Analysis of Pile Tunnel Interaction

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Abstract

The response of the ground to the tunneling is an area of great importance for projects in urban environments characterized by soft soils and other structures neighboring. To reduce the risk of damage resulting from the construction of a tunnel, the engineer designer must be able to make reliable predictions of tunneling induced deformations and their effects on the adjacent structures like pile foundations. This paper presents a FE 2D numerical analysis of tunnel-pile interaction to predicting these ground movements and estimating the additional axial forces and deformations caused to these existing piles after the realization of the tunnel where the deformations become stable and the calculation can be performed in 2D. The results found were compared with others studies provided by other authors in order to make comparisons, they are in good agreement. In addition, the analysis of influence of some parameters on the settlement of single-pile are also investigated, including pile length, diameter and depth tunnel and the horizontal position separating the pile from the vertical tunnel axis. The parametric study proved the influence of the different parameters on the behavior of the soil.

Key words : Shield tunnelling, tunnel– Single Pile Interaction, Finite element analysis; Analytical method, Parametric study.

1 Introduction

To understand the Tunnel- Soil- Pile interaction (TSPI) mechanism, a variety of research has been conducted on the subject, both experimental and theoretical. The first analyses published concerning the interaction of pile-tunnel go back to 1979 based on model tests, it is that of Morton and King (1979) [32]. The authors noticed how the pile response depended on its position to the tunnel and on the subsurface ground deformations, this work elevated interesting questions concerning the effects of the tunnelling on the bearing capacity of the piles.

Followed by other studies, there has been considerable researchers investigated in this axis by numerical, analytical and experimental approches like Loganathan and PouIos (1998) [26], Chen and al. (1999) [8], Loganathan and al. (2001) [25], Xu & Poulos (2001) [37], Jacobsz and al. (2005), Kitiyodom (2005) [21], Kroff (2012) [22], Mair & Williamson (2014) [30], Basile (2014) [1], Zhang and al. (2018) [38-39], Soomro and al. (2019), (2020) [35-36], Franza (2017, 2021) [16-17].

Chen and al. (1999) [8] analyses the lateral and axial pile response caused by tunneling using two stage approach. First, the ground movement caused by tunneling is calculated.: without pile (free-field soil movements) using the analytical method. Second, the estimated soil movements are imposed on the pile to compute the pile responses. The authors make also a parametric study, they showed that the responses of pile is influenced by numbers of parameters (ground loss ratio, pile length to tunnel depth and distance away from the vertical axis of the tunnel). Results show that tunneling cause a pile to develop significant bending moment, lateral, axial efforts and settllement. Xu & Poulos (2001) [37] and Loganathan and al. (2001) [25] investigated a 3D analysis to study the reaction of piles caused by tunnelling. They considered single piles and pile groups. A complete analysis of a foundation system subjected to ground movements induced by tunnelling can be carried out by a finite element analysis (Mroueh and Shahrour, 2002) [33]. However, a finite element analysis is more suited to obtaining benchmark solutions against which to compare simple analysis methods, or to obtaining solutions of a detailed analysis for the final design of a foundation, rather than as a preliminary routine design tool (Kitiyodum, 2005). Kitiyodom and al. (2005) [21] estimate the deformation and load distribution of piled raft foundations caused by tunnelling and incorporated into a computer program. The proposed method was verified through comparisons with some published solutions and those from finite difference program Flac3D. Basile (2014) [1] present numerical method for estimating the effects induced by tunnelling on existing pile foundations, He found that the method is capable of producing judicious predictions of pile. Zhang et al, (2018) [39] were carried out the FE studies to investigate the excavation induced pile behaviours by varying the depth of excavation, pile length, pile distances from excavation, pile diameter, pile-head fixity and axial loadings exerted on the pile, directing to provide design guidelines for the deformation of foundations pile and the structures above and stability evaluation. In the study of Soomro and al. (2019) [35], the authors compares the responses of a pile due to diverse excavations depths in saturated clay using 3D analysis. They found that the pile responses depend of the excavation. Franza et al, (2021) [16] investigated the response of pile groups and piled structures to vertical and tunneling induced loads. They used the continuum approach based on the theory of elasticity for pile-soil interaction. The results show that interaction analyzes require the intervention of all parameters, unloaded single pile analyzes may be unsatisfactory.

In this paper, we focuse principally on numerical modelling using finite element program Plaxis 2D. A series of analyses is carried for the assessment of the vertical and lateral dis-placements of the ground as well as of the single pile. First, using alternative approaches, ranging from analytical methods to 2D numerical analyses were performed using finite element program Plaxis 2D to estimate lateral and vertical movements for two cases (without and with pile). Secondly, a parametric study is presented to study the effect of some parameters on the soil-pile interaction mechanism. The validity of the results is assessed by comparing it to other results found in other studies.

In order to study tunnel-single pile interaction, until today, the model of Chen and al. established in (1999) [8] is still reused by several authors (Chen and al.,1999[8], Loganathan and al., 2001 [26], Xu & Poulos, 2001[37], Kitiyodom, 2005 [21], Mair & Williamson, 2014 [30], Basile, 2014 [1], Zhang and al., 2018, Soomro and al., 2019, 2020 [35-36], Franza, 2021 [17], Huang and al., 2022 [40]) using computer codes specialized in pile calculations (cited below) to estimate the various displacements of the pile as well as the forces and the bending moments induced by tunneling. However, the soil movements are frequently estimated empirically with simple analytical or even empirical methods. In our case we used the Plaxis 2d software dedicated specially to geotechnics and known for its validity to estimate numerically the behavior of the ground caused by the tunneling in the presence and without a pile. using the shield tunneling technique and the ground loss ratio method injected into Plaxis. In this way the behavior of the tunnel- soil-pile system will be calculated numerically and analytically.

2 Analysis Method

The phenomenon of the interaction between the tunnelling and the existing pile foundations is complex. There are two classes of methods for estimating the influence of tunneling on existing foundation piles:

1) Simplified two-step approaches involving the initial separation of soil and piles so that ground movements are first calculated and then imposed on the piles (Chen and al, 1999).

2) Numerical analyses including simultaneous modeling of piles, soil and tunnel excavation (Basile, 2014).

We present a brief description in the following paragraphs:

To describe the behavior of soils caused by the tunneling, several methods exist in the literature, such as: empirical, analytical and numerical methods (such as the finite element method).

The most popular empirical method for describing surface settlements is that of Peck (1969) [34] which is based on Gauss's normal law of probability and was developed by Mair (1993) [29] to describe displacements at depth.

Unfortunately, the method is very limited since it involves only a few parameters and the complexity of the soil-structure interaction mechanism requires an increasingly common use of powerful methods such as the FEM. Hence the utility of involving such more sophisticated methods which make it possible to deal with problems practically insoluble by the other methods. However, the designer should not overlook the complexity and high computational costs involved, especially if 3D effects are to be taken into account as well as the non-linear behavior of the ground.

With all these limitations and difficulties, simple closed-form analytical approaches, such as that of Loganathan and Poulos (1998) [26] which is widely used, can be helpful, especially if site data is lacking.

3 Definition of the Numerical model

The model treated is that of Chen et al, (1999), it consists of a circular tunnel with a diameter D=6m and the depth of tunnel axis H=20m from the natural surface. The tunnel interacts with a single pile with a diameter of d=50cm, a length of L_p=25m and an elastic modulus of elasticity; E_p=30GPa (**Figure 1**). The distance between the center line of the tunnel and the pile is assumed equal to x_p=4.5m.

The soil model is modeled using the Mohr-Coulomb criterion, the horizontal and vertical displacements are assumed to be zero at the level of the substratum and the horizontal displacements are blocked on the lateral sides.

The tunnel lining is composed of reinforced concrete segments forming a ring, and the behavior of the lining and pile is assumed to be elastic-linear. The concrete lining of the tunnel has a thickness equal to 35cm, its stiffness is E=40 Gpa.

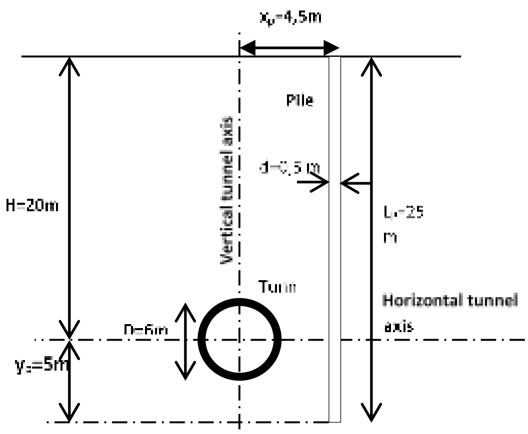

Figure 1. Definition of problem (Chen and al, 1999) [8]

Table 1. Soil parameters (Chen and al, 1999)

Parameter	Name	Clay	Unit
Unit weight	γ	15	kN/m^3
Elastic Modulus	E	24000	MPa
Cohesion	c	10	kPa
Friction Angle	ϕ	25	°

4 Results and Discussions

The tunneling in soft soil inevitably leads to deformations and this is valid for both vertical and lateral components and will have a direct impact on neighboring structures such as the pile. Ground movement around the tunnel leads the tunnel down which can impose negative skin friction on the pile, causing pile settlement and possibly reducing the load carrying capacity of the pile if the pile is in this area of influence (Chen and al, 1999).

According to Chen and al, (1999), the analysis of the interaction phenomenon is carried out in two stages; first, the estimation of ground movements (both lateral and vertical) without the presence of the pile caused by tunneling, second, the imposition of these ground movements on the pile and the calculation of the resulting pile responses.

We will start with the calculation of the lateral and vertical displacements of the ground without the presence of the pile, then, we will analyze the effect of the tunnelling on the already existing single pile. Then, a parametric study will be presented and this by modifying the following parameters:

1 The horizontal position separating the pile axis from the tunnel's vertical axis (noted x_p),
2 The pile length (noted L_p)
3 The tunnel depth (noted H).
4 The tunnel diameter (noted D).

4.1 Case 1: Absence of pile

In the following, we will analyze the soil response to the tunneling without the presence of the pile, our results will be presented at the pile location (x_p=4,5m).

4.1.1 Vertical and lateral soil movements

Figure 2 show the computed vertical and lateral soil movement profiles at the pile location caused by tunnelling calculated by Plaxis2D in comparison with the results of Chen and al., 1999 (PALLAS and PIES); Kitiyodom and al., 2005 (PRAB); Basile, 2014 (PGROUPN)). We can see that the vertical displacements increase gradually with depth to the tunnel key (at y=23m) and this is valid for the four studies including ours, then the movements decrease rapidly at the level of the invert. The vertical movement decreases with x.

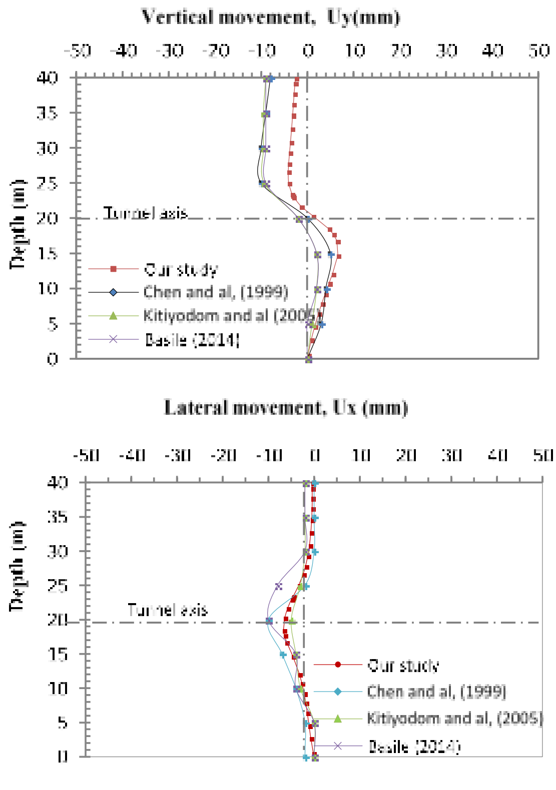

Figure 2. Computed soil vertical and lateral movements at x=4,5m

Compared to our study, the shape of the vertical soil displacement is the same as the other studies with a slight difference. This is a high vertical displacement above the tunnel (Zone of influence) and less below the tunnel axis : therefore the pile will subsequently be stressed in its upper part up to approximately 20 m of its shaft.

The shape of the lateral soil displacements **(Figure 2.)** is identical and the same observations are obtained.They are insignificant from the surface, and increase approaching the tunnel key with a maximum value then they tend towards zero. Laterl soil displacement decreases at tunnel invert.

4.2 Case 2: Presence of Pile

In this part, we assume that the pile existed before the operation of tunneling.

4.2.1 Vertical and lateral Pile movements

Figure 3 shows the vertical and lateral single pile responses calculated using Plaxis2D in comparison with the results of the four studies (Chen and al., 1999 (PALLAS and PIES); Kitiyodom and al., 2005 (PRAB); Xu & Poulos, 2001 (GEPAN); Basile, 2014 (PGROUPN)). We notice that an excellent agreement is found between the different results of Kitiyodom (2005), Xu & Poulos (2001) and Basile (2014). However, the shape of the results found by Plaxis 2D (our study) agrees perfectly with the other profiles with a slight difference. We notice also that the vertical displacements are uniform along the pile shaft, this means considerable pile stiffness (results approved by different authors). We notice a certain similarity between the vertical displacement of the pile and the ground, this was explained by chen and al, 1999, and other authors (caused by the low stiffness of the pile).

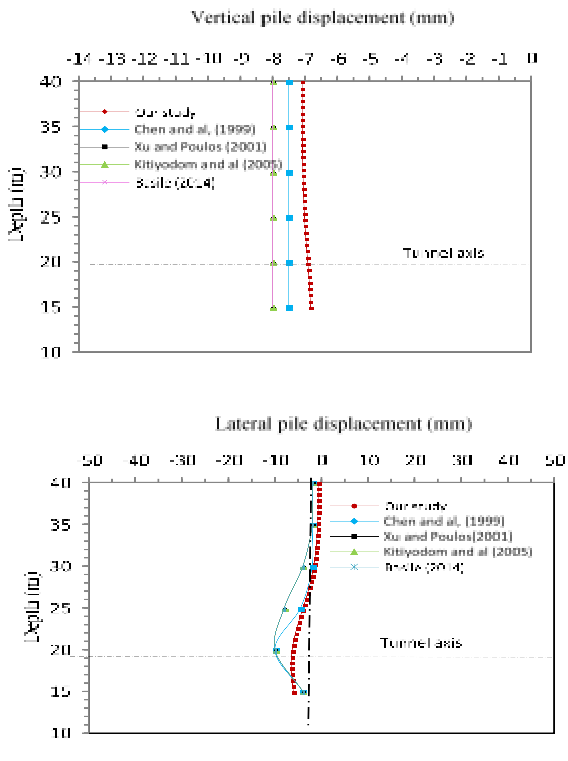

Figure 3. Computed vertical and lateral single pile response at x=4,5m

The profile of the lateral pile displacements **(Figure 3)** agrees with that of Chen and al., (1999) up to the tunnel axis. a small difference about 50% at the side of the tunnel. We also notice that the lateral pile displacements are small until reaching the tunnel axis (H=20m) for the five studies.The studies of Chen and al., (1999), Xu & Poulos (2001), Kitiyodom and al., (2005) and Basile (2014) are in perfect agreement. In general, the lateral displacements caused to the pile are similar to those of the ground with a slight difference.

4.2.2 Pile Bending moments and Axial forces

Figure 4 shows the distribution of bending moments and axial forces at the level of the single pile (at xp=4.5m), in comparison with the results of Chen and al., (1999), Xu & Poulos (2001) Kitiyodom and al., (2005) and Basile (2014).

It is noted that the bending moments increase with the depth, and are maximum at the tunnel axis for all the studies. The shape of the moment profile has two curvatures (in two sides). We see that the pile axial force increases with depth up to the tunnel axis and decreases to the invert of the tunnel. The result obtained by Xu & Poulos (2001) match the results of Kitiyodom et al., (2005) and Basile (2014) for the bending moment and axial force profiles, our results and that of chen and al., (1999) are a little divergent.

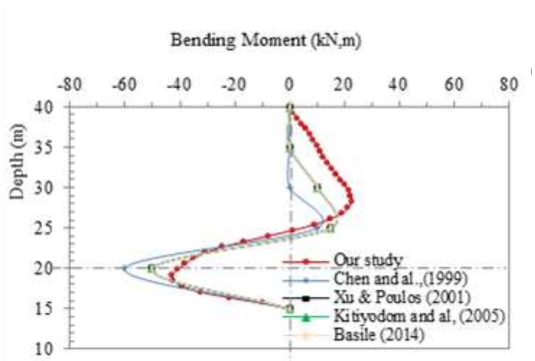

Figure 4. Single Pile Bending moment and Axial force

5 Parametric Studies

To investigate the impacts of various parameters on the ground–single pile responses (vertical displacement), parametric study is performed, through finite-element analysis, by varying the range of input parameters such as :

1. The horizontal position of pile (x_p)
2. The pile length (L_p)
3. The tunnel depth (H)
4. The tunnel diameter (D)

5.1 Influence of the horizontal position of pile (x_p)

Figure 5 shows the single pile vertical displacements at different positions (x_p). We chose : x_p=4,5m (0,75D) (ref.); 7,5m (1,25D) and 10,5m (1,75D). We notice that for the position of the pile x_p=4.5m, the vertical displacement is equal to 7mm and about 8mm for the two positions x_p=7,5m and x_p=10,5m. It is then concluded that the pile closest to the tunnel submit to the most deformations.

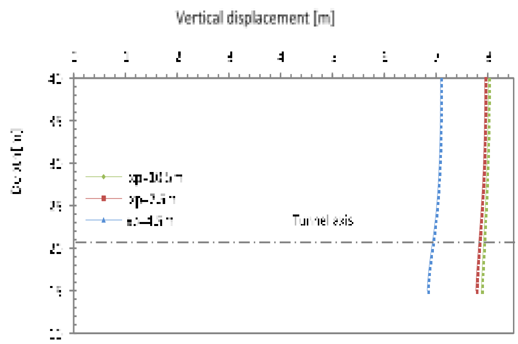

Figure 5. Computed single pile vertical responses for different x_p

We remarque that the pile settlement can be significant if the distance between pile and tunnel vertical axis is less than 1D (4,5m) . (Bezuijen and Schrier, 1994) [4].

5.2 Influence of the Pile length (L_p)

Figure 6 shows the influence of the pile length L_p on the vertical displacements, we opted for the following three lengths:

L_p=25m (Ref.), L_p=20m and L_p=15m. We notice that the vertical pile displacements increase when the pile length decreases and the pile turns out to be stressed by the location of its tip: if the tip is above the tunnel key, we obtain higher vertical displacements compared to if it is positioned below or in the center, this is caused by the zone of influence which exist above the tunnel.

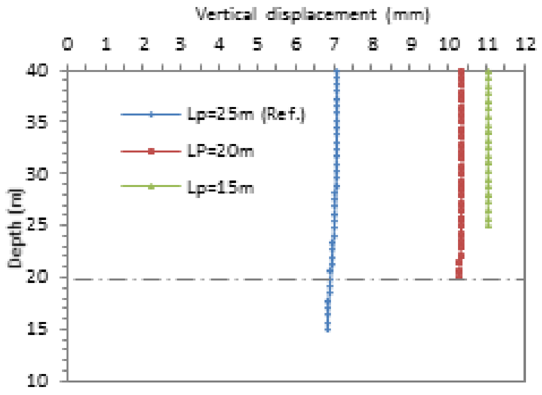

Figure 6. Computed single pile vertical responses for different length pile L_p

5.3 Influence of the tunnel depth (H)

Figure 7 shows the influence of the tunnel depth in relation to the tip of the pile (25m) on the vertical pile displacements. We opted for: H=20m (ref.), 22m, 25m, 28m. We notice that the displacements increase whith increasing the tunnel depth: If the horizontal axis of the tunnel is below the tip of the pile, higher vertical displacements are obtained compared to if it is positioned above, this is induced by the zone of influence above the tunnel. Our results corroborate those of other authors.

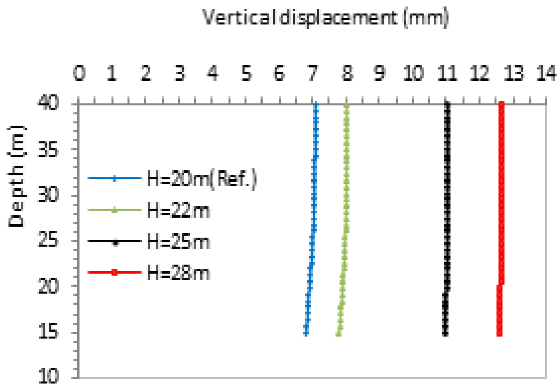

Figure 7. Computed single pile vertical responses for different tunnel depth H

5.4 Influence of the tunnel diameter (D)

Figure 8 shows the influence of the tunnel diameter on the settlements of the pile. we opted for the following three tunnel diameter: D=6m (Ref.), D=8, D=10m and D=12m. We notice that the increase in the diameter of the tunnel leads to a significant increase in settlements. This is logical since the volume lost caused by the tunnel increases with the increase of diameter and the zone of influence will be closer to the pile. [15-14],

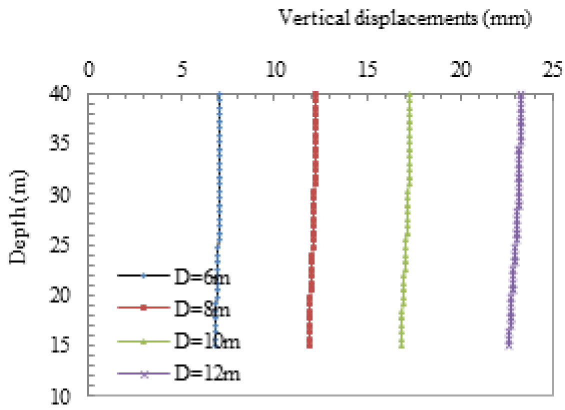

Figure 8. Computed single pile vertical responses for different tunnel depth H

6 Conclusion

This paper describes the tunneling- single pile interaction. The lateral, vertical axial and bending moments were investigated using two case studies. In the first, it is a question of calculating the vertical and lateral displacements of the ground caused by the tunnelling and comparing them with other studies without the presence of the pile. As for the second case study, we modeled this effect in the presence of the pile, which made it possible to predict the displacements and the forces applied to it. The results obtained were compared with the results of other authors to validate them, they agree. Our analyzes have shown that the tunnelling causes the pile vertical and horizontal movements.

A parametric study accompanied these results by modifying four parameters: the horizontal position separating the pile axis from the tunnel axis, the pile length and depth and tunnel diameter.

The following remarks were detected:

(1)The furthest pile is the least stressed by the excavation of the tunnel (far from the zone of influence).

(2)The longest pile is the least deformable due to the fact that its tip is below the tunnel, close to the latter's base (zone less influenced by the excavation work).

(3)When the horizontal axis of the tunnel coincides with the level of the tip or below, higher vertical displacements are obtained.

(4) The increase in the diameter of the tunnel leads to a significant increase in settlements.

(5) The results show that the method is capable of make satisfying predictions of soil- pile response.

7 Future Scope

In future works, we propose 3D studies and introduce the non-linear soil behaviour in order to study with more precision the Tunnel-Soil-Pile interaction (TSPI).

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