.
5. Similar behaviors are also performed for higher values of friction angle (i.e., 30°, 35°, and 40°).

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