Influence of existing nearby tunnel on Frictional resistance of single pile capacity in cohesionless soil

Influence de l'existant à proximité du tunnel sur la résistance de frottement de la capacité du pieu isolé dans un sol pulvérulent

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ABSTRACT: Installation of pile near an existing underground tunnel or buried pipe system is common in urban development. It is a unique problem of soil-structure interaction as well as interaction between existing tunnel or buried pipe and pile system. Estimation of reduction in pile capacity due to existing nearby tunnel or buried pipe system or ensuring a safe distance of pile from the existing buried pipe system (or tunnel) without compromising with the capacity of pile is an important aspect in the pile foundation analysis and design. In the present study, effect on frictional resistance of single pile installed in cohesionless soil due to existence of buried pile system is studied, numerically, using commercially available finite element tool PLAXIS-2D. Parametric study is performed by considering the diameter of tunnel or buried pipe as 5.0 m with lining as plate element (EA = 1.40×10^7 kN/m, EI = 1.43×10^5 kN-m^2/m) and varying the range of input parameters, such as, unit weight (17.0 – 18.5 kN/m^3), Angle of internal friction (25°-40°), Diameter of pile (0.5m – 2.0 m), ratio of Elastic modulus of pile material to the soil (500-2000). Based on the results of the numerical analysis, in terms of load-settlement curves, and their careful study, analytical solution is proposed to estimate the reduction in the frictional capacity of a single pile to be installed in cohesionless soil. Design charts are prepared to directly read the reduction in the friction capacity of the pile based on different design parameters, such as, tunnel or buried pipe diameter, length and diameter of pile, geotechnical properties of sand, relative stiffness of pile material with respect to the surrounding soil within zone of influence.

RÉSUMÉ Installation du pieu près d'un tunnel souterrain existant ou un système de tuyaux enfouis est commune dans le développement urbain. C'est un problème unique d'interaction sol-structure ainsi que l'interaction entre le tunnel existant ou système de tuyau et tas enfoui. Estimation de la réduction de capacité de la pile en raison existant à proximité de tunnel ou un système de tuyaux enfouis ou assurer une distance sécuritaire de la pile du système existant de tuyaux enfouis (ou tunnel) sans compromettre la capacité de la pile est un aspect important dans la conception et l'analyse de la Fondation de pile. Dans la présente étude, effet sur la résistance de frottement du pieu isolé, installé dans un sol pulvérulent en raison de l'existence du système pieu enterré est étudiée, numériquement, à l'aide d'outil disponible dans le commerce par éléments finis PLAXIS-2D. Étude paramétrique est effectué en considérant le diamètre du tunnel ou de tuyaux enfouis comme 5,0 m avec doublure en tant qu'élément de la plaque (EA = 1,40 × 107 kN/m, EI = 1,43 × 105 kN-m^2/m) et en variant l'éventail des paramètres d'entrée, par exemple, le poids unitaire(17,0 – 18,5 kN/m^3), Angle de frottement interne (25°-40°), diamètre du pieu (0,5 m-2,0 m), rapport du module d'élasticité du matériau de pieu dans le sol (500-2000). Solution analytique basée sur les résultats de l'analyse numérique, en termes de courbes de charge-tassement et leur étude attentive, est proposée pour estimer la réduction de la capacité de frottement d'un pieu isolé doit être installé dans un sol pulvérulent. Abaques de calcul sont prêts à lire directement la réduction de la capacité de friction de la halde issue des différents paramètres de conception, tels que, souterrains, ou enterré des tuyaux de diamètre, longueur et diamètre du pieu, propriétés géotechniques de sable, relative rigidité du matériau de la pile en ce qui concerne le sol environnant au sein de la zone d'influence.

KEYWORDS: buried pipe, pile capacity, numerical, analytical, geotechnical, cohesionless soil.

1 INTRODUCTION

Urban development involves the construction of high rise buildings which require deep foundations at the one end and underground conduits or pipes for supply of water, electricity, sewage or other life lines on the other hand. Therefore, there is co-existence of both deep foundations and buried conduits or tunnels. Under such circumstances, it is possible that a pile foundation designed for a structure may exist near the pre-existing underground tunnel or conduit. Hence, it is necessary to understand how the pile- tunnel interaction affects the pile capacity which in turn affects the safety of pile supported structures. In the past, tunnel-pile-soil interaction has been analyzed numerically, analytically and numerically. A lot of literature is available to address the issue of pile capacity and settlement due to construction of new tunnel. In addition to that literatures are also available on understanding of tunnel behavior due to existing deep foundation system.

Chen et al (1999) used two stage approaches to analyze lateral and axial response of piles caused by tunneling. In the first stage, soil movements are estimated and in second stage pile response due to this soil movement is calculated by boundary element analysis. Poulos and Deng (2004) derived an analytical method using cavity expansion theory to calculate the loss in pile capacity due to tunneling and verified their results with finite element method. In the study, it is suggested that the factors which can affect the capacity of existing pile due to tunneling would be distance between pile and tunnel, volume loss, tunnel diameter and pile diameter and the analytical solution proposed can be used to suggest the safe distance of new tunnel from the existing pile foundation system. Although, it should be noted that it is always not possible to maintain a safe distance between a tunnel and foundation system due to space constrain. Francesco Basile (2014) presented method to estimate the effects induced by tunneling on existing pile foundations through numerical analysis and verified experimentally. Although, the method suggested is useful in estimating the pile response to soil movement caused by tunneling and moments induced in pile group, discussion on pile capacity due to tunneling is not presented. Marshall (2012) used an analytical method to evaluate the effects of tunnel construction on the load carrying capacity of end bearing piles. The analytical results were compared with centrifuge test data. The effects of soil properties on the end bearing piles have been calculated. Marshall and Haji (2015) extended this work by changing distance between pile and tunnel. They calculated the effect of tunneling on pile shaft friction also but load – settlement relation before failure has not been studied.

Jacobsz.et.al (2004) carried out the centrifuge model study to investigate the effects of tunneling near piles in dense dry sand. They have recorded data showing surface settlement during tunneling as well as settlement of piles due to tunnels at various distances from it. They also identified a zone around the tunnel where there is possibility of large settlement. Lee and Chiang (2007) studied the responses of single pile under varying loads using centrifuge model tests. They have studied, experimentally, the effects of the tunneling-induced ground deformations on neighboring single piles in saturated sandy ground.

Several researchers have developed numerical methods for evaluating the effects of tunneling on adjacent existing piles. Loganathan et al (2001) developed an analytical solution to estimate the displacement field around tunnel. Using boundary element analysis, they calculated pile response due to tunneling induced displacement and verified the results with numerical results obtained from FLAC software. Soomro et al (2015) used finite element analysis to investigate the effects of tunnel on a 2×2 pile group at different cover to tunnel diameter ratio in stiff saturated clay. The results are also compared with available field data. The reduction in pile capacity for the case of C/D = 1.5, 2.5 and 3.5 are observed to be 14%, 23% and 23%, respectively. Meguid and Mattar (2009) studied the tunnel behavior due to existing pile foundation experimentally in cohesive soil. Lining stresses introduced in tunnel due to existing pile at different distances from it has been studied and it has been seen that stresses are maximum when pile exist at a distance of one tunnel diameter from the tunnel. Lau (2014) presented ground and pile instrumentation data from a full-scale field trial at Dagenham, United Kingdom as part of the Channel Tunnel Rail Link. He collected the data of pile axial load distribution with the known relative pile-soil displacements. Observations on the ground and pile responses to tunneling and zones of influence are also presented.

Literature review suggests that extensive work is done on the pile-tunnel interaction where the response of pile foundation system was studied due to tunneling process. The present study considers the problem in which the pile is installed in the vicinity of the existing tunnel that falls within zone of influence of the stress distribution of pile. The objective of the present study is to propose an analytical method for estimating the % reduction in the pile capacity due to existing nearby tunnel and produce design charts with the help of data obtained from numerical analysis. For the purpose of numerical analysis of the problem, commercially available finite element numerical tool PLAXIS 2D utilized.

2 PROBLEM DEFINITION

Fig 1 shows the problem considered, which indicates the existence of a circualr tunnel in the vicinity of the single pile shaft in a 2-dimensional space occupied by uniformaly distributed cohesionless soil. L_p and D_p indicates the lenght and diameter of the pile, respectively. D_t is the diameter of the tunnel or buried pipe system and L is the distance between center of the tunnel to the center line of the pile shaft. Assuming, pile to be a friction pile, the pile resistance offered is contributed by the surrounding soil within the zone of influence, indicated by distance x from the perimeter of the pile (X is the same distance measured from the center of the pile shaft. The problem is analyzed numrically using finite element tool to investigate the infleunce of existence of buried pipe or tunnel on the pipe capacity, if it exists within the zone of influnce. It's a complex soil –structure interation problem and a simplified analytical solution is proposed to estimate the reduction in pile capacity based on the input design parameters.

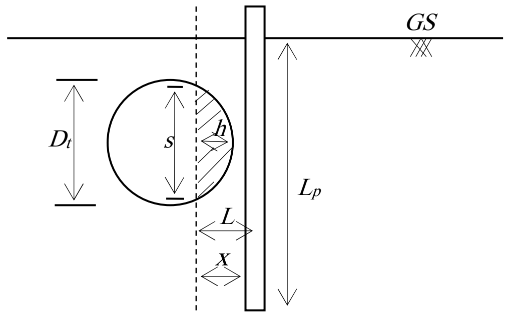

Figure 1. Single friction pile in the vicinity of buried pipe or tunnel

3. PROPOSED ANALYTICAL SOLUTION

If the existing tunnel or buried pile is within the zone of infleunce, it will be intercepted and the same is indicated by shaded portion. Area of the shaded portion of the circular tunnel (A_o) can be calculated as:

Area of segment (A_o)

$$A_o = \frac{2}{3}sh + \frac{h^2}{2s} \quad (1)$$

Where,

Height of the segment (h) is obtained as

$$h = \left(\frac{D_t}{2}\right) - (L - X) \quad (2)$$

Length of the chord (s)

$$s = 2\sqrt{(D_t h) - h^2} \quad (3)$$

Area of Zone of infleunce of the pile-soil interaction while offering frictional resistance to the applied load

$$A = L_p \times x \quad (4)$$

If it is assumed that the pile capacity is reduced in the same proportion as the amount of redution in the zone of infeunce of the pile-soil due to existing tunnel, the % reduction in the pile capacity can be simply calculated as

Reduction in the pile capacity =

$$\frac{A_o}{A} \text{ in } \% \quad (5)$$

It should be noted that estimation of % reduction in the friction pile capacity requires the following input parameters, i.e., length and diameter of the pile, Diameter of the underground conduit or tunnel, as well as estimation of zone of infleunce *x* from the pile parameter. The zone of infleunce (*x*) depends on the complex soil – structure interaction between pile shaft and the surrounding soil and it will depend on the relative stiffness of the pile material and surrounding soil, pile diameter and geotechnical properties of the surrounding soil as well.

For the estimation of zone of infleuence and corresponding reduction in the pile capacity due to existing buried pipe or tunnel system is estimated through numerical analysis using commercially available finite element tool PLAXIS-2D. Further to this, Design charts are prepared to directly estimate the zone of infleunce (*x*) for the input parameters, such as, angle of internal friciton of the soil (ϕ), relative stiffness (E_c/E_s), [Ec is the modulus of elasticity of the pipe material and Es is the modulus of elasticity of the soil within zone of infleunce] and % reduction in the pile capacity through proposed analytical approach is compared with the corresponding results obtained from the numerical analysis.

3 NUMERICAL ANALYSIS

PLAXIS 2D is a commercially available finite element tool dedicated to solve geotechnical engineering problems with complex geometry, boundary conditions, both under static as well as dynamic loading conditions. A detailed discussion can be obtained in the reference or scientific manual of the software. In the present study, the geometry of the problem is first created using geometric line and tunnel elements available as an inbuilt option. The tunnel lining is created using plate element. The input properties for surrounding cohesionless soil as well as tunnel and plate elements that are used for the analysis are provided in the following tables.

Table 1. Soil parameters assumed in the numerical analysis

Description	Parameters
Material model	Mohr-Coulomb
Material behavior	Drained
Unsaturated unit weight	17 – 18.5 KN/m^3
Saturated unit weight	20KN/m^3
Poisson's ratio (μ)	0.35
Coefficient of permeability (k)	1.0 m/day
Effective cohesion (c)	0.1KN/m^2
Effective angle of friction (ϕ)	25^0 - 40^0

Table 2. Input parameters for pile material

Description	Parameters
Material model	Linear elastic
Material behavior	Undrained
Unit weight	24KN/m^3
Characteristic Compressive Strength	30MPa
Ec (Elastic Modulus of concrete)	31220.18MPa

Table 3. Tunnel lining parameter

Description	Parameters
Material type	Elastic
EA (Axial Stiffness)	1.4X10^7
EI (Flexure Stiffness)	1.43X10^5

As the problem in analyzd in 2-dimension as plain strain problem, it is judged that the estimated % reduction in the pile capacity will be on the safer side. This is due to the fact that the actual reduction in the zone of infleunce due to existing tunnel in a three dimensional space will be lower than the corresponding value obtained for the problem analyzed in two dimensional space where the pile is modeled as plate element and it is running parallel to the tunnel. For the finite element discretization of the problem domain, 15 noded triangular elements are used for better accuracy. The discretization of the 2-dimensional space is done internally by the software and boundary and initial conditions are set with no effect of GWT. After providing the required input parameters for soil, pile shaft and tunneling, the analysis was performed in two stages: (i) without underground conduit or tunnel (ii) with underground conduit or tunnel. Load settlement curve for both the cases were obtained and results were analyzed for estimating the % reduction in the pile capacity due to existence of undeground conduit or tunnel in the vicinity of the pile shaft. A parametric study was performed by varying the range of input parameters, such as, unit weight (17.0 – 18.5 kN/m^3), Angle of internal friction (25°-40°), Diameter of pile (0.5m – 2.0 m), ratio of Elastic modulus of pile material to the soil (500-2000).

4. RESULTS AND DISCUSSION

Fig 2 shows typical result obtained for the parameters indicated in the figure itself.

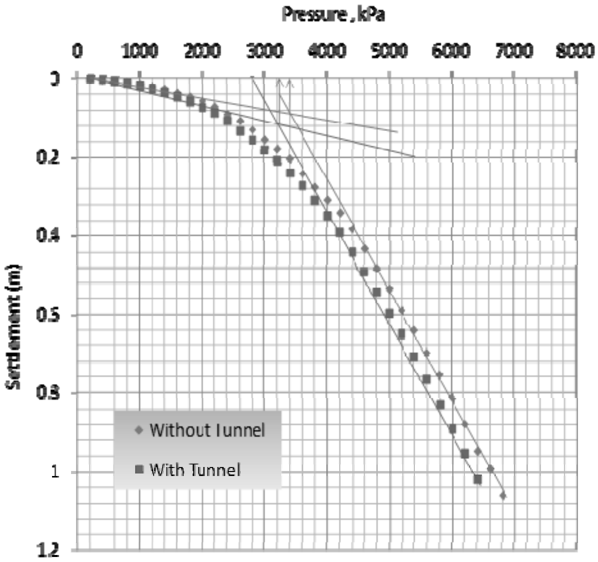

Figure 2. Load-settlement curve from finite element analysis (Diameter of pile = 0.5m, ϕ = 25^0, E_c/E_{soil} = 500)

Similar results were obtained for other cases and % reduction in the pile capacity was estimated numerically that are typically presented in the following table 4.

Table 4a. % reduction in pile capacity (ϕ = 25°)

E_c/E_{soil} (↓)	Diameter of pile (m) → 0.5	1.0	1.5	2.0
500	4.70	6.10	8.59	11.11
1000	7.14	9.57	12.0	13.67
1500	10.42	11.76	13.93	15.29
2000	14.16	16.67	18.33	20.39

Table 4b. % reduction in pile capacity (ϕ = 30°)

E_c/E_{soil} (↓)	Diameter of pile (m) → 0.5	1.0	1.5	2.0
500	2.98	4.95	7.51	9.90
1000	5.05	6.90	10.05	12.27
1500	7.81	9.56	11.95	13.75
2000	11.38	13.66	15.55	17.25

It can be noted that the reduction in the pile capacity ranges from 5% to 20% and it follows a certain trend. With increase in the diameter of the pile, the % reduction in the pile capacity increases and it may be due to increase in the zone of infleunce with increases in the pile diameter. More area is inctercpted of zone of infleunce is intercepted by the existing underground conduit or tunnel. Also, with increase in the E_c/E_s ratio, there is an increase in the % reduction in the pile capacity. As E_c/E_s ratio increases, the stiffness of the surrounding soil is relatively decreasing with respect to the stiffness of the pile material. FEM analysis shows that the zone of infleunce increases with increase in the E_c/E_s ratio and this results in higher reduction in the pile capacity as more area get intercepted by the existing underground conduit or tunnel. It should ne noted that the FEM analysis is a time consuming and constly process and it can not be afforded when someone has to made a prilimary estimate of the reduction in the pile capacity due to existing underground conduit or tunnel falling within the zone of infleunce. Hence, simplified analytical approach is presented to estimate the % reduction in the pile capacity with the help of equaiton (1) to (5). The calculation requires determination of zone of infleunce for which the following design charts are developed based on the results of the finite element analysis. The value of x is estimated from the contour diagram obtained from the numerical analysis. A typical result is presented in the following figure for reading the value of x.

Based on the values of x recorded from the FEM analysis, following design charts (Table 3) are presented for directly reading the values of x and computing the % reduction in the pile capacity through analytical approach.

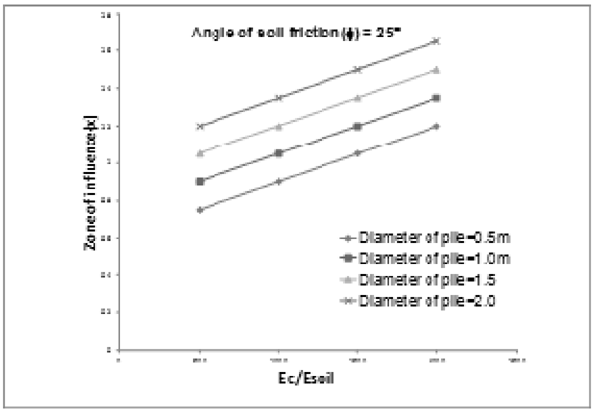

Figure 3a. Zone of infleunce (x) for friction angle $\phi = 25°$

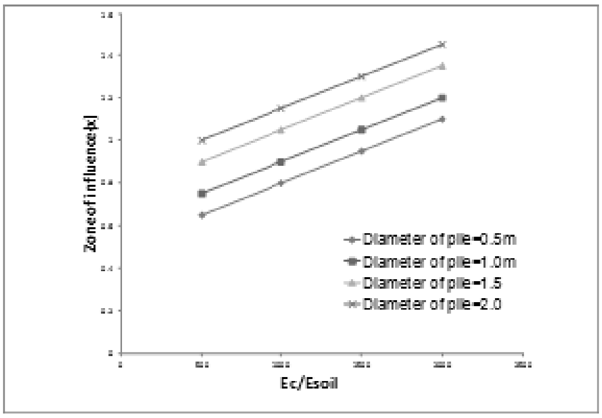

Figure 3a. Zone of infleunce (x) for friction angle $\phi = 30°$

It can be noted that the estimation of zone of infleunce requires the information on pile diameter and relative stiffness of the pile material and the surrounding soil. Estimation of reduction of pile capacity required other informations, such as, pile length, tunnel diameter. Hence, the proposed analytical approach provides a compresensive yet simplified approach to estimate the % reduction in the frictional resistance of the pile due to existing neaby underground conduit or tunnel. The following table 5 provides data on the estimated % reduction in the pile capacity through analytical approach.

Table 5a. % reduction in pile capacity ($\phi = 25°$)

E_c/E_{soil} (↓)	Diameter of pile (m) → 0.5	1.0	1.5	2.0
500	5.03	8.36	11.38	14.08
1000	8.36	11.38	14.08	16.48
1500	11.38	14.08	16.48	18.61
2000	14.08	16.48	18.61	20.56

Table 5b. % reduction in pile capacity ($\phi = 30°$)

E_c/E_{soil} (↓)	Diameter of pile (m) → 0.5	1.0	1.5	2.0
500	3.88	5.03	8.37	10.42
1000	7.28	8.37	11.39	13.22
1500	10.42	11.38	14.08	15.71
2000	13.22	14.08	16.48	17.93

It can be noted that the results presented in table 5 are quite comparable with the corresponding results obtained from the numerical analysis. Similar results are obtained for other two angle of internal friciton of the soil, i.e., $\phi = 35°$ and $40°$

5. CONCLUSION

An estimate of % reduction in the pile capacity is important while designing the pile foundation which is to be installed in the vicinity of the existing underground conduit or tunnel due to space constraints. The proposed analytical approach can be used in this context for preliminary estimate of the % reduction in the capacity of the friction pile which is mostly encountered case in the real world. The approach is simple but comprehensive and takes care of all the relevant input parameters related to pile, tunnel and surrounding soil and it can be used during the preliminary investigations in view of more comprehensive, exhaustive and expensive finite element approach.

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