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Tunneling influence on pile-supported structures: a literature review

Haitham J. M. ODEH

Abstract
This paper reviews the influence of tunnel constructions on neighboring structures supported by pile foundations, using either single or group of piles. This paper focuses on addressing the used methods, namely numerical modeling, analytical methods, and empirical solutions to study tunnel-pile interaction. The limitation of each method is also presented along with a brief introduction about the soil models used in the analysis, followed by illustrating the main pile responses caused by tunneling. Comments are made particularly on the effect of changing the tunnel location relative to the piles, pointing out the critical location that causes the highest effect on piles, and the safest location that leads to the least influence in each method. Relevant case histories and field observations are cited, showing the induced pile settlement by tunneling, and the changes on pile internal forces. The tunnel excavation influence zone is also presented, which gives a better understanding of the interaction between tunnels constructed near the pile-supported structures.

Keywords: Pile-tunnel interaction, Pile responses, Single pile, Group of piles.

1. Introduction
The accelerated pace of urbanization demands the construction of more substructures, facilities, such as transportation infrastructure, service utilities like water supply, sewage waste systems, and tunnel passages as well. In certain circumstances, the current rapid growth of urban areas causes the necessity for tunnel constructions in the vicinity of existing structures and this interface will ultimately induce responses. Therefore, it is essential to take this effect into consideration. This paper will clarify the effect of tunneling work on pile-supported structures.
A tunnel construction near pile-supported structures causes substantial pile responses and this topic has been discussed by a number of authors using different modeling methods (e.g., Chiang, N. Loganathan, Lee, Kim).
Chung-Jung Lee and Kuo-Hui Chiang proved that [tunneling adjacent to an existing pile can induce extra bending moments and extra-axial forces on the pile and cause the pile to suffer larger settlements and lateral deformations] [1] .
Many studies discussed pile-tunnel interaction problems, for instance, C. Y. Cheng, G. R. Dasari, C. F. Leung, Y. K. Chow, H. B. Rosser [2], Alec M. Marshall,Twana Haji [3], M. Wasif Naqvi and Mohd Ahmadullah Farooqi [4], Raid Ramzi Al-Omari, Madhat Shakir Al-Soud, Osamah Ibrahim Al-Zuhairi [5],Francesco basile [6], K. Raja, K. Premalatha, S. Hariswaran [7], T.G.S. Dias, A. Bezuijen [8,9,10,11], Siew-wei Lee, William Cheang, Wendy Swolfs and Ronald Brinkgreve [12], C. J. Lee, S. W. Jacobsz [13]. The studies conclude that tunneling directly induced vertical and transversal soil movements, which resulted in pile internal reactions such as stresses, settlements, bending moments, and axial forces.
In contrast, only few studies have comprehensively compared numerical, analytical, and empirical methods used to analyze the tunnel-pile interaction to provide a better understanding of these methods applied in practice. Furthermore, much less is known about the limitations of each method.
A number of researches have been published to better understand the impact of tunneling on existing piles, including field monitoring by Pang C.H, Yong K.Y., Chow Y.K. [14],

centrifuge modeling [15,16,17,18,19,20], numerical analysis [21,22,23,24], and analytical analysis [25,26,27,28].

For the presented numerical and analytical methods, detailed cases were reviewed, showing the effect of changing the horizontal and vertical clear distance between the tunnel and the pile center axis, clarifying the tunneling construction influence on the pile-supported structures, the induced internal axial forces on piles, bending moments, piles deflections and the resulting pile settlements.

For the empirical methods, to understand the recent practical ways of how to examine the impact of tunneling construction on a pile-supported structure, results of centrifuge modeling are cited by demonstrating the mechanism of the pile failure behavior.

1.1 Pile responses

The construction of a tunnel adjacent to existing piles requires careful consideration of the pile responses and previous studies such as the one in which Nagendran [29] shows that tunneling near piles imposes soil movements resulting in axial movement, lateral deflection, bending moment and pile head rotation. The pile responses may differ based on the structure foundation system, where many high-rise buildings are supported by a group of piles instead of single piles causing a change in foundation stiffness, which leads to varying the pile responses.

Fig. 1. demonstrates an example of the basic problem discussed in this paper, in which a single existing pile is closely located to a tunnel under construction. Tunneling typically causes both vertical and horizontal ground movements. Vertical ground movement above the tunnel's horizontal axis is generally downward, imposing negative skin friction on the pile and potentially causing pile settlement and a reduction in effective pile load carrying capacity. Horizontal soil movement tends to be directed toward the tunnel axis, causing additional lateral deflection and bending moment in the pile [29].

Moreover, the interaction between tunnels and horizontal substructures leads to severe ground settlement, Based on a recent study by Vahab Sarfarazi, Hadi Haeri, and Kaveh Asgari [30] evidently shows changes in ground settlements after constructing a tunnel closeby to an aqueduct, different Tunnel-aqueduct locations were examined to determine the safest and critical configuration for constructing the tunnel near the aqueduct**.**

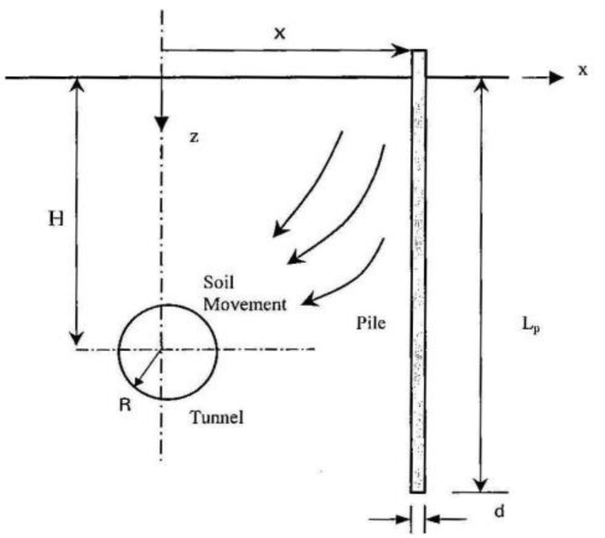

Fig. 1: Effect of tunneling adjacent to single pile foundations [29].

1.2 Soil models

There are three soil models that analyze tunnel-pile problems, a Mohr-Coulomb (MC) model, a Hardening Soil (HS) model and a Hardening Soil model with small strain (HSSmall). A study introduced by Chen, Shong-Loong; Lee, Shen-Chung; Wei, and Yu-Syuan [31] is reviewed, The main finding can be concluded as follows:

1. The value of vertical ground surface settlement (U_z) from the MC model is the smallest compared with the other two models (HS/HS-small) while the (U_z) for the HS model is the largest, and (U_z) for the HS-small model has a middle value in between.
2. As the HS-Small model assumed that soil stiffness decayed nonlinearly with an increasing strain amplitude, it produced more realistic modeling results than (HS/MC) soil models.

2. Numerical modeling

Numerical computations that provide a comprehensive overview of ground movements throughout the soil around the tunnel and adjacent structures are preferred for a precise evaluation of tunneling induced ground movements and their effects on nearby structures. Numerical analysis tools like the finite element method, finite difference method and boundary element method are commonly used to model the difficult and complicated geometries and construction methods that are now frequently associated with tunneling schemes. Although numerical modeling can handle all the different tunnel-pile interaction scenarios, some limitations may arise when dealing with specific software or incorrect input data [29].

A study by Kim, Chungsik Yoo and Sun Bin [32] presented a numerical investigation for a pile-supported building beneath its multi-faced tunneling in a soft ground and water-bearing condition, and they concluded that the axial load tends to decrease or increase depending on how far they are from the tunnel axis, and the pile settlement will change depending on the location of the piles relative to the tunnel face zone of the influence. 60% of pile settlement occurs when the pile is located where the tunnel face passes through the zone -2D to 1.0D from the pile.

Another study by Lee, C.J. [33] conducted a 3D numerical analysis study to determine the impact of changing the location of a tunnel construction on a single pile. The computed results revealed that the axial pile forces changed significantly due to tunneling. The study shows that the influence zone is about ±2D behind and ahead of the piles. Furthermore, when the pile tip was at the tunnel spring line, the pile capacity decreased due to the tunnel causing pile settlement. As a result, the pile capacity can be affected by the piles' relative position in relation to the tunnel position.

To clarify, a study by H. Mroueh, I. Shahrour [34] addressed the tunneling construction effect on the pile foundations taking into consideration the pile-tunnel clear distance, either if it is a vertical or horizontal distance. The author formed a 3D finite element model to numerically calculate the induced internal forces and deflections on the pile. However, two cases have been discussed. Case (1) explains the tunneling effect on single pile foundation, and case (2) illustrates the tunneling effect on a group of pile foundations. Fig. 2. shows the parameters that were used as a reference in the study, where:

itp: Indicates the distance between the pile bottom edge and the tunnel horizontal center axis.

△tp: indicates the distance between the pile center axis and the tunnel center axis.

△fp: Indicates the distance between the pile center axis and tunnel face.

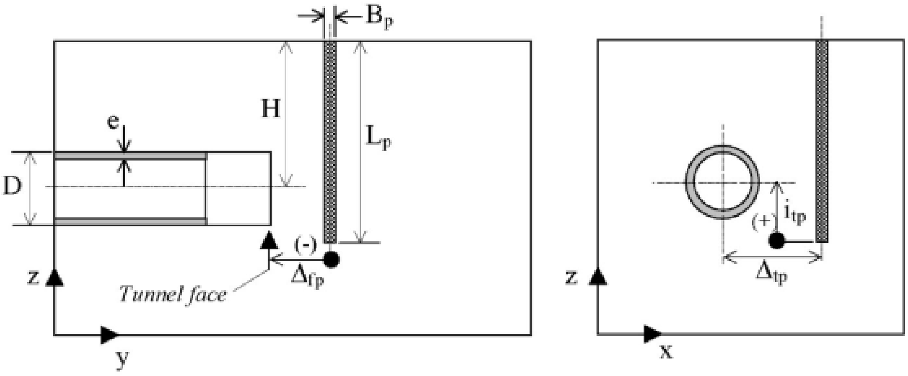

Fig. 2: z-y axis/ z-x axis side view for pile-tunnel interaction showing the parameters for pile-tunnel locations from each other [34].

The study involves the interaction of shallow tunnel constructions near a single pile where the tunnel diameter is D=7.5 m and H=2.5D for the cover depth, the pile width equals 1 m (Bp=1m), and the pile length equals 22.5 m (Lp=22.5m). The soil behavior is modeled based on the Mohr-Coulomb criterion.

Fig. 3. (a) shows that the pile lateral deflection increased noticeably in front of the tunnel face directed to the opposite direction of the pile and toward the tunnel excavation zone. The maximum value for the lateral deflection at the ground level which equals 1.4 mm, also increased when the distance becomes greater than 2D (△fp >2D) the pile deflection stagnates. Fig. 3. (b) shows the pile longitudinal deflection where induced before the tunnel face (△fp < zero) and reaches the maximum value near the ground surface about 0.8 mm, also as clearly shown when Pile-tunnel face clear distance (△fp =3D) the longitudinal deflection declined to zero.

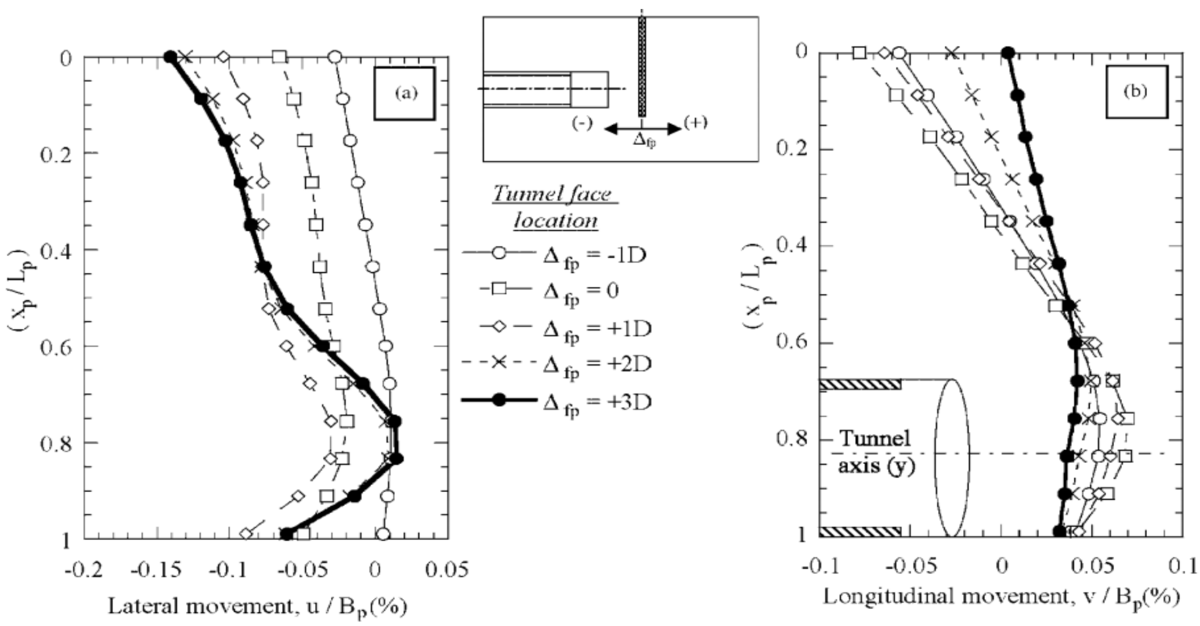

Fig. 3: Pile deflection due to tunneling (Lateral and longitudinal sections) [34].

Fig. 4. clarify the influence of the vertical pile position with respect to the tunnel horizontal axis (itp), it shows that when the pile edge is located above the tunnel horizontal axis the axial forces will gradually increase with a low bending moment, and when it is below the tunnel horizontal axis(itp>zero) it shows increasing of the axial forces reaching the maximum value followed by declining, with a higher bending moment value compared with the one obtained when the pile bottom edge above the horizontal tunnel axis.

Fig. 5. Shows the lateral distance (△tp) influence on the pile axial force and bending moment, when △tp increases from 1D to 1.5D the total effect on the pile will decrease, and the axial force drops down from 540 to 225 kN. Likewise, the bending moment decrease from 170 to 70 kN.m. The presence of a piles group instead of a single pile provides a positive effect. Wherein Fig. 6. Demonstrates the pile internal forces values in the case of a group of piles. The group advantage is shown remarkably on the rear pile responses, in which the maximum axial force value dropped by 60%, similarly, the maximum bending moment value dropped by 45 %, Conversely, the influence on the front pile is much less, in which the maximum axial force value dropped by only 20%. And the influence on the bending moment value is almost negligible.

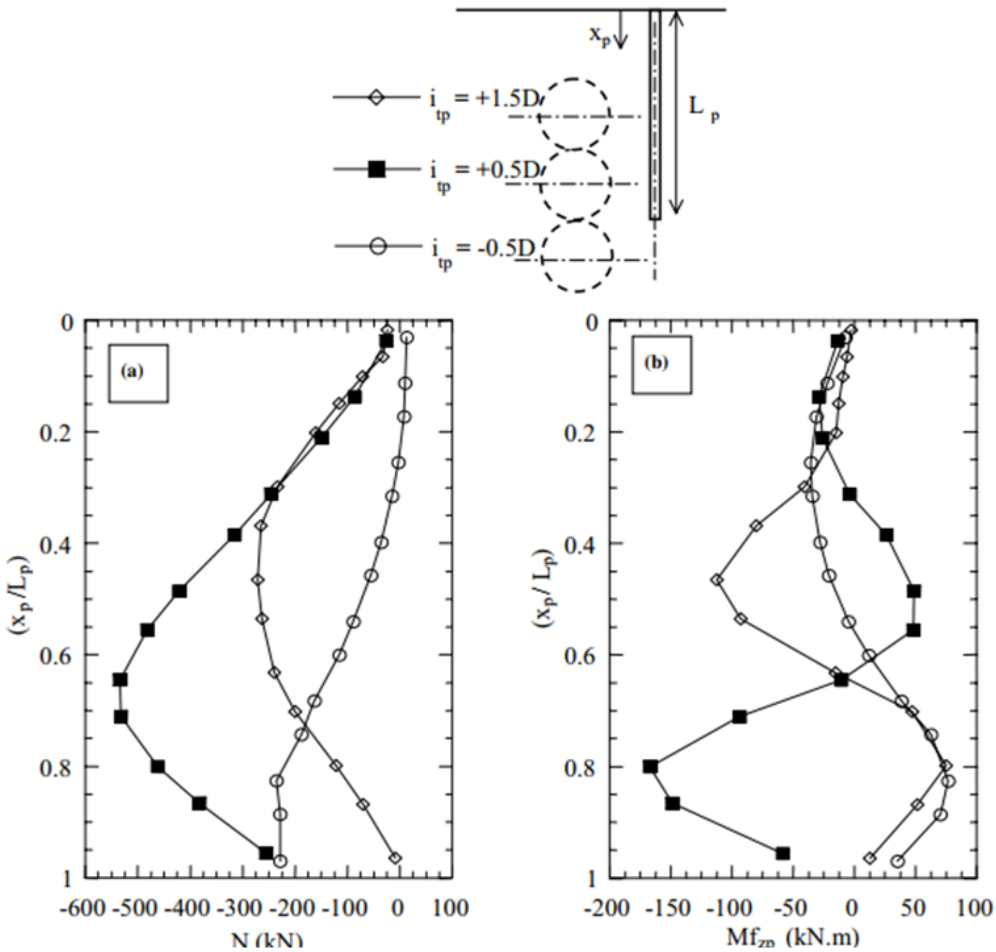

Fig.4: The influence of pile-tunnel vertical distance. (Axial force and bending moment) [34].

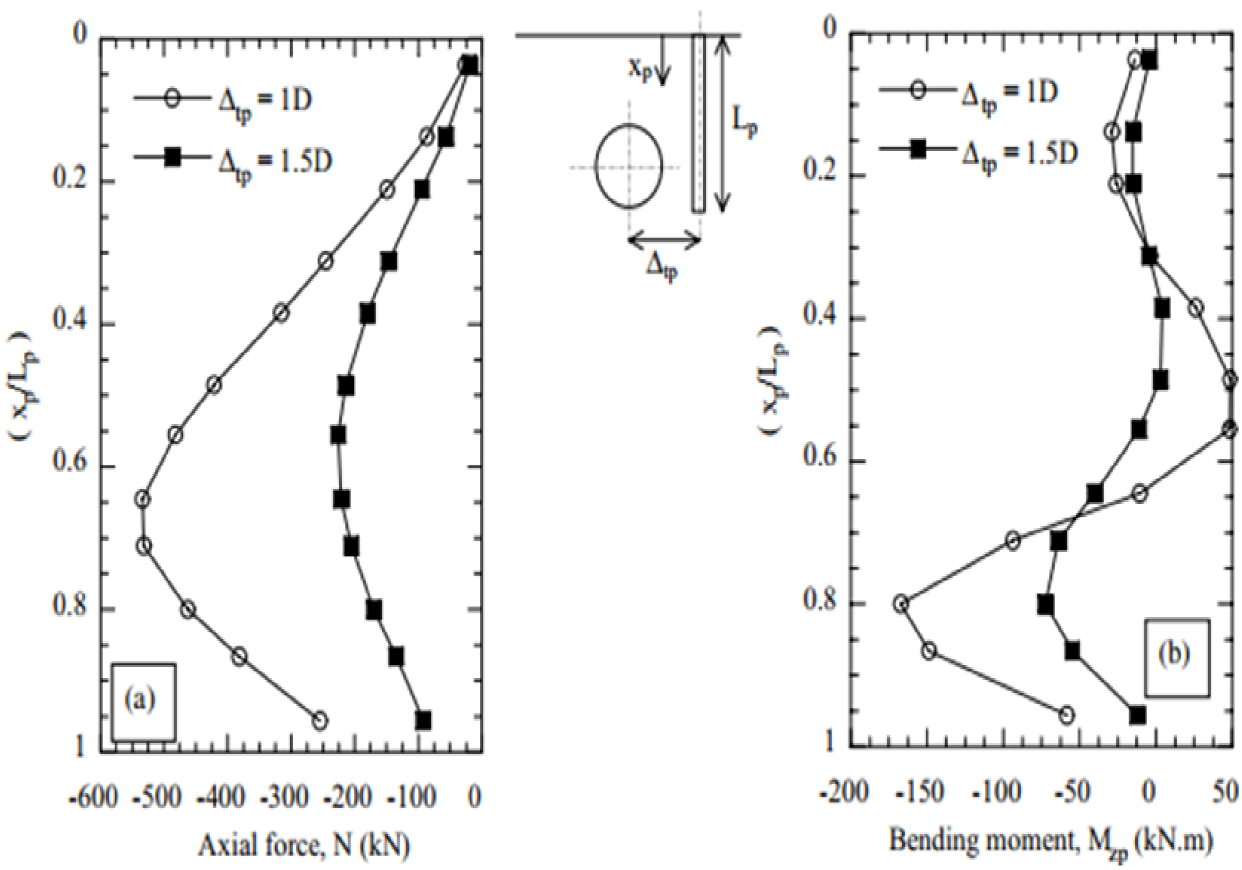

Fig. 5: The influence of the lateral tunnel-pile distance (Δ_{tp}) for axial force bending moment [34].

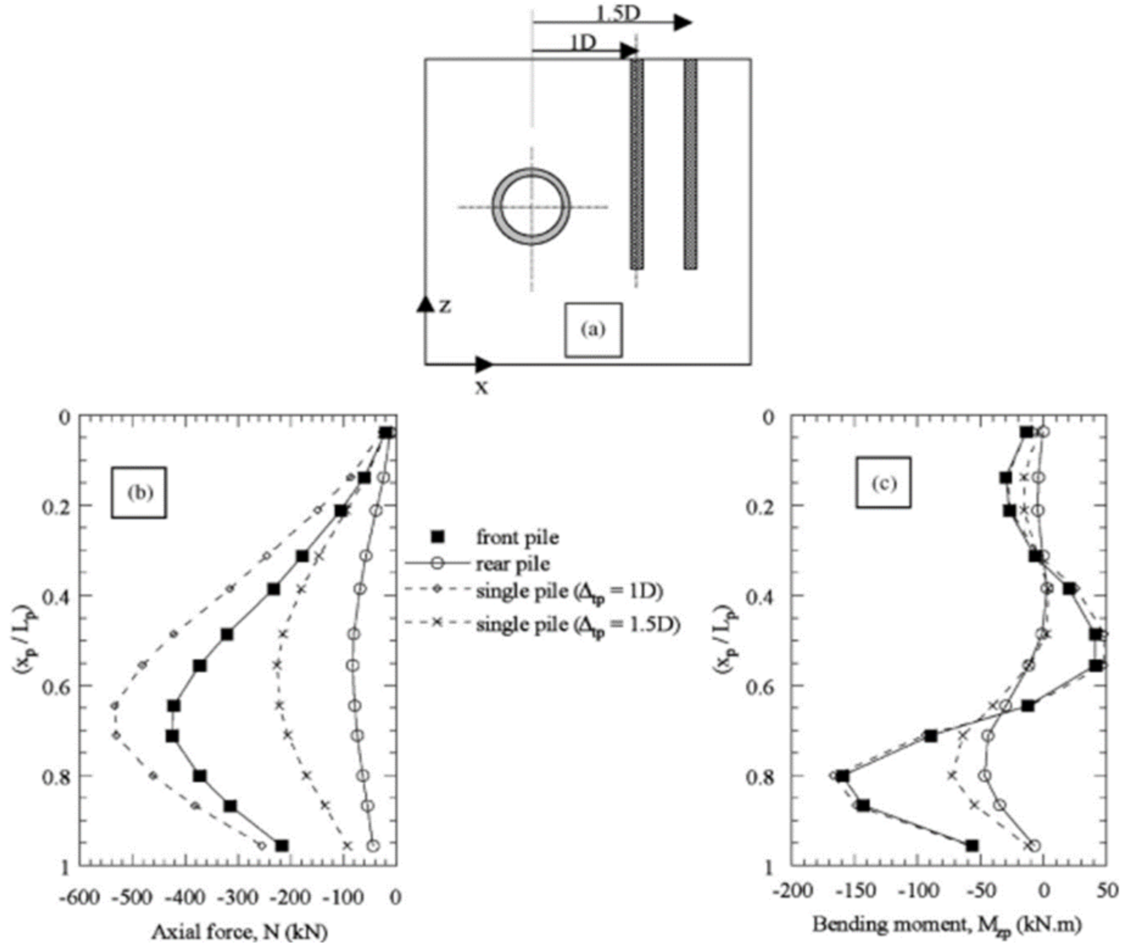

Fig.6: The tunnel construction infuence near group of piles (2×2) [34].

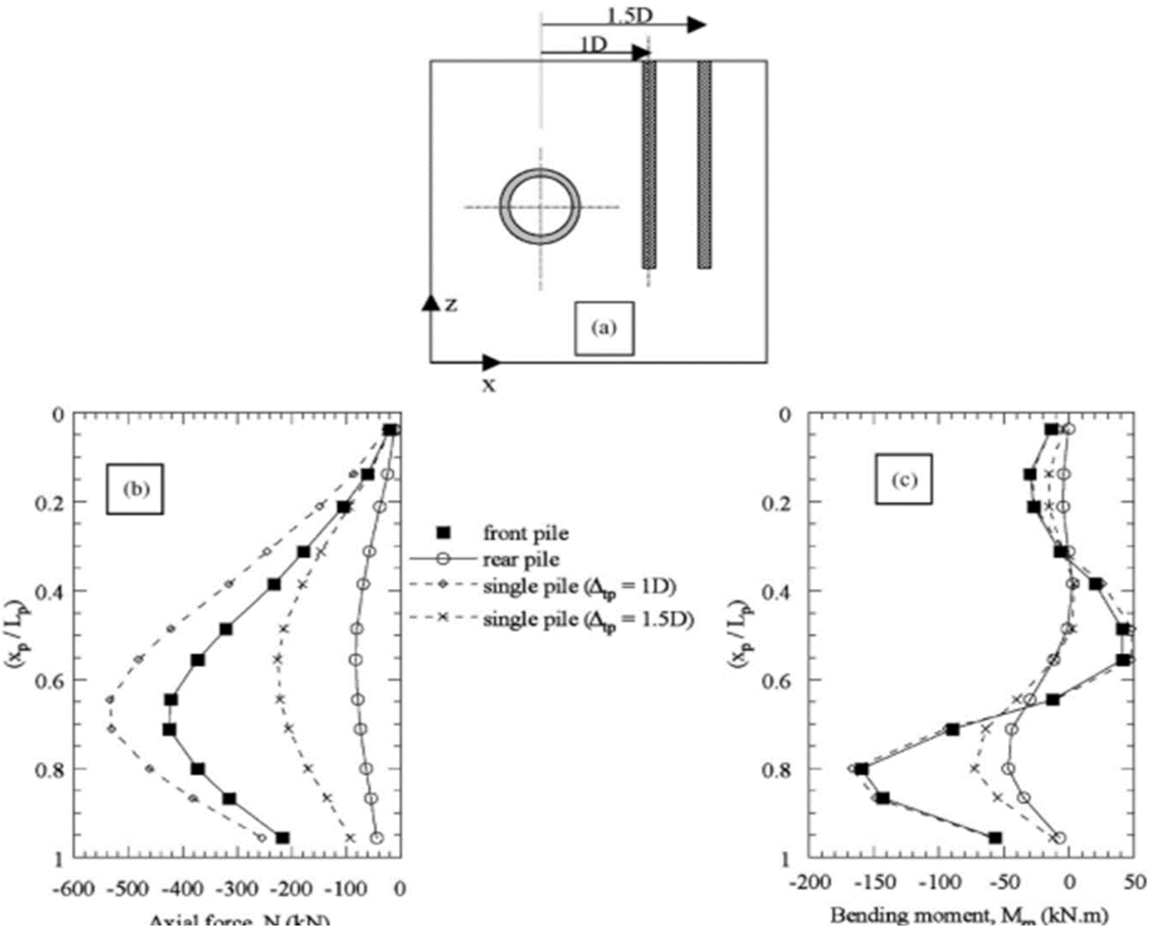

Fig.6: The tunnel construction infuence near group of piles (2×2) [34].

Another study is reviewed which includes a 3D numerical investigation in the Seoul metro project done by Yoo, Chungsik [35] , where the numerical modeling was accomplished using Abaqus finite element software. The purpose of the study is to illustrate the interaction between the tunneling and the nearby road bridge, which is supported by piles foundations. The tunnel is 7.9 meters in height (H=7.9 M) and 11 meters in width (D=11m) and constructed in three soil layers: 14 meters of weathered soil layer followed by a weathered rock layer and ending with a soft rock layer. The Mohr-Coulomb model is used for the soil and the rock, a bench-end method is the applied excavation method for constructing the tunnel, and the primary support is 200mm thick shotcrete.

Fig. 7 shows the constructed tunnel condition and the pile set locations under the bridge piers and its dimensions noting that the vertical clear distance between the tunnel crown and the pile bottom edge is C, while the horizontal distance between the tunnel center line and the center of the bridge pier is E.

Just half of the bridge has been modeled in the 3D finite element modeling taking advantage of the bridge symmetricity, with C=0.0D and E=3D. 2 cases were mainly analyzed based on the tunnel location relative to the bridge pier center axis. In the first case, E/D=0.0 and in the second case, E/D=0.75. As shown in Fig.8, different depth ratios are considered in the study for each case. Table (1) lists the depth ratio C/D range for each case.

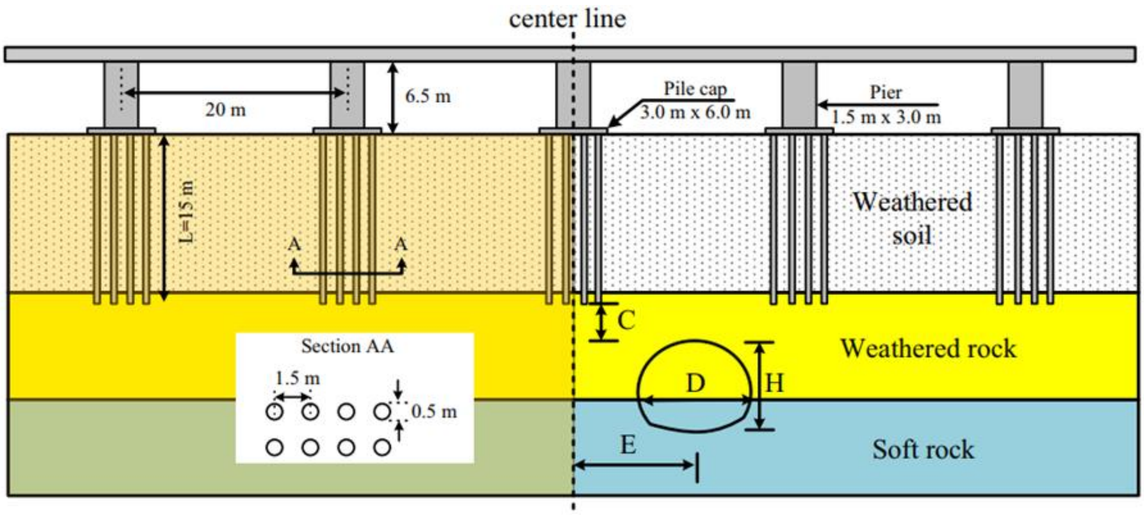

Fig. 7: The tunnel- pile condition from Seoul metro project [35].

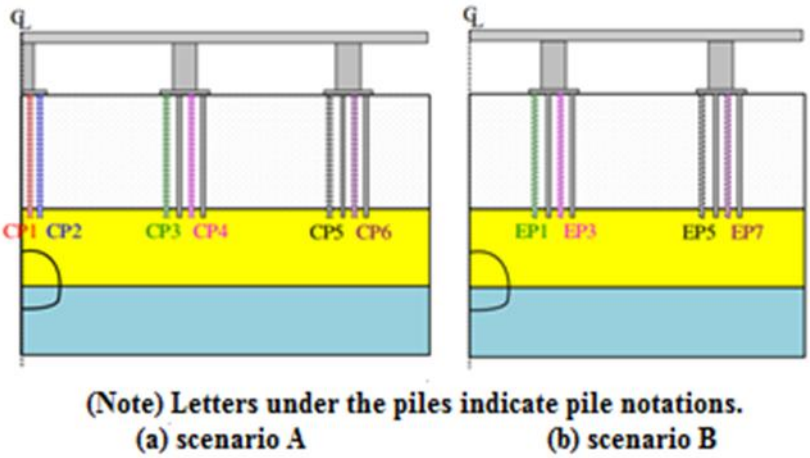

Fig. 8: The analyzed cases in the construction of the Seoul metro project [35].

Table 1: Cases considered [35].

Scenario	pile-tunnel clearances, C/D	Tunnel eccentricity, E/D
Left	18.5 mm	14.5 mm (0.58 in)
Right	18mm	13 mm (0.51 in)

Fig.9 shows the pile tip settlement results after changing the tunnel location regarding the piles. Both scenarios have been taken into account: in the first case, with E/D=0.0, Fig. 9 (a) shows that when the vertical clear distance increases between the pile tip and the tunnel crown (an increase in C/D), the settlement (Sp/D) decreases. For example, in the case of increasing C/D from 0.15 to 1, the settlement decreases by 25%. However, in the second case, when (E/D=0.75) Fig.9 (b) shows a slightly different behavior as a result of the characteristics of transverse settlements profile. However, Fig. 9 (c) shows a combined result of the two scenarios taking into account the different tunnel-pile locations.

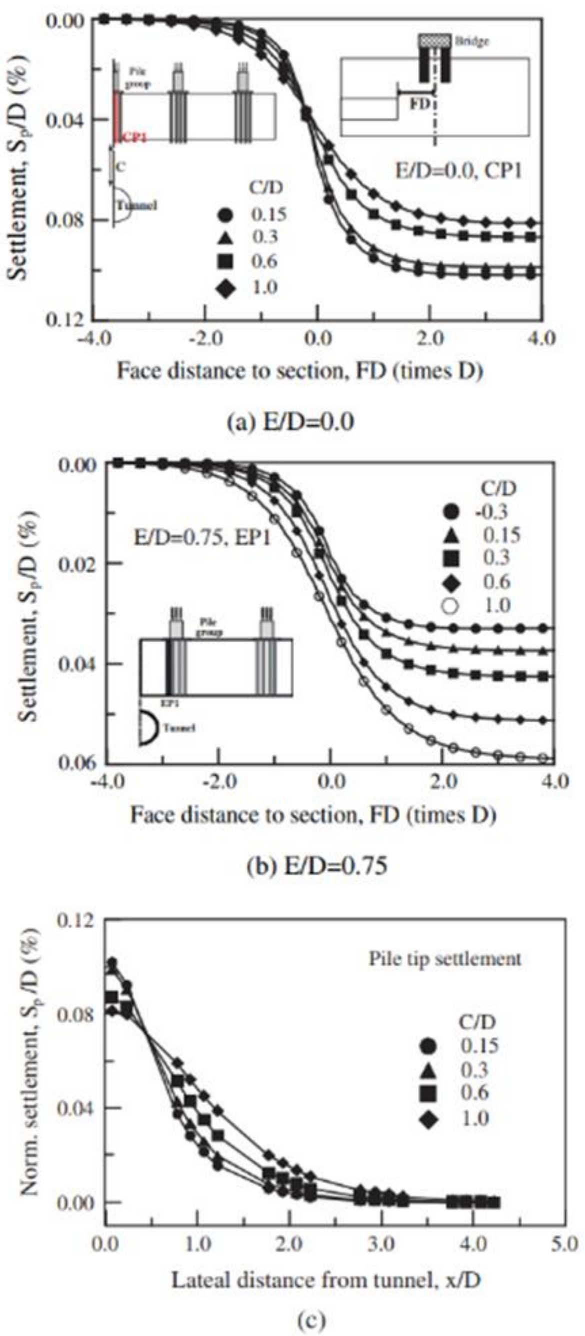

Fig.9: Changes in pile tip settlement relative to Tunnel-pile vertical/horizontal clear distance in many cases [35].

To sum up, when the piles are located right above the tunnel, the pile tip settlements decrease with an increasement of the vertical clear distance. Quite the opposite happens to the pile tip settlement value when the piles are located further away from the tunnel, changing the tunnel-pile horizontal clear distance.

Fig.10 shows the results of the pile tip load △Qb after changing the tunnel location in the two cases examined in the study.

In the first case, with E/D=0.0, Fig. 10 (a) shows that increasing the vertical clear distance between the pile tip and the tunnel crown (means an increase in C/D) the pile tip load (Qp) decreases. For example, in the case of increasing C/D from 0.15 to 1 the pile tip load decreases by 60%. We notice here that the pile tip load is more sensitive to the tunnel pile vertical location than the pile tip settlement (25%). In the second case, (E/D=0.75) Fig.10 (b) shows that changing the vertical clear distance (C/D) has a significant effect on the pile tip load, especially when the pile end is located below the tunnel crown level.

However, Fig.10 (c) shows the normalized change in the pile tip load with the original pile state before the tunnel construction. To sum up, when the distance x/D becomes larger than 2 the tunneling influence on the pile tip load is approaching the least value (< 20%). So, basically, the tunneling effect on the pile tip load for the pile located where (X/D > 2) can be neglected

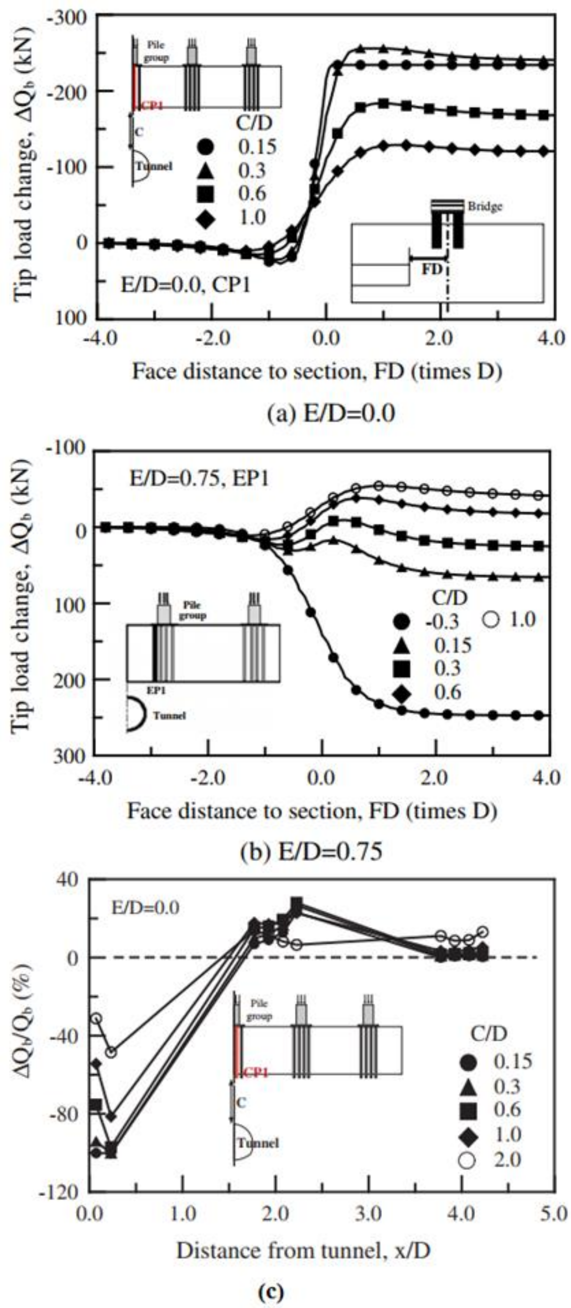

Fig.10: Changes in pile tip load relative to Tunnel-pile vertical/horizontal clear distance in many cases [35].

A number of numerical and finite element analysis studies of tunneling-induced pile response have given valuable knowledge and understanding of the various factors that affect the tunneling-induced performance of pile foundations namely (Broms B B, Pandey P C.[36],Chen L.T.,Poulos H G, Loganathan N. [37], Kitiyodom P, Matsumoto T, Kawaguchi K. [38] , Surjadinata J, Hull T S, Carter J P, Poulos H G.[39] ,Lee R G, Turner A J, Whitworth L J.[40] , Mroueh H, Shahrour I.[41] , Lee T G K, NG C W W [42],Ong C W, Leung C F, Yong K Y, Chow Y K.[43],Cheng C Y, Dasari G R, Chow Y K, Leung C F [44]).

3. Analytical modeling

The main approach in this part of the study is to estimate the lateral and the horizontal response of piles induced by tunnel construction using the analytical method.

Fig. 11. below shows the main case considered in this study introduced by L.T.Chen, H.G.Poulos,N.Loganathan [45] which consists of an existing single pile near a tunnel under construction with undrained conditions due to clay soil. The tunnel diameter is 6 meters (R=3m). It is constructed at a depth of 20 meter (h=20m) and the pile is a precast concrete pile with a diameter equal to 0.5 meters and a length of 25 meters.

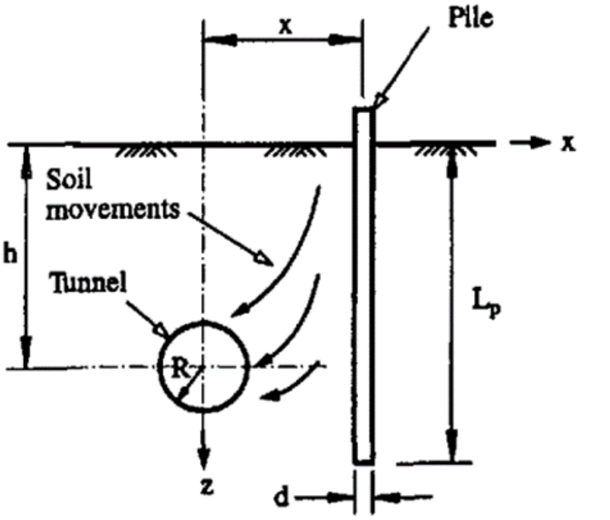

Fig.11: Pile adjacent to tunneling [45].

As for clay soil, Loganathan and Poulos [46] presented closed-form analytical solutions for calculating surface settlement, subsurface settlement, and lateral deformation as shown in Eqs. from (1)-(3).

$$\boldsymbol{U_{Z=0}} = \mathcal{E}\,\boldsymbol{R^2}.\frac{4h(1-\upsilon)}{h^2+x^2}\,.\,e^{-[\frac{1.38x^2}{(h+R)^2}} \quad (1)$$

$$\boldsymbol{U_z} = \mathcal{E}\,\boldsymbol{R^2}(-\frac{z-h}{x^2+(z-h)^2} + (3-4\upsilon)\frac{z+h}{x^2+(z+h)^2} - \frac{2z[x^2-(z+h)^2]}{[x^2+(z+h)^2]^2}.\,e^{\{\left[\frac{1.38x^2}{(h+R)^2}\right]+\frac{0.69z^2}{h^2}]\}} \quad (2)$$

$$\boldsymbol{U_x} = -\mathcal{E}\,\boldsymbol{R^2}x\,(-\frac{1}{x^2+(z-h)^2} + \frac{(3-4\upsilon)}{x^2+(z+h)^2} - \frac{4z(z+h)}{[x^2+(z+h)^2]^2}).\,e^{\{\left[\frac{1.38x^2}{(h+R)^2}\right]+\frac{0.69z^2}{h^2}]\}} \quad (3)$$

Where $U_{(Z=0)}$ = Ground surface settlement

U_z = Subsurface settlement

U_x = Lateral soil movement

R=Radius of the tunnel

h=Depth of tunnel horizontal axix level

x=Lateral distance from tunnel centerline

υ=Poissons ratio

Ɛ= Ground loss ratio

Fig.12 shows the calculated lateral and vertical soil movement by tunneling construction, taking into consideration two ground loss ratio values (e) - 1% and 5 %, the horizontal distance from the tunnel (x=4.5m). It is clearly shown that the maximum values for vertical and lateral soil movement occur above the tunnel horizontal axis. However, the lateral soil movement reaches its maximum value when (x=3), then right after that it starts to decrease by increasing the x value, unlike in the case of the soil vertical movement, where there is a decrease by increasing the x value.

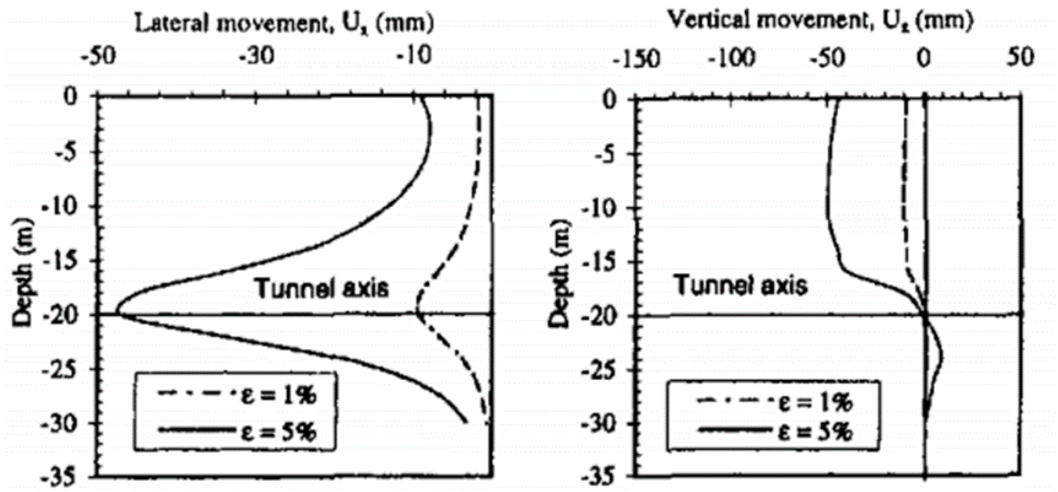

Fig. 12: Calculated vertical/horizontal soil movement induced by tunneling [45].

Fig.13 shows the maximum values of the pile responses when changing the clear distance (x) between the vertical tunnel axis and the pile, which are the bending moment *Mp*, lateral deflection *ρp*, pile head settlement *υp*, tensile axial force *–Pp*, and compressive axial force + *Pp*. It should be noted that there are two values of $\mathcal{E}R^2$ to be taken into consideration. In the first case, $\mathcal{E}R^2$= 0.009 m where tunnel radius equals 3 m and ground loss ratio (Ɛ) equals 1%. In the second case, $\mathcal{E}R^2$= 0.45 m where tunnel radius equals 3 m and ground loss ratio (Ɛ) equals 5%. When the clear distance between the tunnel's vertical axis and the pile increase, all the pile responses (*Mp, ρp, υp –Pp*) will decrease. The tensile axial force -Pp occurs only when the distance (x) is less than 9 meters (X < 3R), and when x=9 meters + Pp reaches the maximum value.

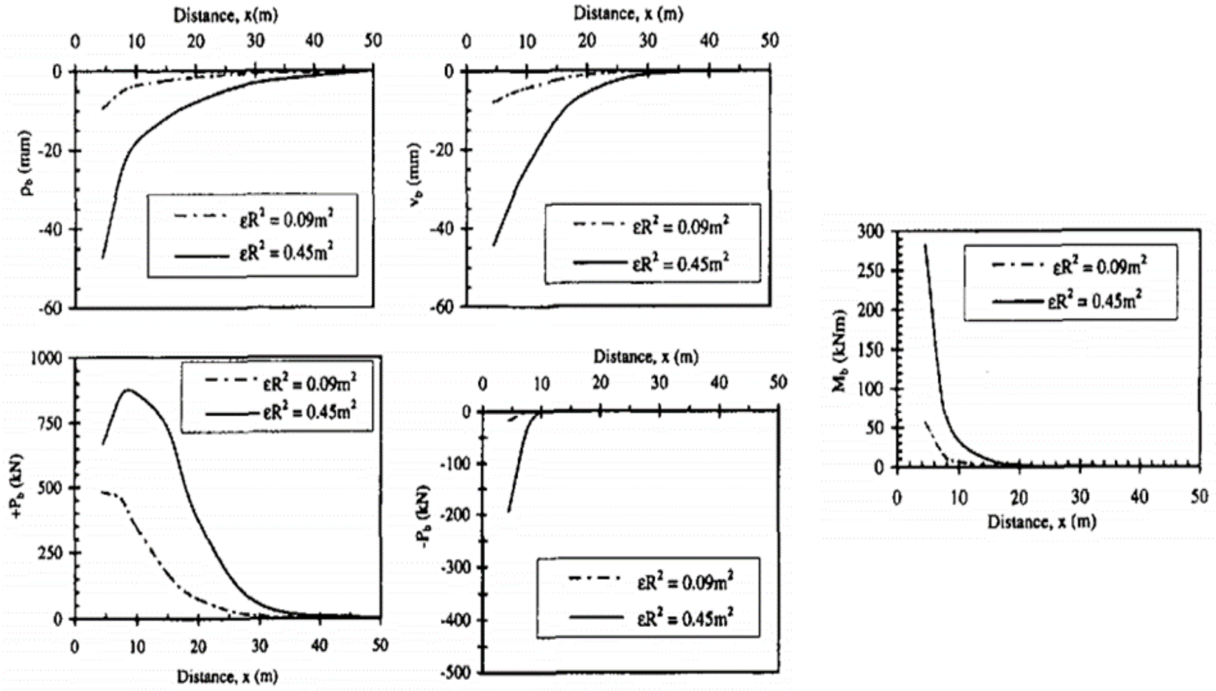

Fig. 13: Maximum pile responses changing tunnel-pile clear distance (x) [45].

Fig.14 demonstrates the effect of changing the vertical distance between the pile tip and the tunnel axis - three pile lengths were examined: Lp=15m, 20m and 25m. Broadly, in the first case with a pile length of 15 meters, the pile tip is above the tunnel horizontal axis level. When the pile length equals 20 m, the pile tip stays at the same depth level of the tunnel horizontal axis, and when the pile length is 25 m, it means the pile tip is below the tunnel horizontal axis.

The conclusion of the observation is that when the pile tip location relative to the horizontal tunnel axis is changed, the pile response changes. Fig.15 illustrates the influence of changing the pile length regarding the pile responses.

When Lp = 15, a small amount of bending moment occurs because the soil lateral movement value below the pile tip is not large.

When Lp = 20, there is an increase in the bending moment and the axial force with increasing the pile length.

When Lp = 25, when the pile tip is below the tunnel horizontal axis, the lateral deflection acts independently from the pile length.

The reason behind the influence on pile responses when changing the pile length is that the soil movement (lateral movement in particular) approaches the maximum value around the tunnel horizontal axis level and starts gradually decreasing above and below it.

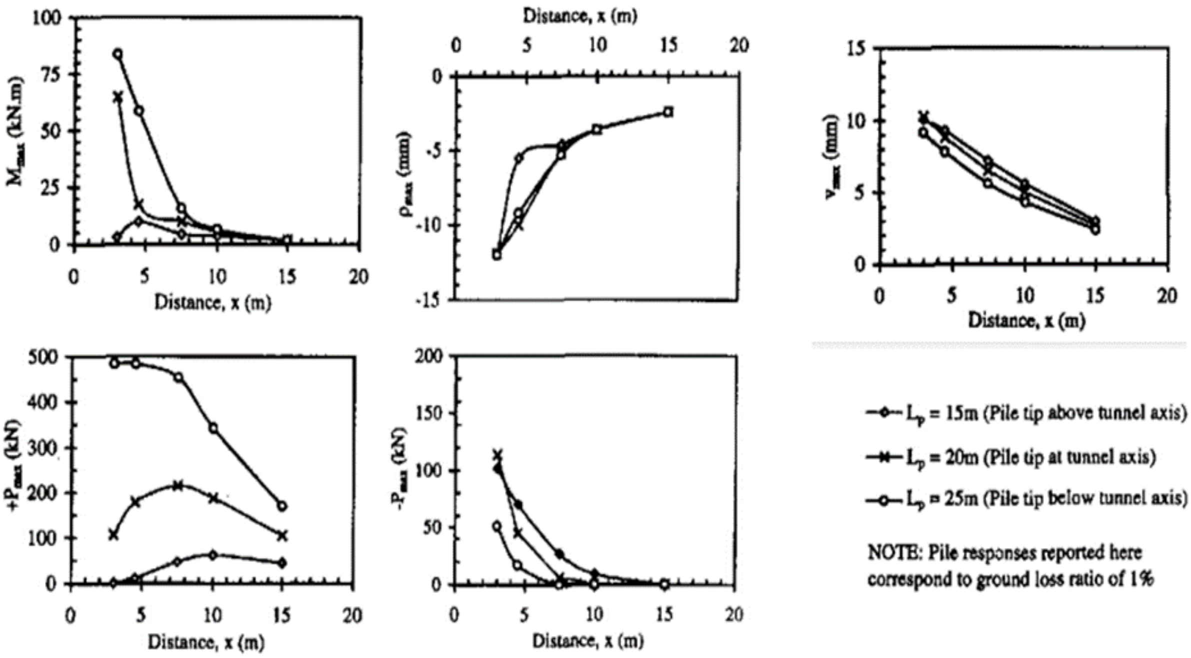

Fig. 14: Pile responses changing the pile length [45].

A study by N. Loganathan , H.G.Poulos , and K.J.Xu [47] presents an analytical method to detect the pile responses, by estimating the displacement imposed on a single pile and group of piles by tunneling.

The study shows that tunneling will induce axial down-drag force for a single pile 20 percent greater than a pile in a group of piles. In addition, when the pile end is located at around the tunnel depth level, a large lateral deformation and pile settlement is induced. Correspondingly, when the pile edge is located at the tunnel invert level, a significant down drag and bending moment occurs.

It should be noted that the analytical methods have some limitations. A study made by K.J. Xu, H.G. Pouls [48] called 3-D elastic analysis of vertical piles subjected to “passive” loadings showed that any new analytical approach requires a number of assumptions regarding the pile and the soil.

Alec M Marshall and Twana Kamal Haji [49] proposed an analytical approach to evaluate the effect of constructing a new tunnel near an existing pile, where Cavity Expansion Methods analysis was used to determine the changes in end-bearing capacity of the pile while taking into account the effect of tunnel location on Pile-tunnel interaction.

In the sake of understanding the tunnel location effect on the pile-tunnel interaction, three cases are illustrated in Fig.15 to calculate the bearing-capacity reduction factor R_{q_b}. In case one, the tunnel-pile tip horizontal location (d_{tp}) is increased while maintaining the tunnel depth value z_t fixed. In case number 2, the tunnels depth increased while the pile tip location remained fixed.In Case 3, increasing the tunnel depth and pile tip while maintaining the Tunnel-pile tip distance.

The tunnel and pile radius are rt =3 m and rp =0.5 m, respectively, while the soil parameter was determined using the method by the Alec M Marshall [50,51].

Equation 4 identified the bearing-capacity reduction factor R_{q_b} by Alec M Marshall [50]:

$R_{q_b} = \frac{q_{b,v_1}}{q_{b,0}}$ (4)

q_b : End-bearing capacity of pile

q_{b,v_1} : Reduced end-bearing capacity of pile after tunnel vol-ume loss

$q_{b,0}$: End-bearing capacity of pile before tunnel volume loss

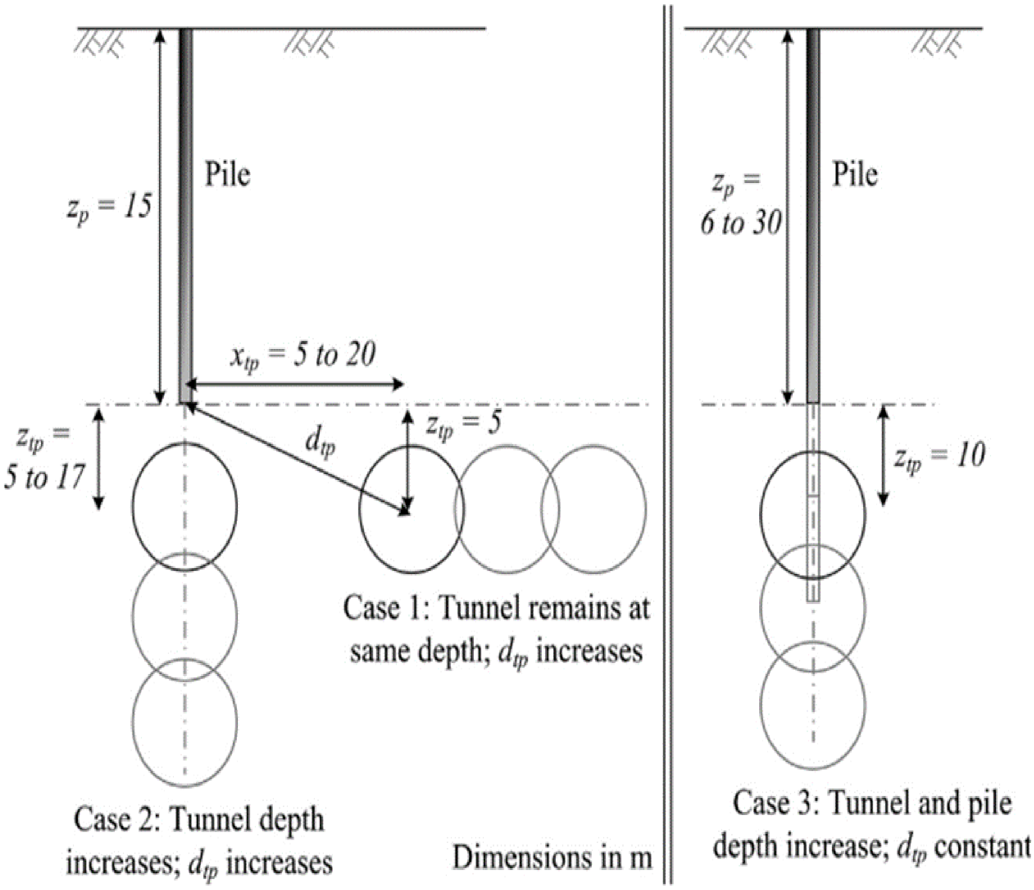

Fig.15: Cases considered in evaluating the effect of tunnel and pile depth [49].

It is worth noting that when the reduction factor R_{q_b} equals 1, it means that changing the tunnel location had no effect on the pile bearing capacity, whereas a lower value of R_{q_b} indicates that the pile bearing capacity was reduced.

Fig.16 shows the R_{q_b} values for the considered cases, with case one having a lower R_{q_b} value than case two, and there is also a clear positive effect of increasing the tunnel depth, whereas cases 2 and 3 have a higher R_{q_b} value when increasing the tunnel depth.

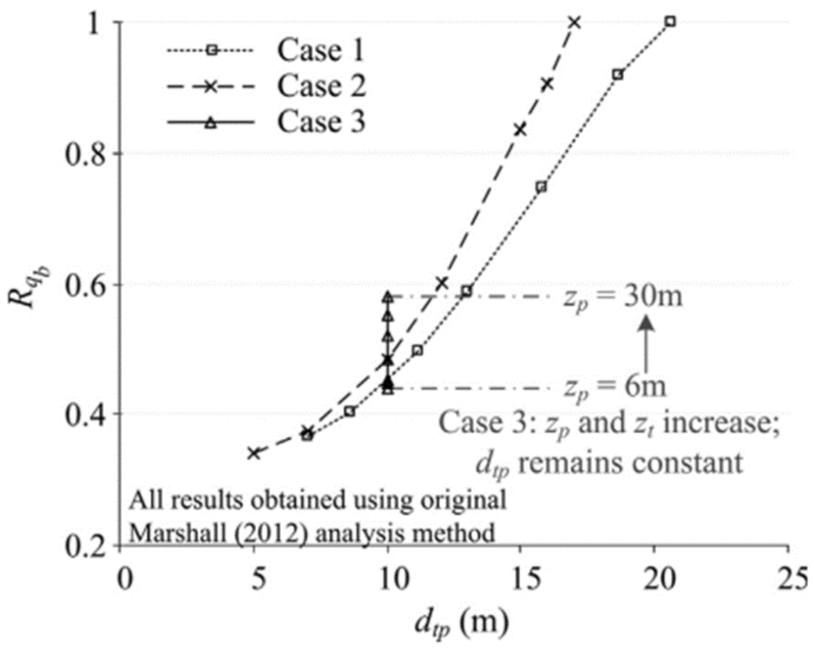

Fig.16: Results of analysis of the considered cases [49].

4. Empirical modeling

Centrifuge modeling is mainly used in practice to check the pile responses. Jacobsz S.W., Standing J.R., Mair R.J., Soga K., Hagiwara T. [52] examined the influence of pile by tunnel construction through centrifuge modeling. The study explained the tunnel location effect regarding the piles, and a driven pile in the sand was discussed. Based on the test results achieved by Jacobsz S.W., Standing J.R., Mair R.J., Soga K., Hagiwara T. [52] Fig. 17 (a) shows the test done first, in which the pile tip is located near to and above the tunnel crown. In this case, the pile responds with an increase in the volume loss whilst the baseload reduces. To maintain stability and equilibrium a small amount of settlement of the pile occurs alongside increasing shaft friction. It should not be left unmentioned that when all the pile friction is mobilized, the pile will reach failure.

On the other hand, when the tunnel is both located at some distance to the side of the pile tip and the pile tip is below the affected zone of the ground movement, as shown in Fig. 17 (b), the baseload increases alongside the increase in the volume loss, unlike in the first case, where inducing a lowering of the positive skin friction leads to generating a small amount of pile settlement.

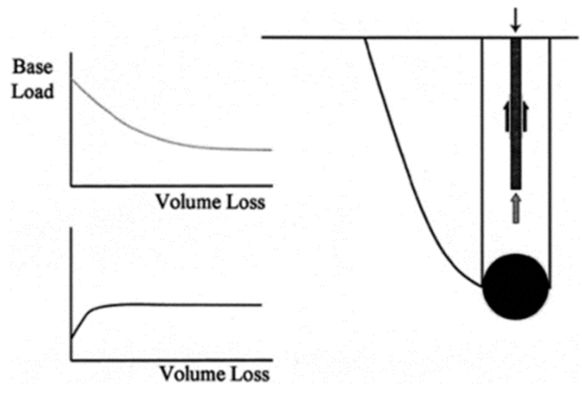

Fig. 17: (a) Mechanisms of pile load distribution changes for pile close to the tunnel.[52].

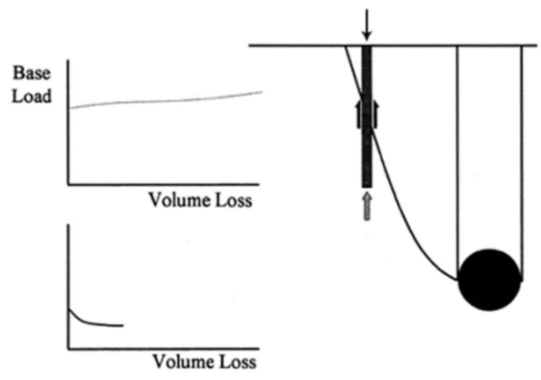

Fig. 17: (b) Mechanisms of pile load distribution changes for pile close to the tunnel [52].

Furthermore, a number of centrifuge model tests were carried out in saturated sandy ground to evaluate tunneling-caused ground deformations and their influence on surrounding single piles by Chiang, Chung-Jung Lee and Kuo-Hui [1]. Based on the study, in which the pile is located above the tunnel axis by 1.5D (where D is the tunnel diameter), the skin friction decreases incredibly quickly alongside an increase in ground loss, causing more load to be transferred to the pile and eventually causing pile settlement, especially when the distance ratio (x/R) is less than 1.5.

Only the depth ratio was found to have a massive impact on the distributions of the bending moments along the piles. Shallow tunneling near a long pile generates bending moments - either negative or positive, whilst deeper tunneling generates significant negative bending moments. For deep tunneling near a pile, a pile settlement grows significantly resulting in the loss of a significant amount of end bearing resistance due to ground loss [1].

Morton J D, King KH [53] conducted a laboratory investigation to initiate research on the effects of tunnel construction on nearby pile foundations. And since, the number of researchers performing such research has risen. Several centrifuge model experiments have been conducted by a number of scientists such as H. J. A. M. Hergarden J. T. vanderPoel J. S. vanderSchrier [54] , N. Loganathan, H. G. Poulos, and D. P. Stewart [55], Jacobsz S W, Standing J R, Mair R J, Soga K, Hagiwara T, Sugiyama T [56] , and Ong C W, Leung C F, Chow Y K [57] . It has been confirmed that piles may be subjected to substantial vertical and lateral forces as a result of nearby tunnel excavations.

When it comes to having different tunnel geometry and different ground conditions, such as a different soil type or special groundwater conditions, or even changing in-situ stress conditions, the empirical method has a limitation. However, these limitations are overcome by other methods, such as numerical methods [29].

5. Field trials

An investigation done by Standing Standing, D. Selemetas J. R. [58] reported field measurements of the influence of tunneling underneath the piles for the CTRL project in London. The tunnels were twin bored applying Earth Pressure Balance (EPB) machines with an 8.15 m OD (Dt) from center to center and 18.9 m depth to tunnel axis (zt). Four piles of 480 mm diameter were built, two of which were friction piles and two of which were end-bearing piles. All piles were built by embedding a steel tube into the ground, excavating the soil inside, filling the hole with concrete, extracting the tube, and inserting the reinforcing cage. The piles were loaded to 50% of their ultimate design capacity and held in place with hydraulic jacks attached to the kentledge reaction platform. Due to the low volume losses (0.2 percent and 0.5 percent for the first and second tunnels, respectively), the reported pile settlements were quite small (a few millimeters). Fig. 18 summarizes the results of the field trial. In conclusion, as shown in Fig. 18,

- Piles with bases in zone A settled 2–4 mm higher than the ground surface (R > 1).
- Piles located in zone B (defined by a 45° inclined line connecting zones A and C) settled by equal amount as the surface (R = 1).
- Piles with their bases in zone C settled less than the surface (R < 1).

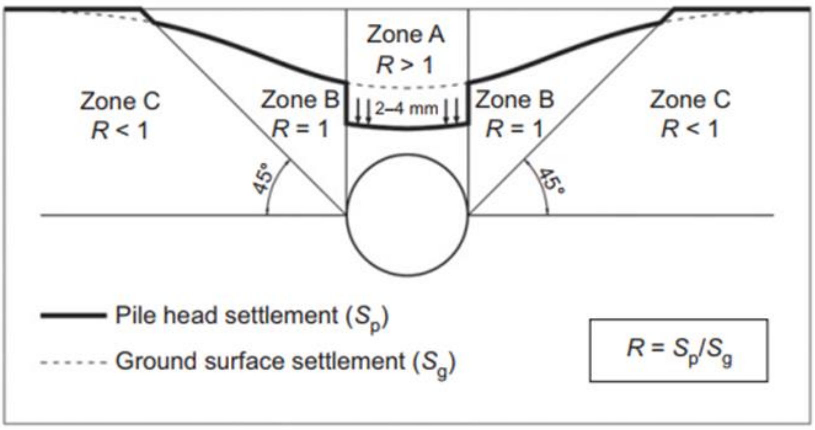

Fig. 18: Zones of influence surrounding an EPBM demonstrating pile settlement in relation to ground surface settlement [58].

A similar study done by Kaalberg, F.J., Teunissen, E.A., van Toi, A.F., & Bosch,J.W. [59] used the Second Heinenoord tunnel for comprehensive field tests. The field trials were carried out in strata comprised of a 4 m layer of soft clay covered by fine sand. The twin tunnels were 8.3 m OD with a 16.3 m center to center spacing and were built with a slurry tunnel boring machine. The height of the cover above the tunnel ranged between 12 and 13 meters.

The piles were driven within pre-installed 2 m diameter clay columns to simulate the 10–13 m of soft clay in Amsterdam. 130 mm timber and 250–350 mm concrete square piles, either single piles, two piles, or a group of piles, were driven from the tunnels (each of diameter Dt) in different spots between 0.25Dt and 2.5Dt. The piles were loaded to provide safety factors of 1.5 and 2.0 for timber and concrete piles, respectively.

The analysis results revealed significant stress-relieving movements only at pile toe distances of 0.25Dt from the tunnel extrados. Fig. 19 illustrates the effect of pile toe location on induced settlement, with the following results:

- Piles with toes founded in zone A experience pile toe movement that is equal to or slightly greater than the surface-level settlement at a corresponding location.
- Piles with toes founded in zone B movement that is roughly equal to the surface-level settlement.
- The pile movement is noticeably smaller than the corresponding ground level settlement in relation to the deformation of the piles founded in Zone C.

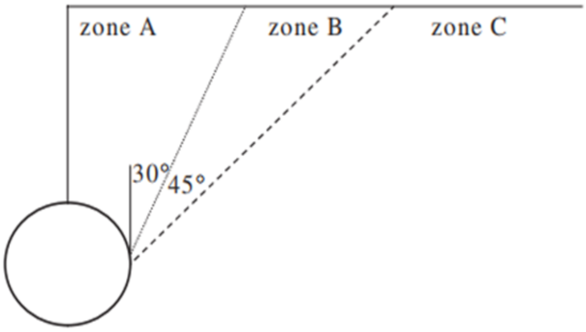

Fig.19: The influence of pile toe locations on studied pile settlements in the second Heinenoord tunnel field tests [59].

6. Case histories

Jacobsz, S.W., Bowers, K.H., Moss, N.A., & Zanardo, G. [60] aaddressed three case studies involving tunneling underneath the piled foundations. Fig.20 shows twin 8.2 m OD tunnels built for the UK Channel Tunnel Rail Link (CTRL) underneath the driven piles that support Renwick Road Bridge. The piles are driven through peats and soft alluvium and serve as end-bearing piles supported by a gravel layer. The tunnels were built with Earth Pressure Balance (EPB) tunneling machines in London Clay near the stratum's top, with the clear distance of the tunnel crowns beneath the pile toes being around 3 m. The observed volume loss for each tunnel was approximately 1%. The recorded settlement of the bridge was very close to the predicted Greenfield settlement at the pile toes.

Fig.21 shows the twin 8.2 m OD CTRL tunnels built extremely close underneath the toes of both driven and bored piles in London Clay that support the Ripple Road Flyover. The nearest pile toe to the tunnel crown is just 1 m above the tunnel crown. The piles are classified as friction piles, with just a minor end-bearing component. The Terrace Gravels underneath the pile caps were grouted as a safety measure. Both tunnels were built with measured volume losses of less than 1%. The recorded pile settlements were 8 mm above the Upline tunnel and 10 mm below the Downline tunnel; these are quite similar to the ground surface settlements at the pile cap locations. Fig.22 shows the behavior of the A406 viaduct supported by friction piles designed and built as bored piles primarily in very stiff to hard clays.

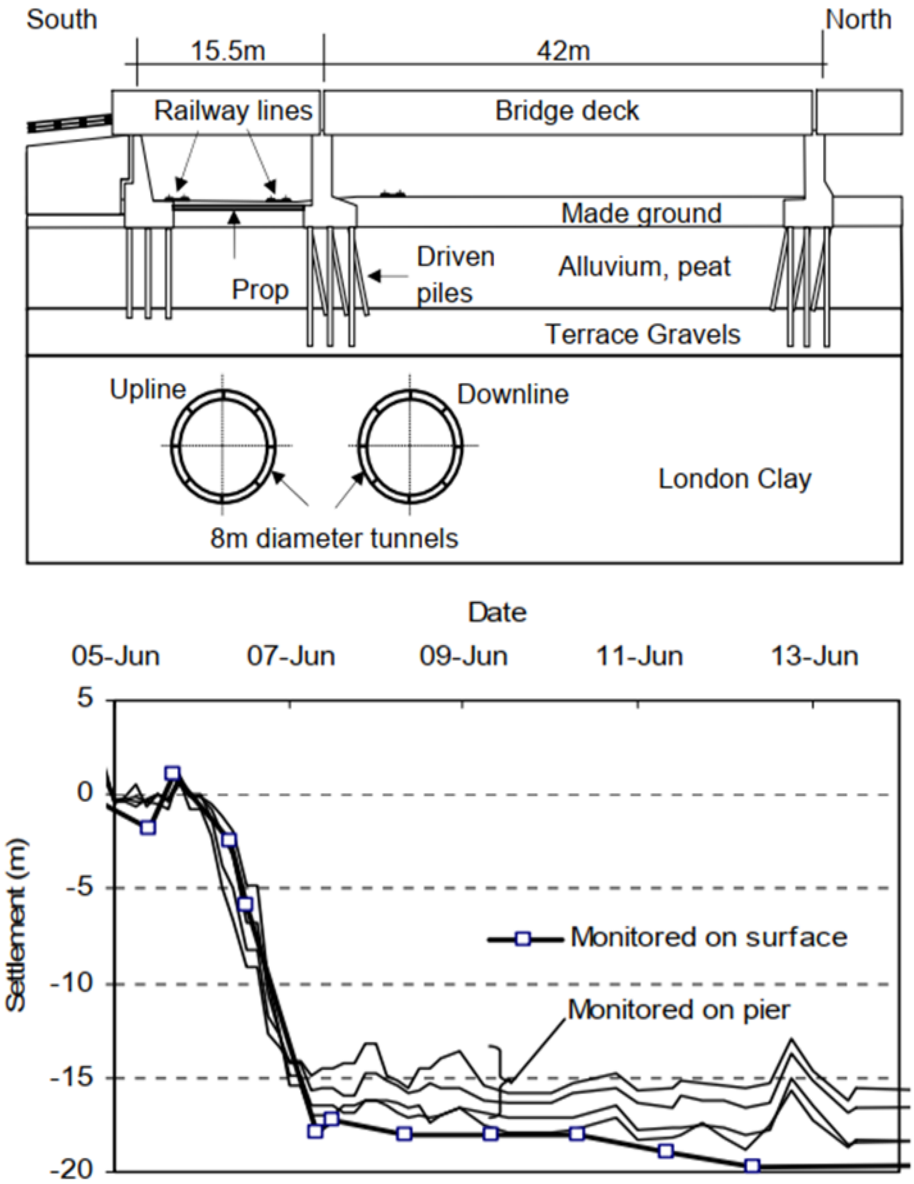

Fig. 20: Tunnelling for CTRL beneath end-bearing piles at Renwick Road Bridge [60].

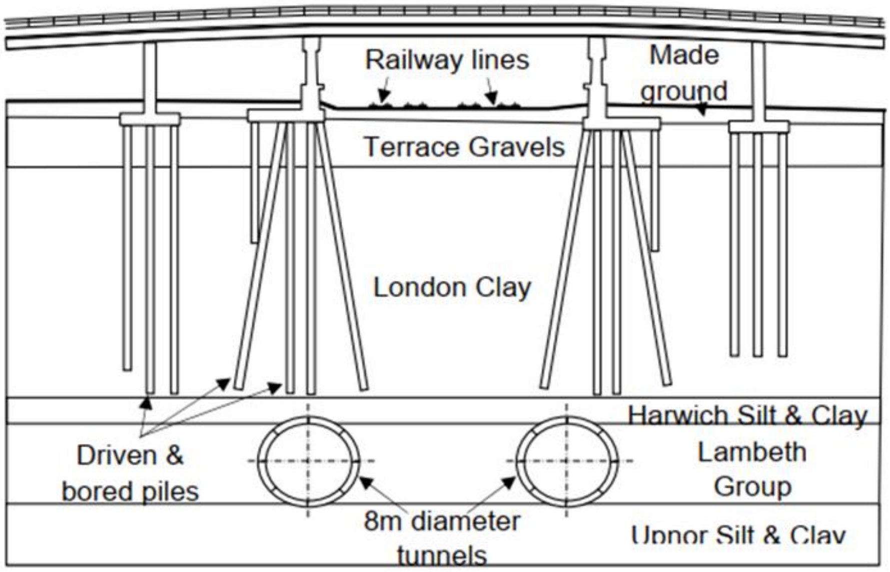

Fig. 21: Tunneling for CTRL beneath friction piles at piles at Ripple Road Flyover [60].

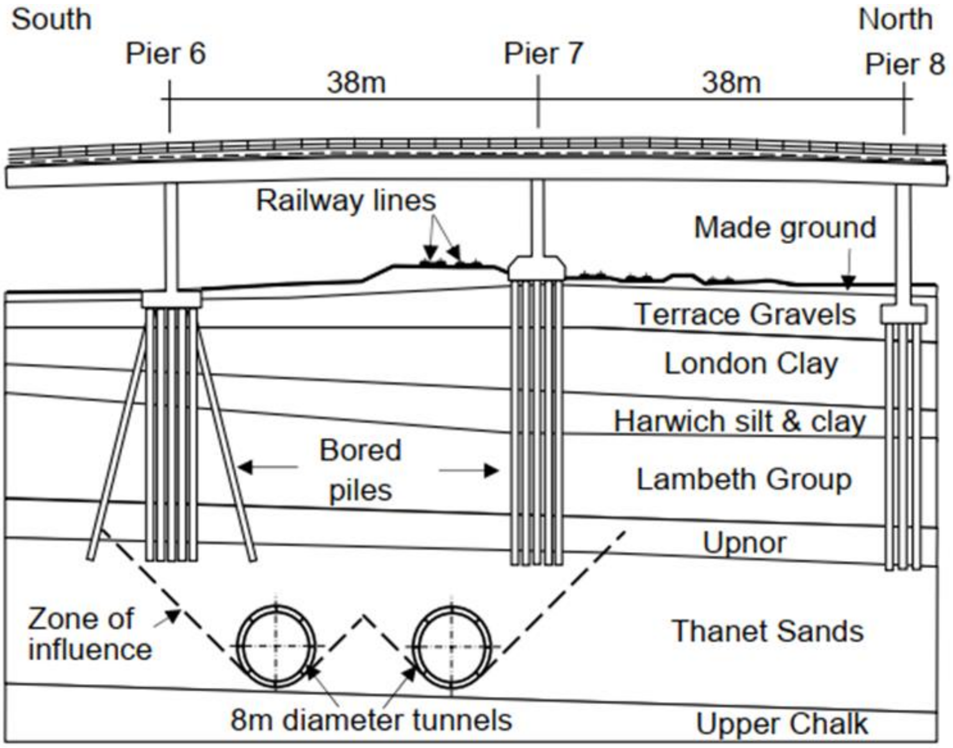

Fig. 22: Tunneling for CTRL beneath friction at A406 viaduct [60].

Conclusion

1) Tunnel construction near a pile-supported structure will cause horizontal and vertical soil movement, which will result in pile responses such as axial movement, lateral deflection, bending moment, and pile settlement.
2) When analyzing the tunnel effect on the surrounding soil, three soil models can be used: the Mohr-Coulomb (MC) model, the Hardening Soil (HS) model, and the Hardening Soil with small strain (HS-Small), with the HS-Small model being the most realistic.
3) For the applications of numerical modeling, changing the tunnel's horizontal and vertical location relative to the pile will result in the pile's responses changing as follows:

a) As the Tunnel-pile horizontal clear distance (△fp & △tp) increases, the pile responses (lateral and longitudinal pile deflection, axial forces, and bending moment) decrease gradually and approach zero at certain points.
b) Changing the Tunnel-pile vertical location (itp) will have an effect on the pile responses, with the responses being greater and approaching the maximum values when the pile tip is located below the tunnel horizontal axis.
c) When using a group of piles instead of a single pile, a positive effect of reducing pile responses will occur, and this effect will be more noticeable on the rear piles.
d) When the tunnel is beneath the pile, increasing the vertical distance reduces the pile settlement value (S_p/D) and pile tip load (Q_p).
e) Reducing the horizontal clear distance between the tunnel and the piles when the tunnel is beneath the pile

will lead to increasing the pile settlement value (Sp/D). A significant increase in pile tip (Q_p) will occur, particularly when the pile tip is below the tunnel crown.

4) For the applications of the analytical method, changing the horizontal and vertical location of the tunnel relative to the pile will result in the pile's responses changing as follows:
a) The maximum lateral and vertical soil movement will occur above the tunnel's horizontal axis.
b) As the lateral distance from the tunnel horizontal centerline (x) is reduced, the lateral soil movement increases.
c) As the lateral distance from the tunnel horizontal centerline (x) increases, the vertical soil movement decreases.
d) As the lateral distance from the tunnel horizontal centerline (x) increases, the pile responses (Mp, ρp , ʋp –Pp) decrease.
e) As the vertical clear distance between the pile tip and the tunnel horizontal axis increases, the bending moment gradually increases.

5) For the applications of the empirical modeling, changing the horizontal and vertical location of the tunnel relative to the pile will result in the pile responses changing as follows:
a) When the pile tip is above and near the tunnel crown level, the baseload will decrease with an increase of the volume loss with a small amount of settlement and an increase of the pile friction.
b) When the pile tip is located at some distance to the side of the tunnel, the baseload will increase with an increase of the volume loss and lowering of the pile friction.

6) From the field trials:
a) Piles with toes founded in zone A experience pile toe movement that is equal to or slightly greater than the surface-level settlement at a corresponding location.
b) Piles with toes founded in zone B movement that is roughly equal to the surface-level settlement.
c) The pile movement is noticeably smaller than the corresponding ground level settlement in relation to the deformation of the piles found in Zone C.

7) Most of the limitations in the analytical and empirical methods may be overcome by numerical methods.

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