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# A numerical study on the influence of tunnel excavation on pile foundation

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## ABSTRACT

Tunnel construction in cities faces many geotechnical challenges, and the effect on pile foundation is possibly one of the most complex ones. Most tall buildings in big cities mostly have pile foundations, and any tunneling nearby might significantly influence those existing foundations. In the present study, a 3-dimensional Finite Element (FE) analysis has been carried out to investigate tunneling effects on pile foundations. The investigation is done for a single pile with multiple stages of tunnel excavation where the pile foundations are assumed to reach below the base of the excavation of tunneling. A tentative rate of excavation was also included in this investigation and found that a faster rate of excavation results in better performance of foundations affected by tunneling. The study also extended to see the effect of tunneling on pile groups. Attempts were made to compare the results with some of the previously published literature.

**Keywords:** *Pile, Tunnel, Staged excavation, FE analysis, PLAXIS3D .*

## 1. Introduction

Due to the lack of available space, many underground constructions such as tunneling activities have increased tremendously in cities of many developing countries like India. Tunnel construction in cities with high-rise buildings poses many geotechnical challenges. For any tunnel excavation, existing buildings are usually one of the main constraints (Mair and Taylor, 1997). Most of the tall buildings are found to have pile foundations and any tunneling nearby can have a significant influence on these existing foundations. Tunneling possibly affects existing pile foundations by imposing axial and lateral forces resulting in additional deformation. Any ground settlement or movement beyond a prescribed limit may seriously affect the existing buildings with the formation of multiple cracks. It becomes essential to have an idea of estimating forces induced on piles and corresponding ground movements due to tunneling. A study on the effect of tunneling on existing buildings has been started during the 1980s with the estimation of surface and subsurface settlements induced by tunneling (Sagaseta, 1987; Verruijt and Booker, 1996; Loganathan and Poulos, 1998; Park, 2004). The effect of tunneling on pile foundation was studied by many researchers including studies using small scale physical modeling (Lee and Bassett, 2007), centrifuge modeling (Jacobsz, 2002, Jacobsz et al., 2004, Ng et al.,2013), numerical modeling with a single pile (Chen at al., 1999; Loganathan et al., 2001; Xu and Poulos, 2001; Mroueh and Shahrour, 2002; Lee and Ng, 2005; Wang et al., 2019 and Li et al., 2020), the full-scale field monitoring (Solemetas et al.,2006; Pang et al., 2006), pile groups (Xu and Poulos, 2001; Huang et al.,2009; Huang and Mu, 2011) and pile rafts (Kitiyodom et al., 2005, Nasrollahi and Hosseininia, 2019) and pile tunnel interaction studies by Dias and Bezuijen (2015) and Lueprasert et al. (2017). The zone of influence affects the piles in different ways depending on the relative position to the tunnel centreline namely the possible reduction in the base resistance and also the development of negative skin friction (Dias and Bezuijen, 2015; Chen et al.,1999). Tunneling adjacent to the foundation causes differential settlements and when the soil above the tunnel's horizontal axis settles downwards can create negative skin friction on adjacent piles thereby reducing the load-carrying capacity of piles (Chen et al., 1999). To prevent differential settlements that could lead to damage to an existing building, it is important to align the tunnel along with the relatively stiffer soil (Huang and Mu, 2011). It is found that usually when the piles were relatively deeper than the tunnel depth, the axial stress in the piles increases from the surface to the tunnel spring line and subsequently decreases up to the pile tip. When the piles were found to be above or at the tunnel spring line, the axial stress increases from the surface until the pile tip (Dias and Bezuijen, 2015). The effect of tunneling on pile foundation is found to be signed up to 1D ahead and behind the face of the tunnel (Lee and Ng, 2005) and 3D in the lateral direction along the axis of the tunnel (Chen et al., 1999). Recently Basile (2014) discussed the effect of soil nonlinearity and the corresponding reduction in the maximum axial force in the pile and attempted to compare the results with the linear elastic analysis.

Chen et al. (1999) investigated the pile response due to tunneling by calculating the ground movement using the analytical solutions given by Loganathan and Poulos (1998) subsequently using the Boundary Element Method (BEM). Huang and Mu (2011) analyzed the pile raft response due to tunneling in two stages, first using the analytical solutions given by Loganathan and Poulos (1998) and in the second stage, studying the ground movements on pile rafts using the Finite Difference method (FDM). Tunneling is found to be relatively safer closer to pile foundations than shallow foundations, especially in soft to medium stiff clays. Moreover, tunneling was found to influence up to certain boundaries and beyond that zones, and it has a negligible effect on foundations. That influence depends on several factors including the rate of excavation of tunneling. The complex interactions between the pile and tunnel are three-dimensional and could not be easily captured

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using analytical methods. With the new developments in computational technology and related numerical codes, the researchers are now attempting to model the complex behavior of pile and tunnel interaction. In the present study, the effect of tunnel excavation adjacent to a pile foundation is investigated and a FE model in PLAXIS-3D is developed. The rate of tunnel progress is one of the important factors deciding all auxiliary activities and the stability of the tunnel and surrounding medium. It is essential to have predictions on responses of nearby foundations at each stage of excavation. A tentative rate of excavation was also included in this investigation and found that a faster rate of excavation results in a better performance with lesser effect of tunneling on foundations. Results obtained for piles due to tunneling are also compared with the previously published literature. Parametric analysis is done for understanding the influence of various parameters of tunneling on pile foundation.

## 2. Effect of tunnelling on single pile

A three-dimensional finite element (FE) model for a single pile with TBM tunnel excavation is adopted in the present analysis. This PLAXIS-3D-based model is similar to those analyzed using the Boundary Element Method (BEM) by Xu & Poulos (2001) and Loganathan et al. (2001). Numerical modeling is done with the finite element program PLAXIS-3D, a commercial tool for the analysis of geotechnical structures in three-dimension. An elastic model is adopted to simulate the influence of tunneling on the existing pile foundation. Due to the symmetry of the problem, only one half of the tunnel-soil system is analyzed with a pile. The tunnel construction is modeled by the progressive removal of elements. The soil volume is modeled employing 15-node triangular prism elements. The various phases of the applied excavation scheme are also studied and discussed in later sections. A schematic of the tunnel with single pile geometry is shown in figure 1. The corresponding Finite Element half symmetric tunnel model with pile is shown in figure 2. The tunnel is of diameter 6m at a depth of 20m from the ground surface. Pile is of diameter 0.5m and has a length of 25m kept at a distance of 4.5m from the tunnel axis. Soil considered here is medium stiff homogeneous clay. A plane of symmetry is a vertical plane passing through the center of the tunnel. Hence right half of the tunnel and a pile behind the tunnel is analyzed. Mesh is 40m in length, 25m in width, and 50m high. 10 node trapezoidal elements are used for soil and 3 noded beam elements are used for the pile. The bottom boundary of the mesh is considered fixed in both vertical and horizontal directions. Side boundaries of soil mesh are fixed only in the lateral direction. Soil considered here is linear elastic with a modulus of elasticity 24MPa and Poisson's ratio of 0.5. Pile and tunnel lining is also modeled as linear elastic with a modulus of elasticity 3GPa and Poisson's ratio of 0.25. Concrete tunnel lining parameters with TBM are shown in Table 1 and soil and pile material properties are given in Table 2.

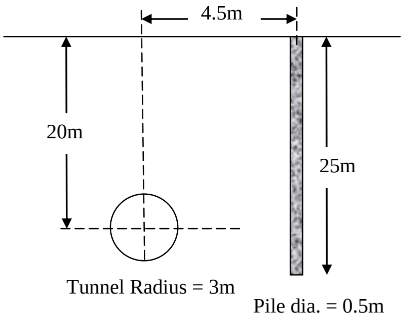


**Fig.ure 1.** Tunnel cross-section with single pile geometry (adapted from Kitiyodom et al., 2005; Basile, 2014).

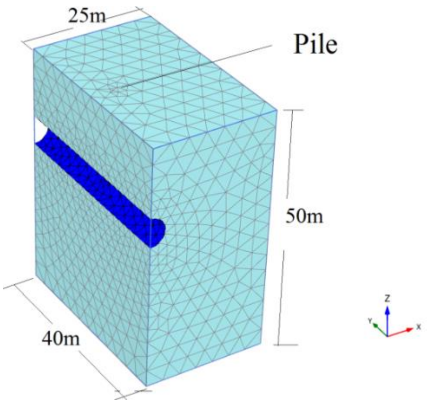


**Figure 2.** 3D Finite element mesh using PLAXIS-3D considering half symmetry for tunnel excavation with a single pile.

**Table 1.** Material properties of tunnel lining and TBM machine .

| Concrete lining | TBM |
|---|---|
| Thickness of lining = 170mm,<br>Unit weight = 24 $kN/m^3$<br>Poisson's ratio = 0.25<br>Modulus of elasticity = $30\times10^6$ kPa | Unit weight = 80 $kN/m^3$<br>Young's modulus = $200\times10^6$ kPa<br>Grout pressure: 100kPa at top and increases at the rate of 20kPa /m depth<br>Face pressure: 90kPa at top and increases at the rate of 14kPa /m<br>Jack pressure: 635.4kPa<br>Ground loss ratio = 2.5% |

**Table 2.** Material properties used for the FE analysis.

| Parameter | Values |
|---|---|
| Elastic Modulus (Pile) | 30000 MPa |
| Elastic Modulus (Soil) | 24 MPa |
| Poisson's ratio (Pile) | 0.25 |
| Poisson's ratio (Soil) | 0.5 |

## 3. Results and discussion

The process of analysis together with the results for tunnel influence on pile foundation is highlighted here. In the present study, single piles under the tunnel influence as described by Xu and Poulos (2001) and Loganathan et al., (2001) respectively are analyzed using finite element (FE) analysis, and comparisons are presented. Parametric analysis on pile foundations influenced by tunneling and performance under different conditions are studied. Excavation of tunnel is considered in stages with 2m excavation in each stage. Observations on the rate of excavation of tunneling on the performance of a single pile are presented. Ground movements observed from the FE analysis are shown in Fig. 3(a and b). Fig.3(a) shows the lateral ground movements induced in the tunneling which is around 23mm maximum at the spring line region in the present case. Fig. 3(b) shows the vertical ground movement which is around 26mm settlement in the crown region and 23mm of heaving in the floor region. Ground movements at pile locations are plotted against depth and are shown in Fig. 4 (a and b). It is evident from Fig. 4 that, soil moves towards the tunnel axis laterally and has the maximum lateral movement at depth along the tunnel axis (Fig. 4a). It is also found that from Fig.4 (b), the soil above the tunnel axis settles down and the soil below the tunnel axis heaves up. Pile foundation has responded to tunnelling and the corresponding effect for Ground loss ratio (GLR) of 1%, 2.5% and 5% are shown in figure 5 (a,b,c & d). Corresponding pile responses at GLR of 1%, 2.5% and 5% from literature Xu and Poulos (2001) also highlighted in Fig. 5 (a, b, c & d). The critical depth is around 17m below ground level at which the pile has maximum lateral deformations, axial force, and bending moment, which is at the crown point of the tunnel as shown in Figs.5 (a,b,c & d). The same study with the Boundary element method (BEM) (Xu & Poulos, 2001) is found to be around 18m. All the pile response parameters are found to be comparable except for the vertical deformation of the pile. This could be because of the slip condition considered along with the piles in Boundary element analysis and the difference in contraction pattern in Finite Element and Boundary element analysis. In FE analysis using PLAXIS-3D, contraction considered is uniform, whereas that in the Boundary element method by Xu & Poulos (2001) is oval-shaped as defined by Loganathan and Poulos (1998). That variation in vertical deformation is seen as significant only at higher Ground Loss ratios (GLR). Fig.6 shows (a) Lateral displacement, (b) Bending moment, and (c) Axial force profile of the pile after the complete excavation of the tunnel. From figure 6, the maximum lateral displacement, bending moment, and axial force are observed at the horizontal center line, that is the tunnel axis.

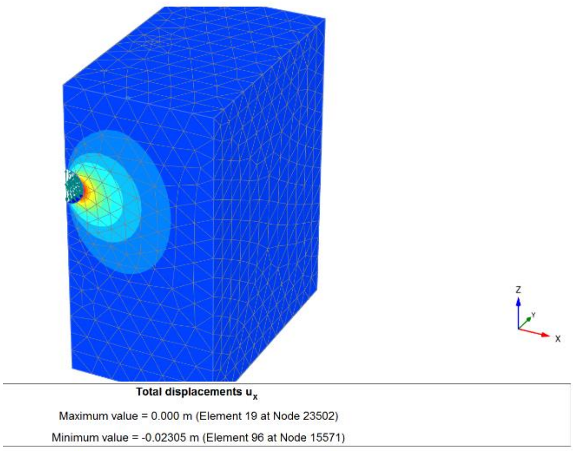


**Figure 3 (a)**. The lateral ground movements induced by tunneling

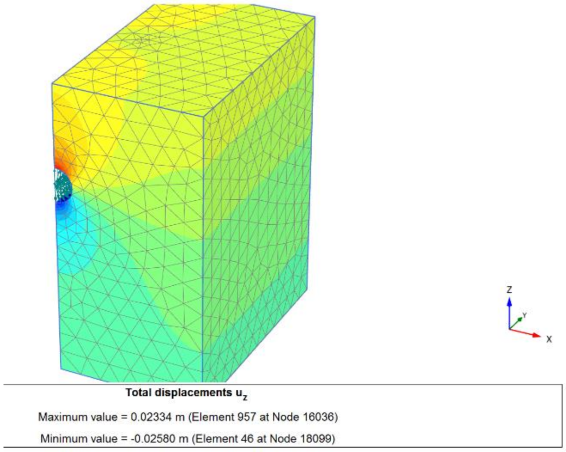
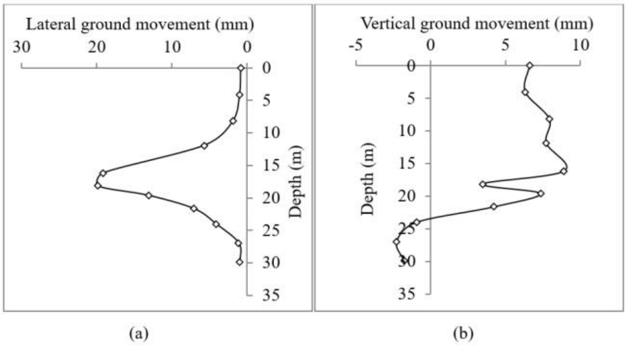


**Figure. 3 (b)**. The vertical ground movements due to tunnelling.



(a)

(b)

**Fig.ure 4.** Ground movements at pile location against depth.

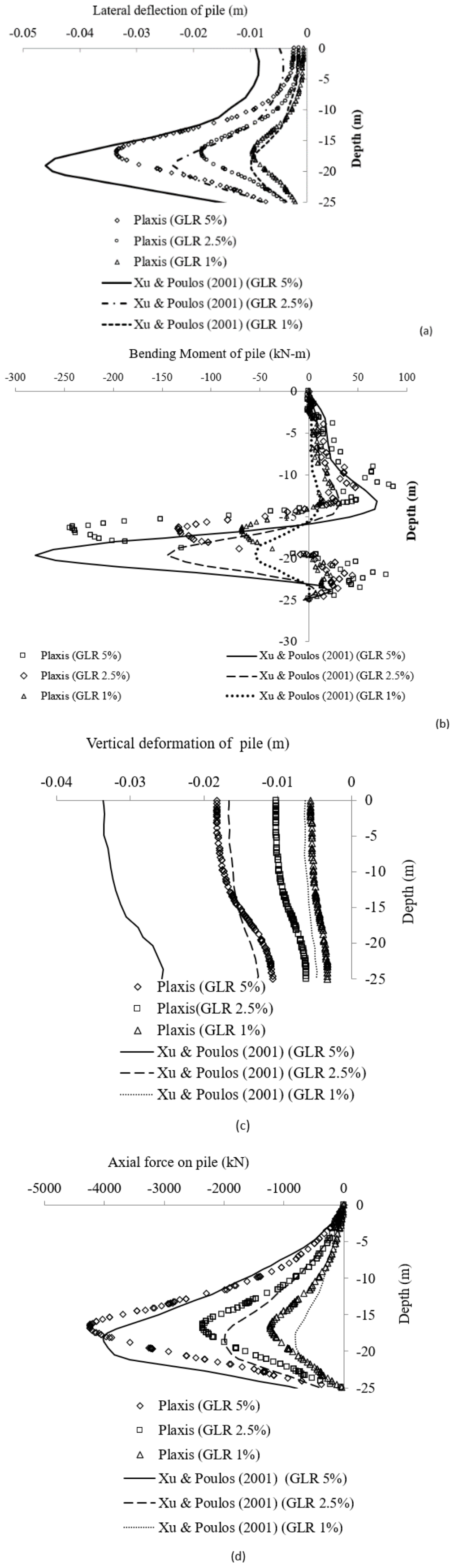


**Figure 5.** Response of single pile due to tunneling with varying ground loss ratio (GLR).

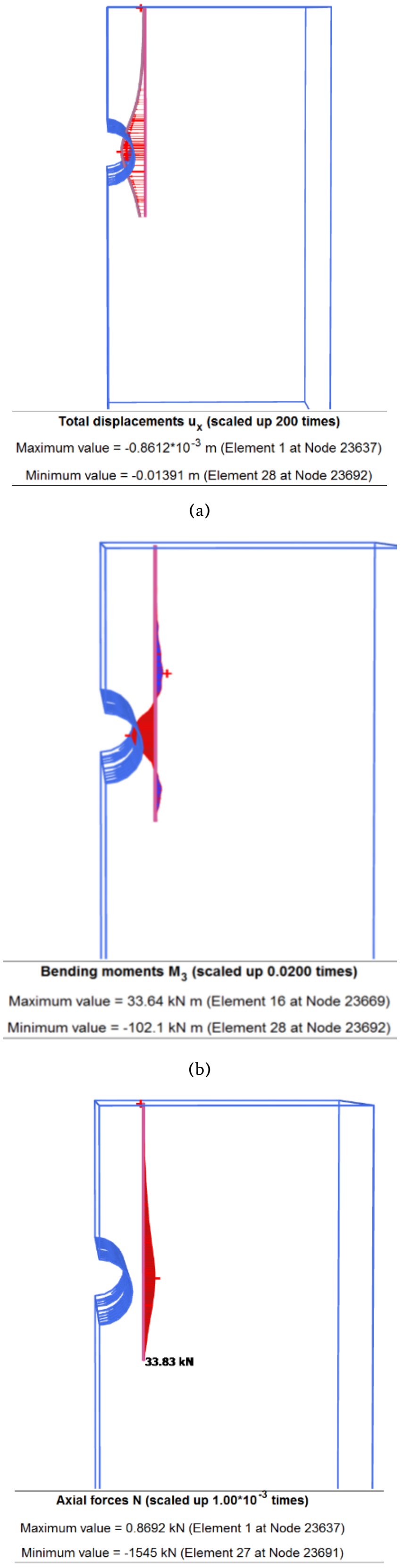


**Figure 6 (a).** Lateral displacement, (b) Bending moment, and (c) Axial force profile of the pile after the complete excavation of the tunnel

## 4. Staged excavation of tunnel

Staged excavation is considered for single piles for their performance under tunneling with gradual advancement. Tunnel excavation is assumed to progress in a 2m interval (Fig. 7) for a total tunnel length of 40m. A TBM is assumed to advance for this excavation from right to left as shown in Fig. 8. Properties of TBM are mentioned in Table. 1. The complete excavation of the tunnel with 40m length is done in 16 stages with excavation progressing 2m in each step. 2m length of soil behind the TBM is unsupported and the rest of excavated tunnel is supported with concrete lining. Distance between pile and face of TBM is considered as 'y' as shown in Fig. 8. This distance 'y' is considered negative when the tunnel face is behind the pile and is positive when the tunnel face passes the pile. y is (-10) corresponding to 10m in the first stage of excavation and likewise is (-8) and (-6) in stage 2 and stage 3 respectively. The concrete lining also progressed in stages with 2m in each interval. The complete process with some selected stages of excavation of tunneling is shown in figure 9.

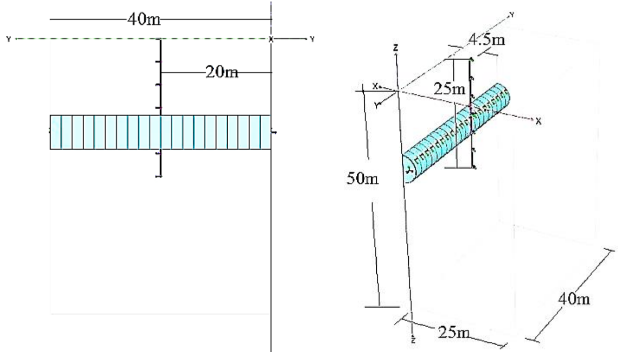


**Figure 7.** Numerical model of the open face tunnel excavation with single pile.

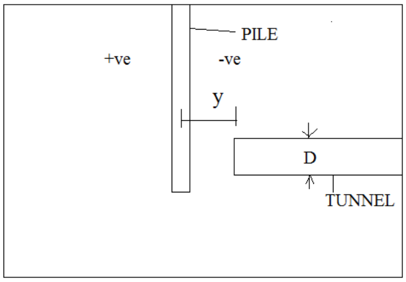


**Figure 8.** Schematic of the open face tunnel excavation

Single pile response due to tunneling in stages as depicted in figure 9, is systematically followed and the influence is observed at each stage of excavation. Response of pile section close to tunnel axis is very critical. The maximum values of axial force, lateral deflection, bending moment, and vertical settlement at each stage of excavation are plotted and are shown in figure 10 (a, b, c). From figure 10, it can be seen that the influence of the tunnel is more prominent when the face comes closer than 6m. Lateral deflection of pile and bending moment are visible when tunnel face is even closer (2-4m). There is no further effect of tunneling on the pile when the tunnel face passes by it, up to 8m. The possibility of a plane strain condition starts in the pile-tunnel system when the tunnel advances more than a certain distance. From this, one can see that zone of influence of the tunnel is from 6m in front of the tunnel face to 8m behind the tunnel face. It is 1-1.5 time's diameter (1.5D) of the tunnel on both sides of the tunnel face. This zone of influence is found to be comparable with that described by Lee and Ng (2005). An increase in the rate of excavation from 2m at each interval to 4m and 6m has been investigated and the observations are as shown in Fig. 11. It is found that, though the excavation rate does not have any direct relation with time, with the increase in the rate of excavation maximum lateral and vertical deflection, bending moments and axial forces reduce giving a hypothetical scenario of less disturbance with faster excavation. The disturbance is also associated with many other governing aspects in addition to rate. From Fig. 11, a higher rate of tunnel excavation considerably reduces its effect on the pile provided the tunnel advances more than 1D from the pile location.

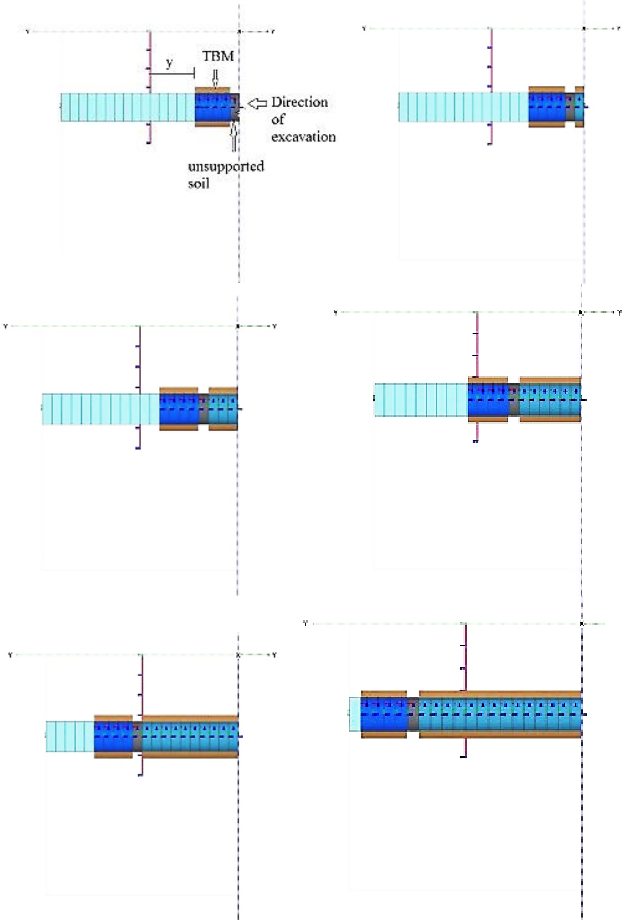
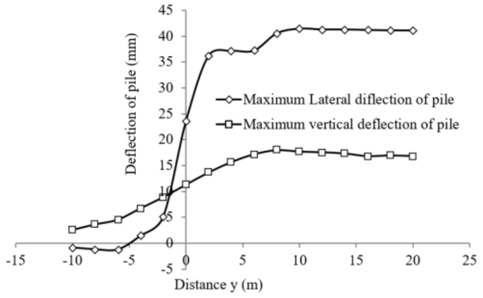


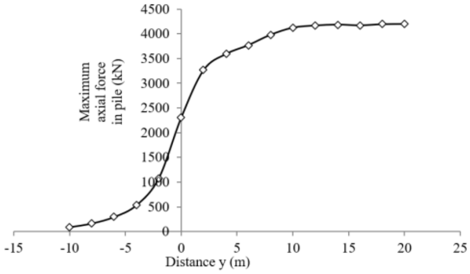
**Figure 9.** Staged excavation at various intermediate stages with the pile .

## 5. Response of pile group

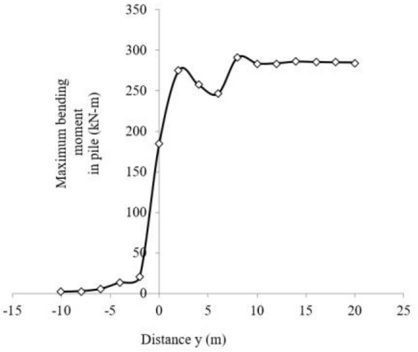
The response of a pile group as shown in Fig. 12 is also analyzed with PLAXIS-3D keeping lining parameters the same as in single pile analysis. The pile cap is kept at a distance above the ground level without having in contact with soil. Loganathan et al. (2001) have already analyzed this pile group problem and the material properties are borrowed from the same literature (Table 2). Results of this 3D FE analysis and that done with the Boundary element method (BEM) by Loganathan et al. (2001) are compared. Response of piles near the tunnel (front piles) and away from the tunnel (back piles) of the pile group foundation are observed and compared (Fig. 13). The results of FE analysis are found to be comparable with the previously published literature (Loganathan et al., 2001). It is clear from figure 13, that the influence of the tunnel excavation is less on the back piles of the pile group than that of piles near to tunnel. Here, the front piles in the pile group are at the same distance as in the single pile case from the tunnel axis. So, the performance of front piles in a pile group can be observed in comparison with that of a single pile.



(a) Maximum lateral and vertical deflection of pile

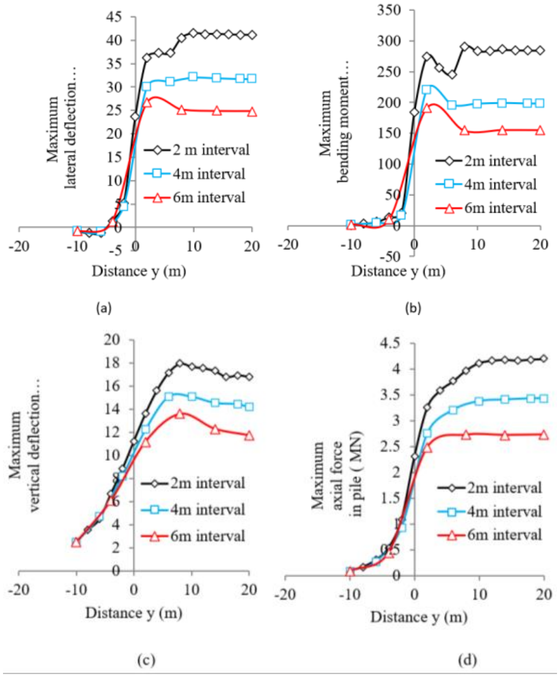


(b) Maximum axial force in pile



(c) Maximum bending moment in pile

**Figure 10.** Maximum axial force in pile due to open face



(a) (b)

(c) (d)

**Figure 11.** Response of pile at a different rate of excavation.

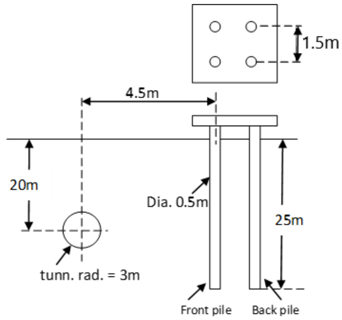


**Figure 12.** Pile group with the tunnel (Adapted from Loganathan et al., 2001).

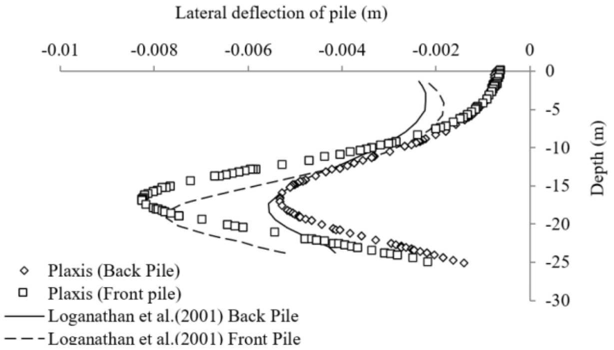


Figure 13(a) Lateral deflection of piles in pile group due to tunnelling .

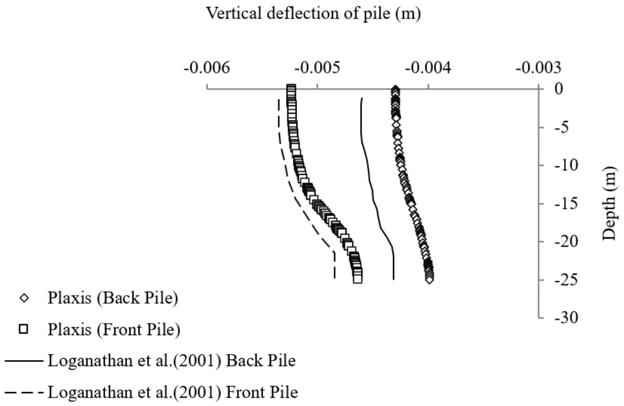


**Figure 13 (b).** Vertical deflection of piles in pile group due to tunnelling..

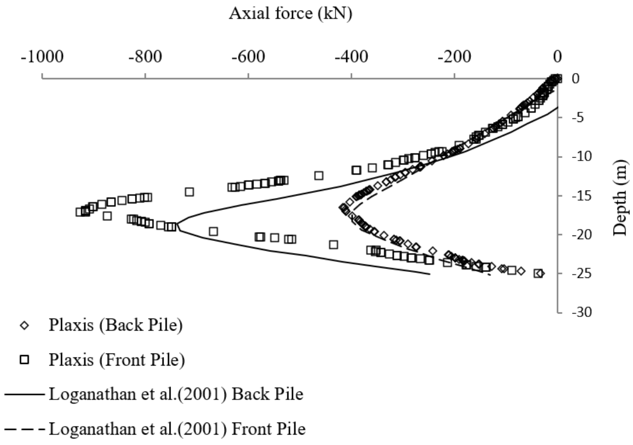


**Figure 13(c).** Axial force of piles in pile group due to tunneling..

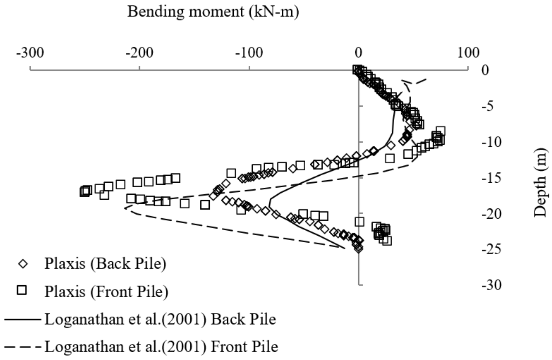


**Figure 13 (d).** Bending moment of the pile in pile group due to tunneling.

## 6. Conclusions

A 3D finite element (FE) analysis has been carried out to investigate the effects of tunneling on pile foundations. The investigation is done for a single pile with multiple stages of tunnel excavation, where the pile foundations are assumed to reach below the base of the excavation of tunneling. A tentative rate of excavation was included in this study and it was observed that a faster rate of excavation leads to better performance of foundations affected by tunneling by reducing the effect of tunneling. The study also extended to pile groups. Attempts were made to compare the results with some of the previously published literature. The effect of tunneling on the pile starts from a distance when the tunnel face reaches near 1D behind the pile. The pile and Tunnel system reaches plain strain condition after the tunnel advances approximately 1.5D of the tunnel. The effect of the tunnel on axial force and vertical deflection of the pile is more predominant than the lateral deflection and bending moment for the same distance of tunnel face position. The zone of influence of the tunnel is more on the lateral performance of piles than that on vertical performance. The tunnel effect on lateral deflection and bending moment is much more visible when the tunneling is at a closer distance from the pile. This indicates that the zone of influence of tunneling on the vertical performance of the pile is more than the zone of influence of tunneling on the lateral performance of the pile. Piles that are near the tunnel axis are more critical than piles at a farther distance from the tunnel.

### Conflict of Interest

This work is carried out as part of the student's M.Tech project work with no funding from any sources and the authors confirm that there is no competing interest in this research.

### Data availability statement

Additional data or information that support the findings of this study can be made available from the corresponding author, upon reasonable request.

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