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Investigation on Axial Response of Pile Due to Staged Tunneling: A Numerical Approach

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Abstract. Estimation of foundation and subsequently, superstructure response due to tunneling is essential to assess the preliminary risk. Several aspects of pile, tunnel, and soil characteristics influence the pile response during staged tunneling. In the present study, the response of a single and group pile due to staged tunneling has been investigated in cohesionless soil through finite element analysis in three dimensions. Numerical modeling procedure and parameters studied are described here. Volume loss of tunnel, load level on the pile, and lateral distance of pile from tunnel axis have been investigated and reported here. Results of a large number of numerical analyses can identify and quantify the parameters influencing the pile response due to tunneling. Volume loss of the tunnel significantly influences the axial response of the pile. Lateral and longitudinal influence zone of pile settlement due to tunneling has been identified and reported here. Working load on the pile significantly reduces the initial factor of safety due to tunneling. The results of the present study are useful for preliminary assessment regarding the safety and stability of the existing pile foundation for a range of practical parameters of tunnel and pile.

Keywords: Tunnel, Excavation, Volume loss, Pile, Settlement, Influence zone

1 Introduction

The distress on the substructure ultimately influences the response and stability of superstructures. This causes a threat and permanent risk to the stability of the structure. The vulnerability of the pile foundation to tunneling is more compared to other foundations as it extends up to a larger depth than a shallow foundation. The larger depth of the pile foundation possesses a greater possibility of extending into the influence zone of the tunnel. The length and location of piles are key parameters for the estimation of tunneling induced settlement. Therefore, the response estimation of pile foundations due to staged tunneling is essential for preliminary hazards analysis of structures situated on or adjacent to the alignment of the tunnel.

A large number of numerical, analytical, experimental studies in 1g and centrifuge contributed to a greater understanding of tunnel - pile interaction. Experimental studies in the scaled-down model in 1g and centrifuge are mostly conducted. Model studies on tunnel-pile interaction are primarily conducted in plane strain conditions. Controlled volume loss within the soil mass has been adopted to simulate the tunnel construction procedure. Instrumentation like earth pressure cell, strain gauge, and pore pressure transducer is employed to measure the bending and axial response of pile, change in earth and pore water pressure within soil medium (Loganathan et al. 2000, Jacobz et al. 2004, Lee and Bassett 2006 & 2007, Meguid and Mattar 2009, Marshal 2012). Deformation patterns of ground and pile, delineation of zone of influence, and pile response are the main focus of these studies. The result shows that the pile settles more exactly above the tunnel. Higher deformation occurs around the centerline of the tunnel. The end bearing capacity of the pile significantly reduces, leading to stability issues in the foundation.

Evaluation of tunnel-pile interaction numerically is done in two ways. First, greenfield settlement due to tunneling is estimated, and subsequently, in the second stage, estimated settlement are superposed to pile foundation to obtain the pile response due to tunneling. Also, a combined analysis involving tunnel construction stages and existing piles are simulated to obtain the response of piles due to tunneling. Finite element method (FEM), Boundary element method (BEM) or a combination of FEM and BEM are used for numerical analysis of pile – tunnel interaction (Chen et al. 2000, Mroueh and Shahrour 2000, Surjadinata 2006, Cheng et al. 2007, Mahmood et al. 2011, Lee 2013, Wan 2017, Nematollahi and Daniel 2019). Observations from the field studies also contributed to understanding the different aspects of the soil - tunnel and soil - pile - tunnel interaction (Standing and Selman 2001, Yu 2014, Jiang and Li. 2016, Wan et al. 2017). Existing piles are usually in-service piles and are subjected to the working load. It is necessary to investigate the loaded pile response due to tunneling to a realistic framework of estimating the tunneling induced hazards to existing adjacent structures. The undrained response of cohesive soil mainly governed the short-term behavior of the pile foundation during tunnel construction. Dilatancy a major factor controlling the cohesionless soil behavior and soil - tunnel and soil –pile -tunnel interaction.

In the present study, the axial response of free head single pile has been investigated through three-dimensional finite element analyses in a cohesionless medium. Different pile and tunnel parameters, i.e., volume loss of tunnel and offset distance on the axial response, are investigated and reported. Particular attention has been paid to the influence of the working load of a pile on the axial response. Results of the present study are useful for preliminary hazards analysis of pile foundation situated adjacent and/or alignment of tunnel construction.

2 Materials and Methods

An extensive three-dimensional numerical analysis has been conducted using Plaxis 3D. Tunnel construction procedures, numerical analysis stages, geometric domain, and discretization of soil, tunnel, and pile have been discussed here.

2.1 Validation of Numerical model

The present numerical model has been validated with a 1g experimental study conducted at the institute and published results from the literature. A scaled-down laboratory experimental study has been carried out in 1g conditions to investigate the tunnel - pile interaction. Model studies have been conducted in a mild steel tank of size 2 m x 2 m x 1.5 m. A hollow cylindrical pipe of 114 m diameter has been used as a model tunnel. A staged fluid extraction technique has been used to simulate the staged tunneling construction. Hollow circular aluminum pipe of 19 mm outside diameter and 1 mm wall thickens has been used as a model pile foundation. The response of the pile foundation has been studied for a volume loss in the range of 0.5 % to 10%. All the model studies are conducted in a cohesionless soil medium. Properties of the soil medium are evaluated through a drained triaxial test. Details of the experimental procedure, sample bed preparation are out of the scope of the present paper. The same has been modeled numerically through Plaxis 3D. Results of the vertical settlement of the pile from experimental and numerical analysis match quite well with a variation of 4 – 6%.

Another benchmarking of the present numerical model has been done with the published results by Lee et al. (2016). Authors introduced a three-dimensional numerical model to simulate the Double O-tube staged tunnel construction procedure and estimate the surface settlement. The numerical model has created adopting material properties and layering systems, as mentioned in the paper. The present numerical model shows a maximum surface settlement adopting a small strain hardening soil model for the monitoring section 1 of 31.5 mm. The reported surface settlement from numerical analysis and field measurement is 29.5 mm and 22.5 mm, respectively. This close resembles of the present results, with the reported numerical results established the accuracy of the present model.

2.2 Soil and Tunnel parameters

This section describes different soil parameters, tunnel parameters employed in the present numerical study. Soil parameters of the present numerical model are evaluated from a series of drained triaxial tests on cohesionless soil medium at a relative density of 76%. The test small strain hardening soil parameters are evaluated and employed in the numerical analysis. Table 1 shows the different soil parameters. The embedded pile option available in the Plaxis library has been to simulate the pile in the present study. Table 2 shows the different properties of the pile. Maximum skin resistance and base resistance are calculated from soil parameters following IS procedure, and values are employed in numerical analysis. Tunnel lining has been model with plate element. Table 3 shows the lining properties used in the present study.

Table 1. Small Strain Hardening Soil Parameters

Soil Parameters	Value
Cohesion, C (kN/m2)	9.0
Angle of internal friction, θ (°)	35.8
Minimum unit weight (kN/m^3)	16.6
Maximum unit weight (kN/m^3)	17.7
Secant stiffness in the standard drained triaxial test/tangent stiffness for primary oedometer loading, E_{50}^{ref}/ E_{ode}^{ref} (kN/m^2)	8.374E3
Unloading/ reloading stiffness at engineering strains, E_{ur}^{ref} (kN/m^2)	25.122E3
Dilatancy angle, Ψ (°)	10.5
Poisson’s ratio, μ	0.2
Shear strain at which Gs = 0.722Go; $\gamma_{0.7}$	0.65E-3
Reference shear modulus at very small strains, G_0^{ref} (kN/m^2)	106E3
Power for stress-level dependency of stiffness, m	0.6
Failure ratio, R_f	0.9
Earth pressure coefficient, K_0^{nc}	0.415

Table 2. Pile Properties

Parameters	Value
Pile Type	Circular
Pile Diameter (m)	0.6 m
Unit weight (kN/m^3)	25
Young’s modulus (kN/m^2)	2.5 E 10^7
Poisson’s ratio, μ	0.15

Table 3. Tunnel Liner Properties

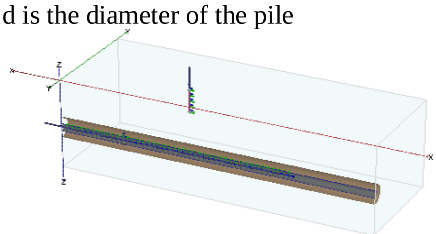
Parameters	Value
Unit weight (kN/m3)	25
Young’s modulus, (kN/m^2)	2.5 E10^7
Poisson’s ratio, μ	0.25
Liner thickness (m)	0.12

2.3 Numerical modelling

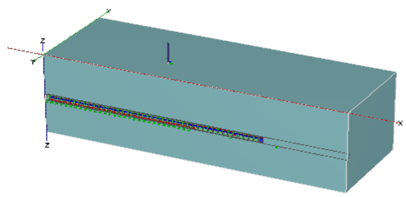
The numerical validation is done using the Finite Element software Plaxis 3D. The borehole option available is utilized in creating the soil medium. From the initial trial analysis, the size of the numerical domain has been fixed as 150 m x 52 m x 48 m. 10

noded tetrahedral elements with three translational degrees of freedom have been used to discretize the soil domain. Six noded triangular plate elements with six degrees of freedom have been used to discretize the tunnel liner. Mesh convergence studies have also been carried out before actual analysis. In the numerical analysis, the number of elements varies in the range of 50,000 – 60,000 for the different parameters and geometric conditions used in the present study. The bottom of the numerical boundary is fixed in all directions. Side boundaries are free to move in the plane, but the perpendicular movement is restricted, i.e., roller boundary conditions are applied at the side of the numerical model. The top surface is free to move in any direction. A 4 m diameter circular tunnel has been simulated in the present study. The volume loss control method has been used to simulate the tunnel construction procedure. Volume loss in the present study varies in the range of 0.5 % to 2.5%. Staged excavation with each excavation length of 2.5 m is used in the present study. Linearly increasing face pressure with depth calculated from earth pressure at rest condition has been applied at the tunnel face during excavation. The crown of the tunnel is at a depth of 24 m from the top surface. Piles length of 8 m and 16 m is used in the present study.

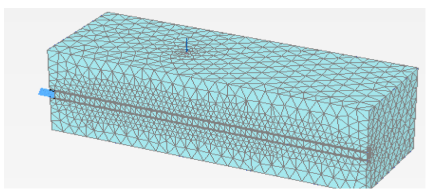
The location of the pile varies from 0D, i.e., crown, to 6D from tunnel centerline, D being the diameter of the tunnel. Pile is located at a longitudinal distance of 44 m from the tunnel face. Fig. 1(a-c) shows different stages of numerical modeling of half of the numerical domain. Fig. 2 (a-d) shows the different lengths of the tunnel excavation. Stages of tunnel construction in a single step include deactivating soil volume for a length of 2.5 m within the tunnel and activating the tunnel liner material, subsequently applying specified volume loss at the surface of the tunnel. In the present case, one half of the full geometry has been numerically analyzed. Pile situated at other distance rather than crown represent two pile condition in the full model. No interference is expected as the minimum distance between the two piles is more than 25d, d is the diameter of the pile



(a) Tunnel with pile

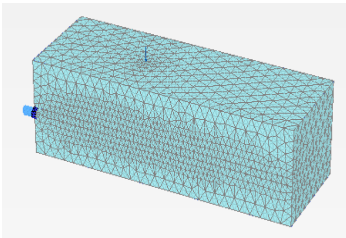


(b) Soil, tunnel and pile

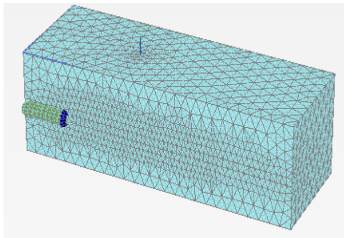


(c) Discretized model

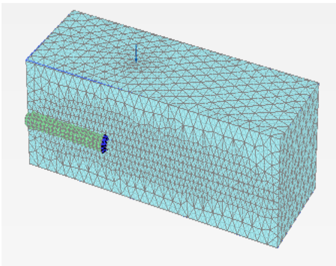
Fig. 1. Different stages of numerical modelling



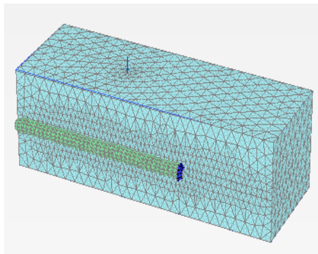
(a) 2.5 m



(b) 25 m



(c) 50 m



(d) 100 m

Fig 2. Different length of tunnel excavation

3 Results and Discussions

3.1 Pile Head settlement

Fig. 3 shows the load-displacement relation of 8 m and 16 m pile. The load-displacement responses of piles are established from the separate analysis. The analysis aims to estimate the pile head load corresponding to equal settlement induced to pile due to tunneling. Fig. 4 shows the increase in pile head settlement with the lateral location of the pile from tunnel centerline for 1.5% volume loss and 16 m pile for different tunnel excavation length. Pile head settlement is expressed in the percentage of pile diameter, and tunnel excavation length is expressed in terms of tunnel diameter. Pile head settlement presented here is due to tunneling only. The settlement of pile due to installation has been found from another set of numerical analysis. The result shows that the pile suffers significant settlement depending on the location up to 6D lateral distance from tunnel centerline. Pile head settlement linearly decreases with an increase in lateral distance from the tunnel centerline.

Fig. 5(a - d) shows the increase in head settlement for the different lateral positions of the pile from tunnel axis for different volume loss of tunnel for no working load on the pile head. Pile head settlement decrease and increase with an increase in lateral distance of pile from tunnel axis and tunnel volume loss, respectively. The maximum settlement of the pile head is 0.703 % of pile diameter for pile located at the crown and tunnel volume loss of 2.5 %. At a lateral distance of 6D, pile head settlement is 0.182% of diameter for the same volume loss of tunnel. From the graph, a clear zone of influence of tunnel excavation where pile suffers significant settlement may also be identified. For all the analysis, the pile is located at a longitudinal distance of 11 times tunnel diameter from the tunnel face. The settlement of the pile started increasing rapidly when tunnel excavation length reached a distance of 6.25D from the tunnel face. Within a tunnel excavation length of 6.25D and 18.75D from the tunnel face, significant pile settlement occurs. Beyond 18.75D, pile settlement almost remains constant. From the present analysis, a zone of pile settlement of 5D distance ahead of pile location and 7.75D distance beyond of pile location may be identified. A similar result has been obtained for all the volumes loss of tunnel. For comparison purposes, settlement of pile due to tunneling has been compared with the pile load-displacement graph obtained from another set of numerical analyses employing the same soil material parameters. To obtain the same settlement of pile situated at the crown as induced by tunnel construction for 2.5% volume loss of tunnel, an equivalent load of 2600 kN is required. Equivalent load corresponding to the same pile settlement induced by tunnel construction varies in the range of 300 kN to 2600 kN for the parameters considers in the present study. It is to be noted here that the pile situated away from the center line may suffer rotational displacement also. This study mainly focuses on the axial response of pile, and rotational response is out of the scope of the present study.

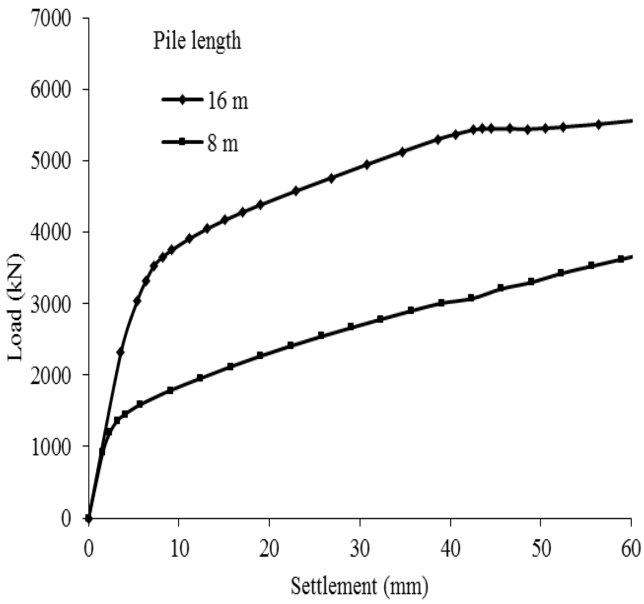


Fig. 3. Load displacement relationship of pile

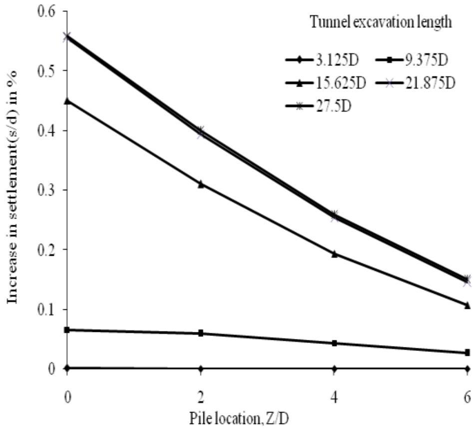
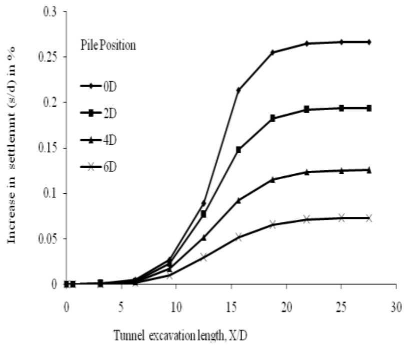
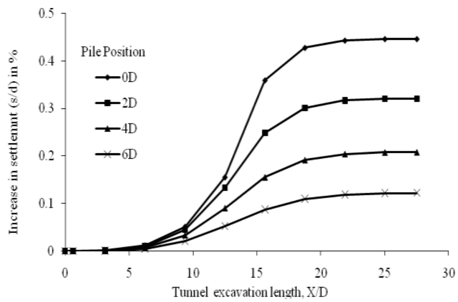


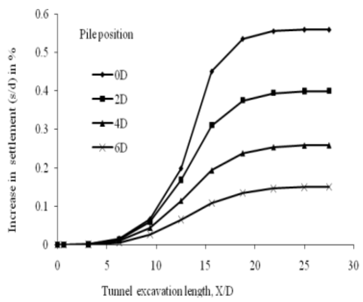
Fig. 4. Increase in displacement with position of pile for 1.5% volume loss



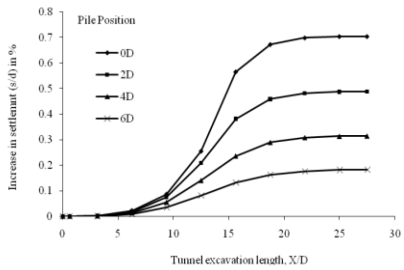
(a) 0.5 % Volume loss



(b) 1 % Volume loss



(c)1.5 % Volume loss



(d) 2.5 % Volume loss

Fig. 5. Pile head settlement with progressive tunneling for different volume loss

3.2 Effect of length of the pile

Pile head settlement for pile length of 8 m and 16 m has been investigated in this section. Fig. 6 shows the variation of pile head settlement for 8 m and 16 m pile situated at the crown with different volume loss of tunnel without any axial load on the pile head. Pile head settlement increases with an increase in pile length. The distance between tips of the pile to tunnel crown is 16 m and 8 m for 8 m and 16 m pile, respectively. Due to the volume loss of the tunnel, the soil around the tunnel undergoes volume contraction, resulting in a drag down force along the pile shaft. Drag down force is proportional to the surface area of the pile with the influence zone of tunnel excavation. A longer pile of the same diameter subjected to greater drag down force, which results in a higher settlement smaller length of the pile. Results also clearly show the effect of volume loss on pile settlement. Settlement varies nonlinearly with volume loss of tunnel, and the settlement rate is observed to increase with volume loss of tunnel.

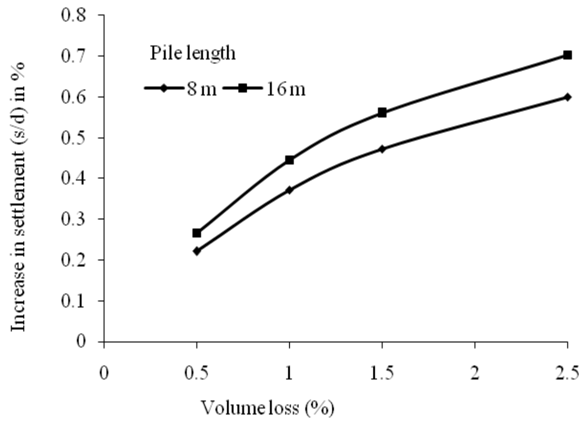
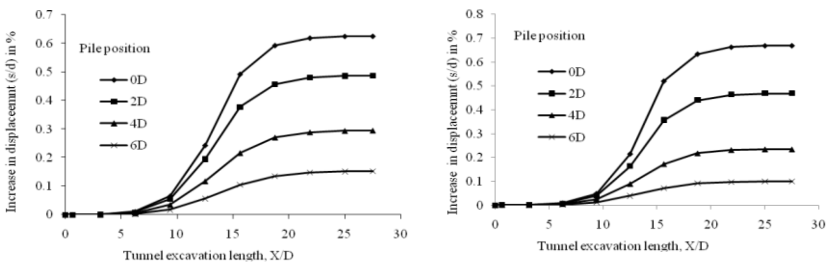


Fig. 6. Pile head settlement with volume loss

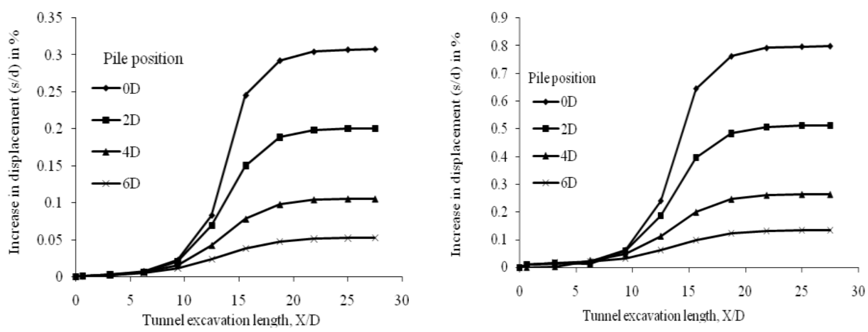
3.3 Effect of working load on pile

In this section, the influence of working load on pile head settlement due to progressive tunnel construction has been investigated for 16 m length of the pile. Axial vertical load on pile has been applied before the start of the construction of the tunnel. Different levels of the working load have been chosen from a load-displacement relationship of pile established beforehand for the same material properties (Fig. 3). Axial load is so determined to represent the different trend of load-displacement graph. A working load of 512 kN, 1778 kN, and 3537 kN have been applied at the pile head. While load-displacement relation remains linear for 512 kN and 1778 kN of axial load, nonlinearity starts from an axial load of 3537 kN and onward. Fig. 7 (a &b) shows the pile head settlement response at an axial load of 512 kN and 1778 kN for 2.5% volume loss. Fig. 8 (a &b) shows the pile head settlement response at 3537 kN at 2.5 % volume loss of tunnel. For pile situated at the crown, an increase in pile head settlement of 0.63 %, 0.67 %, and 0.8 % has been observed for the above-mentioned working load for 2.5% volume loss. The equivalent load obtained from the load-displacement relationship is 2600 kN, 3500 kN and 3900 kN for a settlement of 0.734 %, 1.1 %, and 1.84 % of pile diameter. A load increment of approximately 2088 kN, 1722 kN, and 363 kN has been observed for different working loads applied on the pile foundation. Load level 1778 kN corresponds to a safety factor of 2.5 as determined from the isolated pile load-displacement relationship. The factor of safety after tunnel construction is 1.27. Results show that the level of working loads significantly influences the settlement of the pile foundation. For smaller working loads, the reserve capacity of the pile comes into effect during tunnel construction and prevents excessive pile settlement. If the working load is high or the safety margin of the pile at working conditions is minimal, an excessive settlement of pile during tunneling is expected, and the pile may fail.



(a) Load 512 kN (b) Load 1778 kN

Fig. 7. Pile head settlement with progressive tunneling for different axial load at 2.5 % volume contraction



(a) 0.5 % Volume loss (b) 2.5 % Volume loss

Fig. 8. Pile head settlement with progressive tunneling at 3537 kN axial load

4 Conclusions

The present study investigates the axial response of a free head single pile due to progressive tunnel construction. A three-dimensional numerical model of soil, tunnel, and pile has been adopted to investigate the axial pile response. First, a numerical model has been benchmarked against experimental and published results in the literature, and subsequently, a parametric study has been conducted. Different parameters, i.e., volume loss of tunnel, pile length, pile position, and working load on the pile on the axial response of the pile foundation, have been investigated and reported here. Following conclusions may be drawn from the present study

1. Tunneling induced volume loss significantly influences the pile head response. The settlement of pile increases with an increase in volume loss of tunnel. The rate of increase increases with volume loss of the tunnel. In the present study, volume loss in the range of 0.5 % to 2.5 % has been considered.
2. A zone of influence where pile suffers excessive settlement has been identified. A zone, five times the diameter of the tunnel ahead and 7.75 times beyond pile location has been identified as the most vulnerable zone of pile settlement. Beyond a distance of 7.75D, pile settlement remains almost constant.
3. The level of working load plays a significant role in the pile head response. For smaller working load, the reserve capacity of the pile comes into effect during tunnel construction and prevents excessive pile settlement. If the working load is high or the safety margin of the pile at working conditions is minimal, an excessive settlement of pile during tunneling is expected, and the pile may fail. A 50% reduction of safety factor has been observed for the adopted parameters in the present study.
4. The lateral influence zone of pile settlement has been extending up to 6 times of tunnel diameter from the tunnel centerline for the parameters and conditions adopted in the present study. Pile settlement varies linearly with a lateral distance of pile location from tunnel axis.

References

1. Alec M Marshall; Tunnel Pile Interaction Analysis using Cavity Expansion Methods. Jorunal of Geotechnical and GeoEnvironmental Engineering. 2012, 138(10): 1237-1246. DOI: 10.1061/(ASCE)GT.1943-5606.0000709. (2012)
2. Cheng C.Y; Dasari, G.R. Chow, Y.K; and Leung, C.F; Finite element analysis of tunnel–soil–pile interaction using displacement-controlled model. Tunnelling and Underground Space Technology 22 (2007) 450–466. DOI: 10.1016/j.tust.2006.08.002. (2007)
3. Chen, L. T.; Poulos H. G.; and. Loganathan, N; Pile Response caused by tunnelling. Journal of Geotechnical and GeoEnvironmental Engineering. 1999, 125(3): 207-215. (2000)
4. Chen, S. L; Lee, S. C and Wei, S. Y., Numerical Analysis of Ground Surface Settlement Induced by Double-O Tube Shield Tunneling. Journal of Performance of Constructed Facilities, (ASCE), 30(5), 1-10, (2016).

5. Eunsu Sung, Hossain M Shahin, Teruo Nakai, Masaya Hinokio, and Makoto Yamamoto; Ground Behaviour due to Tunnel Excavation with Existing Foundation. Soil and Foundations, Japanese Geotechnical Society Vol 46, No 2, 189-207. (2006).
6. Gordon T. K. Lee and Charles W. W. Ng; Effects of Advancing Open Face Tunneling on an Existing Loaded Pile. Journal of Geotechnical and Environmental Engineering. February 2005. 193-201. (2005)
7. Hadi Khabbaz, Robert Gibson and Behzad Fatahi; Effect of constructing twin tunnels under a building supported by pile foundations in the Sydney central business district. Underground Space. DOI: 10.1016/j.undsp.2019.03.008 (2019)
8. Indian Standard 2911; design and construction of pile foundations — code of practice; New Delhi (2010)
9. Jacobsz, S.W.; Standing, J.R., Mair R.J; Toshiyuki Hagiwara and Tadashi Sugiyama ; Centrifuge modelling of tunnelling near driven piles. Soils and Foundation. Vol 44, No 1, 49-56. Feb 2004. Japanese Geotechnical Society. (2004)
10. Khalid Mahmood, Won Beom Kim and Hyung Sik Yang; A parametric study of Tunnel-Pile interaction using numerical analysis. Geosystem Engineering 14(4), 169-174, (2011).
11. Lee, C.J; Numerical analysis of pile response to open face tunnelling in stiff clay. Computers and Geotechnics 51, 116–127, (2013)
12. Loganathan, N; Poulos H. G. and Stewart, D. P.; Centrifuge model testing of tunnelling-induced ground and pile deformations. Geotechnique 50, No. 3, 283-294, (2000)
13. Mroueh, H and Shahrour, I; Three-dimensional finite element analysis of the interaction between tunneling and pile foundations. International Journal for Numerical and Analytical Methods in Geomechanics. Int. J. Numer. Anal. Meth. Geomech., 2002; 26:217–230. DOI: 10.1002/nag.194. (2000)
14. Mohamed A; Meguid and Joe. Mattar; Investigation of Tunnel-Soil-Pile Interaction in Cohesive Soils. Journal of Geotechnical and Environmental Engineering. 973-979. DOI: 10.1061/_ASCE_GT.1943-5606.0000004, (2009)
15. Standing, J. R. & Selman, R; The response to tunnelling of existing tunnels at Waterloo and Westminster. In Building response to tunnelling: case studies from construction of Jubilee Line Extension, vol. 2, *case studies* (eds J. B. Burland, J. R. Standing and F. M. Jardine), pp. 509–546. London, UK: Thomas Telford, (2001).
16. Surjadinata, J; Carter, J.P., Hull T.S., and Poulos, H.G; Analysis of the effects of tunnelling on single piles. Geotechnical aspects of Underground construction in Soft ground-ISBN 0415391245. (2006)
17. Wan, M. S. P., Standing, J. R., Potts, D. M. & Burland, J. B; Measured short-term ground surface response to EPBM tunnelling in London Clay. Géotechnique 67, No. 5, 420–445, http://dx.doi.org/10.1680/jgeot.16.P.099, (2017)
18. Xinghong Jiang and Ke Li; Research on Pull-out Mechanical Characteristics of Pile Foundation in Submerged Floating Tunnel. Procedia Engineering 166 (2016) 389 – 396. DOI: 10.1016/j.proeng.2016.11.570, (2016)
19. Yong Joo Lee and Richard H Bassett, A model test and numerical investigation on the shear deformation patterns of deep wall-soil tunnel interaction. Can. Geotech. J.43: 1306-1323. DOI: 10.1139/T06-088. (2006)
20. Yong-Joo Lee and Richard H. Bassett, Influence zones for 2D pile–soil-tunnelling interaction based on model test and numerical analysis. Tunnelling and Underground Space Technology. 22 (2007) 325–342. DOI: 10.1016/j.tust.2006.07.00. (2007)
21. Yu, J. B. Y; Assessing ground interaction effects and potential damage on Existing Tunnels before and after new excavation works. PhD Thesis, Imperial College London, London, UK. (2014).