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ORIGINAL ARTICLE

Analytical solution for evaluating the responses of existing pile caused by adjacent tunnel excavation

Zheng Wei[1]

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Abstract
Tunnel excavation in short distance will change the physical equilibrium stress field of stratum and cause adverse effects on adjacent existing pile. In this paper, a simplified analytical solution is thus proposed to evaluate the existing pile behaviors due to adjacent tunnel excavation. First, tunneling-induced horizontal free field soil movement calculated by a modified Loganathan's formula during shield tunnel excavation is presented. Then, consider that the existing pile is a Euler–Bernoulli beam resting on the Pasternak foundation model. The differential equation of lateral displacement of existing pile is established by combining the coupling condition of soil-pile interaction. Finally, the analytical solution of lateral displacement of the existing pile caused by adjacent tunneling is obtained by finite difference method. The reliability of the analytical solution is validated by comparing with boundary element program, finite element simulation and field measurements. Parametric studies are also preformed to estimate the effects of various factors on an existing pile, including the clearance distance, tunnel depth, tunnel radius, pile diameter and tunneling-induced soil loss rate. A prediction formula for evaluating the maximum lateral displacement of a pile caused by adjacent tunneling was presented, which the deviation rate between predictions and the results of published case reports is less than 10%.

Keywords Adjacent tunnel excavation · Existing pile · Simplified analytical Solution · Prediction formula

Introduction

Nowadays, the urban metro transit system plays an extremely indispensable role in traffic system. Owing to the rapid urbanization of China and exploration of underground space in many cities (Chiang and Lee 2007; Lu et al. 2020; Lueprasert et al. 2020; Ng et al. 2013; Simic-Silva et al. 2020; Soomro et al. 2015, 2017; Yoo 2013). The construction of subway tunnels will inevitably affect the demand for safety and stability of adjacent building foundation structures along urban metro lines (Gokuldas et al. 2020; Liu et al. 2014; Ng and Lu 2014; Sohaei et al. 2020; Wei 2023; Wei et al. 2022). Figure 1 shows the relative position between the existing pile and tunnel excavation. The adjacent tunnel engineering activities may cause damage risks or even potential adverse impacts to the adjacent existing pile. If the induced deformation exceeds the bearing capacity of the existing pile, compression bending failure, overall shear failure and penetration failure of the existing pile may subsequently cause adverse impacts, which will severely affect the safety and stability of the adjacent piles.

A lot of scholars have investigated the mechanical responses of the existing pile to construction of a new tunnel adjacent it by centrifuge test. Zhang et al. (2022) carried out a three-dimensional centrifuge test, including a single tunnel construction and twin tunnel construction, to predict the effects of existing pile caused by adjacent large-scale tunneling. The results performed that interaction mechanism is mainly due to relative position between adjacent tunneling and existing pile. However, as for parallel tunnel tests, the measured displacement of piles caused by the excavation of tunnel near the pile toe is about 2.7 times of that caused by the excavation of tunnel near the mid-depth of the piles. In the report by Lu et al. (2020), centrifuge tests were conducted to predict the interaction mechanism between the existing pile and the newly excavated tunnel during excavation of a new tunnel the existing pile. The results showed that the unloading effect contributed significantly to the redistribution of earth pressure by construction of tunnel.

✉ Zheng Wei
weizheng001@mail.tsinghua.edu.cn

[1] Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

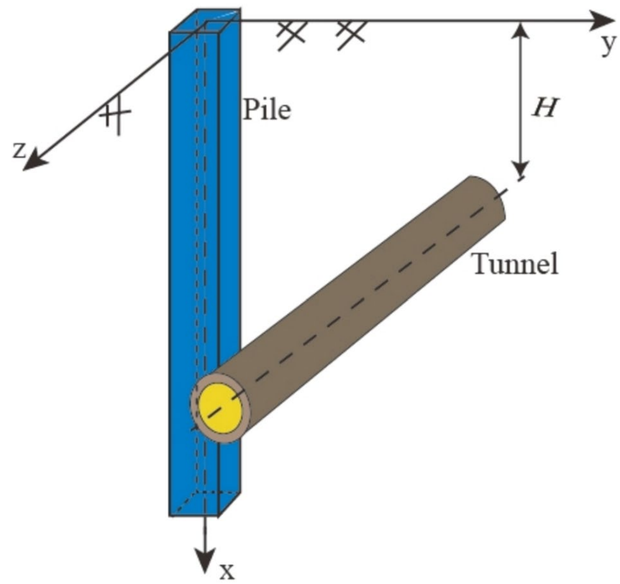


Fig. 1 Excavation tunnel and existing pile models

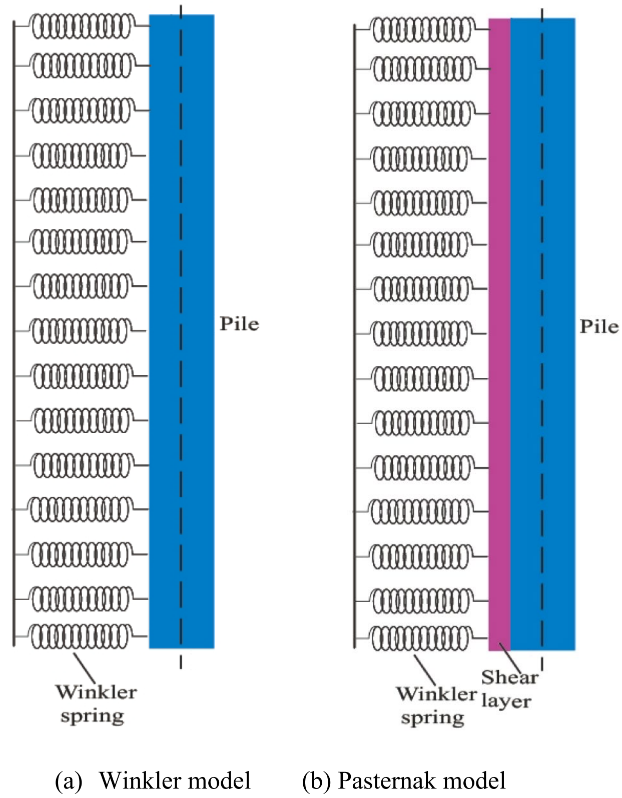


Fig. 2 Winkler model and Pasternak model. **a** Winkler model, **b** Pasternak model

Franza and Marshall (2017) presented a large amount of centrifuge tests to predict the influence of the construction of tunnel on existing pile by quantifying the responses to newly excavated tunnel of axially loaded displacement and non-displacement piles. According to the results, it found the importance of initial safety factor. Song and Marshall (2020) conducted various centrifuge tests to evaluate the influence of tunneling on piles in sand and the relationship between stress relief caused by tunneling and pile head load changes related to connected superstructures.

The field measurement is an important and straightforward method for evaluating the interaction between existing pile and adjacent tunneling. Jacobsz et al. (2006) described the measured results of existing piles supporting a road bridge beneath the UK Channel Tunnel Rail Link (CTRL) during the construction of new tunnel beneath them. It is showed that pile displacement happened when a new tunnel was excavated beneath it. Williamson (2014) reported and analyzed the deformation of existing pile and greenfield ground surface settlements due to tunnels excavation for the Cross rail project by Earth Pressure Balance Machine in London. Selemetas et al. (2017) reported the responses of the friction piles and end-bearing piles due to newly tunnel construction for the CTRL project in London. The observed data indicated that the pile deformation was fairly small due to low volume losses during construction of a new tunnel.

Lee (2012) reported a various of numerical analyses to predict the influence of various factors, such as the centerline mechanical distributions on the pile and pile displacement, relative shear settlement between pile and the soil during construction of a new tunnel. According to the analyses results, it is easy to understand that shear stresses along the pile are severely affected with the changes of relative shear stiffness due to tunneling. Jongpradist et al. (2013) conducted lots of elastic–plastic numerical analyses to study the problem of tunneling nearby existing pile and the influence zones generated by the artificial data of pile responses from tunneling. Zidan and Ramadan (2015) carried out several finite element analyses to study the effects of face pressure, tunnel boring machine, pile caps and final tunnel lining on existing pile.

When relative space position between tunnel and existing pile or geological condition is changed, the previous approaches (centrifuge test, field measurement, numerical analyses cannot quickly and directly estimate the responses of the pile to the construction of tunnel. Thus, the analytical solution that can be proposed to directly evaluate the pile response due to adjacent tunneling is urgently required. Wei et al. (2022) performed an analytical solution to evaluate the responses of existing pile. In their method, the existing pile is based on Euler–Bernoulli model hypothesis on a discontinuous Winkler model that is used to estimate pile-ground mechanical characteristics, as shown in Fig. 2a. Zhang et al. (2018) showed an analytical solution to investigate the problem of tunneling adjacent pipe and the relationship between lateral soil and displacement of pile in Pasternak foundation, as shown in Fig. 2b.

In this paper, an analytical solution is proposed to predict lateral displacement of a pile associated with the adjacent tunneling. The excavation induced horizontal free field soil movement acting on the existing pile is estimated via the modified Loganathan's formula (Loganathan et al. 1998), ignoring the presence of the pile. In proposed model, the existing pile is assumed as an elastic Euler–Bernoulli model on the Pasternak model (1954). A higher order differential equation for horizontal displacement of pile due to the tunneling-induced horizontal free field soil movement, combined with the finite difference method, is proposed for estimating the interaction mechanisms between surrounding soil and existing pile. The reliability of proposed analytical solution is validated by comparing it with the results from boundary element program, finite element simulation and field measurement. Parametric studies are also preformed to evaluate the influences of various factors on an existing pile, including the clearance distance, tunnel depth, tunnel radius, pile diameter and tunneling-induced soil loss rate. Finally, a prediction formula for evaluating the maximum lateral displacement of the existing pile caused by adjacent tunneling is presented.

Analytical solution

Tunneling-induced horizontal free field soil movement

Loganathan et al. (2000) provided a method for evaluating the tunneling-induced horizontal free field soil movement at the pile location. By further combing with Sagasta's expression (Sagaseta 1987) of soil loss rate along the excavation direction, Zhang (2006) presented a solution of tunneling-induced horizontal free field soil movement u at the pile location by considering the spatial effects. In order to calculate the horizontal free field soil movement u along the existing pile more applicable, the three-dimensional coordinate system is applied in the proposed model, as shown in the Fig. 1 and Fig. 3.

$$u = -\frac{V_1}{2}R^2 x_0 \left[1 - \frac{z}{\sqrt{y^2 + z^2 + H^2}}\right] \left\{ -\frac{1}{x_0^2 + (H-x)^2} + \frac{3-4\nu}{x_0^2 + (H+x)^2} - \frac{4x(x+H)}{\left[x_0^2 + (H+x)^2\right]^2} \right\} \exp\left\{ -\left[\frac{1.38x_0^2}{(H+R)^2} + \frac{0.69x^2}{H^2}\right] \right\} \quad (1)$$

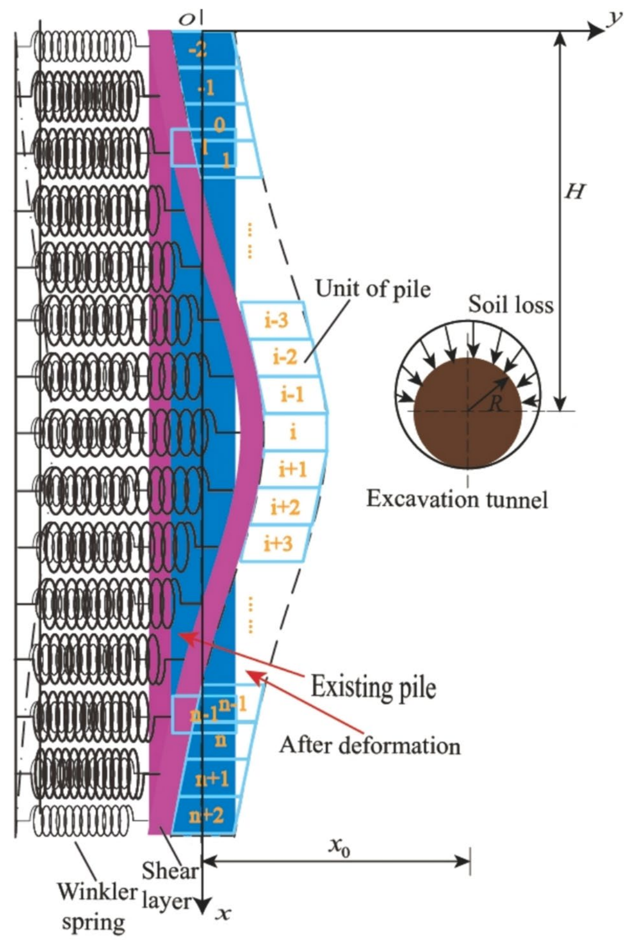


Fig. 3 The Interaction mechanisms between existing pile and tunnel

where, u is the horizontal free field soil movement caused by adjacent tunneling; V_1 is the soil loss rate, R is excavation radius of tunnel, H is buried depth of the tunnel from the ground surface, and ν is the Poisson's ratio of surrounding soils in the calculation.

Pile responses to horizontal free field soil movement

The horizontal free field soil movement at the pile location caused by the adjacent tunneling is calculated through the modified Loganathan's method in Sect. 2.1, ignoring the presence of the existing pile. Then, the pile-soil interaction due to the horizontal free field soil movement is estimated base on the two-parameters Pasternak foundation model (1954). Figure 3 shows the prediction model of the existing pile responses to tunnel excavation.

To overcome the shortcoming of nonconnection in the single-parameter foundation model, Pasternak (1954) derived a shear layer on top of nonconnected discrete springs to consider the interaction behaviors between adjacent discontinuous springs. The interaction can be presented in the following form:

$$p = kw(x) - G_c \frac{\partial^2 w(x)}{\partial x^2} \quad (2)$$

where, p is the pressure at the top of the spring layer in the Pasternak model, k and G_c are foundation reaction coefficient and shear stiffness, respectively. $w(x)$ is the lateral displacement of existing pile.

The general assumption of proposed model is that the existing pile remains contacting with the surrounding soils after bending and soil-pile relative movement is not involved in the proposed model. Moreover, the analysis solution takes isotropic elastic material of soil into account and the creep behavior of soil is not involved in the proposed model.

Figure 4 shows the unit force analysis of the existing pile. According to the material mechanics, the equilibrium equation of the unit is as follows:

Static balance:

$$Q + q(x)Ddx + pDdx = Q + \frac{dQ}{dx}dx \quad (3)$$

Moment balance:

$$M + Qdx + q(x)D\frac{(dx)^2}{2} + pD\frac{(dx)^2}{2} = M + \frac{dM}{dx}dx \quad (4)$$

where, D is pile outer diameter; Q and M represent shear force and bending moment acting on the unit of the existing pile; dx is the unit width of the existing pile; dQ and dM are shear and bending moment increments along the dx direction, respectively; $q(x)$ is the foundation reaction acting on the existing pile.

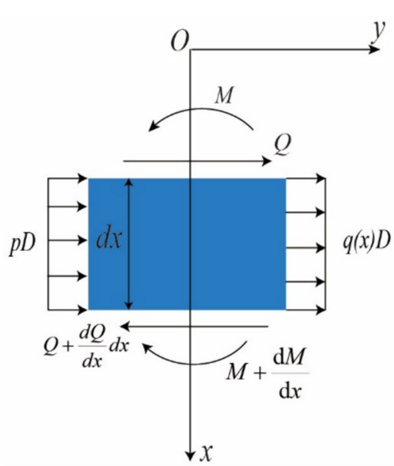


Fig. 4 Unit force analysis

Moreover, the relationship between the internal force and lateral displacement of the existing pile based on the Euler–Bernoulli theory can be expressed as follows:

$$M = EI\frac{d^2 w(x)}{dx^2} \quad (5)$$

$$Q = EI\frac{d^3 w(x)}{dx^3} \quad (6)$$

where M and Q donate bending moment and shearing force of the pile, respectively; and EI is the equivalent bending stiffness.

According to the Pasternak foundation model (1954), the interaction between the pile and the foundation can be expressed as

$$q(x) = ku(x) - G_c\frac{d^2 u(x)}{\partial x^2} \quad (7)$$

where, k and G_c are foundation reaction coefficient and shear stiffness, respectively.

Substituting Eqs. (4)–(7) into Eq. (3),the equilibrium equation for the lateral displacement of existing pile resting on the Pasternak model subjected to the tunneling-induced horizontal free field soil movement $u(x)$ can be expressed as follows:

$$EI\frac{d^4 w(x)}{dx^4} - G_c D\frac{d^2 w(x)}{dx^2} + kDw(x) = \frac{kD}{(EI)_{eq}}u(x) - G_c D\frac{d^2 u(x)}{dx^2} \quad (8)$$

Equation (8) is the higher order equilibrium differential equation and it is no easy to estimate it directly. For simplifying the calculation more rationally, the finite difference method is recommended to solve Eq. (8) numerically. Equation (8) can be obtained in the following:

$$\begin{aligned} EI\ & \frac{6w_i - 4(w_{i+1} + w_{i-1}) + (w_{i+2} + w_{i-2})}{l^4} \\ & - G_c D\frac{w_{i+1} - 2w_i + w_{i-1}}{l^2} + kDw_i \\ & = kDu_i - G_c D\frac{u_{i+1} - 2u_i + u_{i-1}}{l^2} \end{aligned} \quad (9)$$

Assuming that both ends of the pile are free, namely:

$$M_0 = M_n = -(EI)_{eq}\frac{d^2 w(x)}{dx^2}\bigg|_{x=0,n} = 0 \quad (10)$$

$$Q_0 = Q_n = -(EI)_{eq}\frac{d^3 w(x)}{dx^3}\bigg|_{x=0,n} = 0 \quad (11)$$

According to the principle of finite difference theory:

$$M_0 = -(EI)_{eq}\frac{d^2w(x)}{dx^2} = -(EI)_{eq}\frac{w_1 - 2w_0 + w_{-1}}{l^2} = 0 \quad (12)$$

$$M_n = -(EI)_{eq}\frac{d^2w(x)}{dx^2} = -(EI)_{eq}\frac{w_{n+1} - 2w_n + w_{n-1}}{l^2} = 0 \quad (13)$$

$$Q_0 = -(EI)_{eq}\frac{d^3w(x)}{dx^3} = -(EI)_{eq}\frac{w_2 - 2w_1 + 2w_{-1} - w_{-2}}{2l^3} = 0 \quad (14)$$

$$Q_n = -(EI)_{eq}\frac{d^3w(x)}{dx^3} = -(EI)_{eq}\frac{w_{n+2} - 2w_{n+1} + 2w_{n-1} - w_{n-2}}{2l^3} = 0 \quad (15)$$

Combined with Eqs. (12)–(15), four new expressions for the horizontal displacement of virtual elements can be obtained as follows:

$$w_{-2} = 4w_0 - 4w_1 + w_2 \quad (16)$$

$$w_{-1} = 2w_0 - w_1 \quad (17)$$

$$w_{n+1} = 2w_n - w_{n-1} \quad (18)$$

$$w_{n+2} = 4w_n - 4w_{n-1} + w_{n-2} \quad (19)$$

Combined with Eqs. (16)–(19), Eq. (9) can be further written as the following matrix equation:

$$\left[K_1\right]\{w\} + \left[K_2\right]\{w\} - \left[K_3\right]\{w\} = \left[K_2\right]\{u\} - \left[K_3\right]\{u\} \quad (20)$$

In the formula, $\left[K_1\right]$, $\left[K_2\right]$, and $\left[K_3\right]$ are the stiffness matrix; $\{w\}$ and $\{u\}$ represents the lateral displacement column vector of existing pile and the tunneling-induced horizontal free field soil movement column vector, respectively.

The stiffness matrix in Eq. (20) can be written as follows:

$$\left[K_1\right] = \frac{EI}{l^4}\begin{bmatrix} 2 & -4 & 2 & & & & & & \\ -2 & 5 & -4 & 1 & & & & & \\ 1 & -4 & 6 & -4 & 1 & & & & \\ & 1 & -4 & 6 & -4 & 1 & & & \\ & & \ddots & \ddots & \ddots & \ddots & \ddots & & \\ & & & 1 & -4 & 6 & -4 & 1 & \\ & & & & 1 & -4 & 6 & -4 & 1 \\ & & & & & 1 & -4 & 5 & -2 \\ & & & & & & 2 & -4 & 2 \end{bmatrix}_{(n+1)\times(n+1)} \quad (21)$$

$$\left[K_2\right] = kD\begin{bmatrix} 1 & & & & & & & & \\ & 1 & & & & & & & \\ & & 1 & & & & & & \\ & & & \ddots & & & & & \\ & & & & 1 & & & & \\ & & & & & \ddots & & & \\ & & & & & & 1 & & \\ & & & & & & & 1 & \\ & & & & & & & & 1 \end{bmatrix}_{(n+1)\times(n+1)} \quad (22)$$

$$\left[K_3\right] = \frac{G_cD}{l^2}\begin{bmatrix} 0 & 0 & 0 & & & \\ 1 & -2 & 1 & & & \\ & \ddots & \ddots & \ddots & & \\ & & 1 & -2 & 1 & \\ & & & 1 & -2 & 1 \\ & & & 0 & 0 & 0 \end{bmatrix}_{(n+1)\times(n+1)} \quad (23)$$

$$[w] = \left[w_0, w_1, w_2, w_3, \cdots, w_{n-3}, w_{n-2}, w_{n-1}, w_n\right]^T_{n+1} \quad (24)$$

$$[u] = \left[u_0(x), u_1(x), u_2(x), u_3(x), \cdots, u_{n-3}(x), u_{n-2}(x), u_{n-1}(x), u_n(x)\right]^T_{n+1} \quad (25)$$

By calculating the unloading load, the horizontal displacement of the existing pile due to adjacent tunneling can be acquired. Combining Eqs. (21)–(25), the horizontal displacement of the existing pile due to adjacent tunneling can be solved.

Parameters of soil foundation

The subgrade modulus coefficient k is deduced by Vesic (1961). The shear stiffness G_c of shear layer of soil foundation in the Pasternak model was recommended by Tanahashi (2004).

$$k = 0.65\left(\frac{E_sD^4}{EI}\right)^{\frac{1}{12}} \cdot \frac{E_s}{(1-v)^2} \quad (26)$$

$$G_c = \frac{E_st}{6(1+v)} \quad (27)$$

where, v is the Poisson's ratio of the soil, E_s is elastic modulus of soil, and t is thickness of shear layer of Pasternak model.

Verification

Boundary element simulation

Xu and Poulos (2001) provides a boundary element program to analyze the impact of adjacent tunneling on the existing pile. To simplify calculation and establish a simplified model, the surrounding soil and the existing pile are made of a single material of elastic body. The diameter, length and elastic modulus of pile are 0.5 m, 25 m and 24 MPa. Excavation of the tunnel diameter is directly taken as 6 m. The clearance distance between tunnel and existing pile is as close as 4.5 m. The excavated tunnel centerline is buried at the depth of 20 m. Assuming boundary conditions are free at the top and end of the existing pile.

Figure 5 shows the comparison of lateral displacements of pile calculated by the simplified analytical solution and the calculation results of the boundary element method. It can be shown in Fig. 5 that maximum lateral displacement of pile occurs above the tunnel centerline, with a maximum lateral displacement of 9.1 mm. The overall lateral displacement trend of the existing pile is general agreement with the simulation results, although the predicted result slightly overestimated the maximum values for the pile. It appears that the excavated soil will inevitably cause local reduction of the soil-pile relative stiffness, which cannot be directly applied in the proposed model.

Finite element simulation

Mu et al. (2012) used finite element simulation to calculate the lateral displacement effects of tunnel excavation on

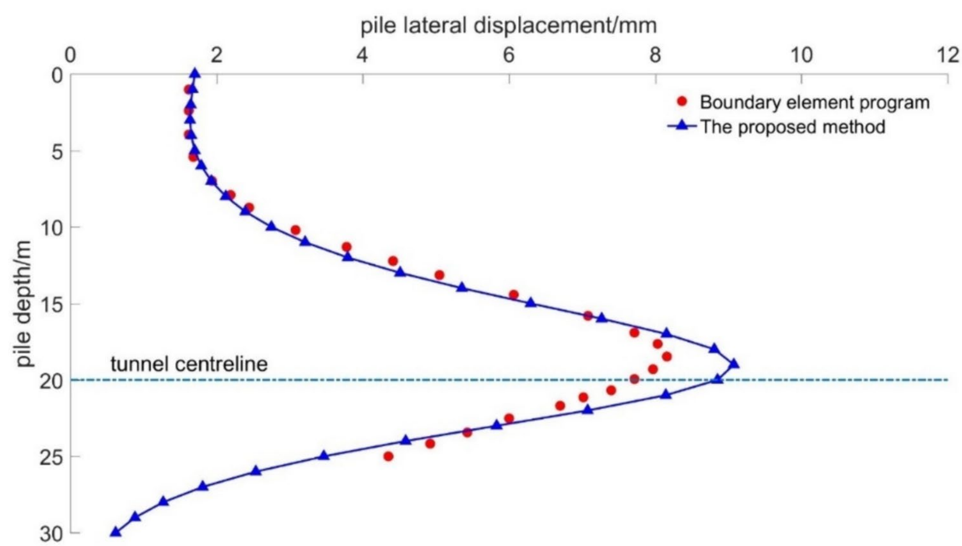


Fig. 5 Comparison of the boundary element program and calculated lateral displacement due to tunnel excavation

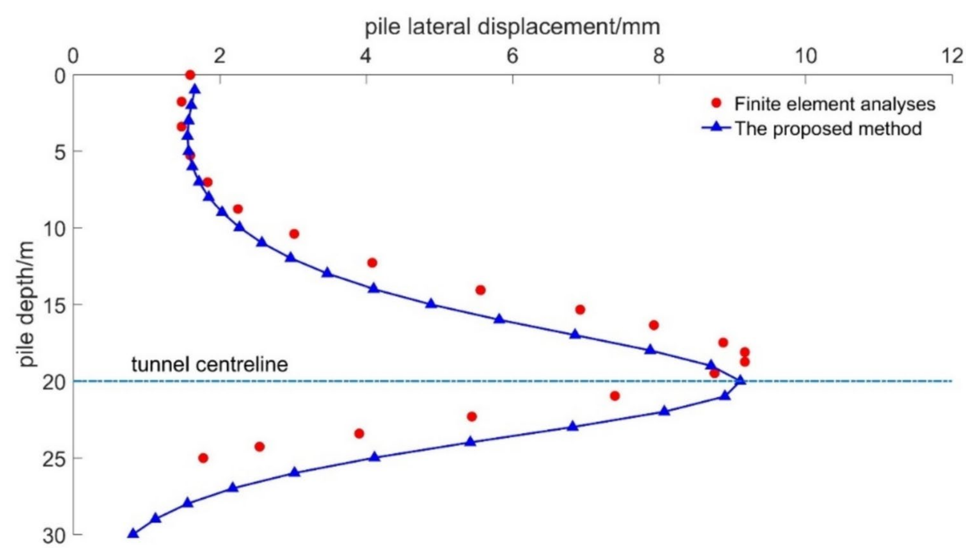


Fig. 6 Comparison of the finite element simulation and calculated lateral displacement of the existing pile due to tunnel excavation

adjacent existing pile. The model assumes that the diameter, length and elastic modulus of existing pile body are 0.8 m, 25 m and 10 GPa. To simplify the calculation, the average elastic modulus, the Poisson's ratio and Cohesive force are taken as 18 MPa, 0.5 and 15 kPa. Diameter of excavated tunnel is 6 m, buried depth of tunnel centerline is 20 m, and the clearance distance between existing pile centerline and excavation tunnel centerline is 4.5 m.

Figure 6 shows the comparison between analytical solution of lateral displacement of the existing pile and finite element simulation results. Maximum lateral displacement of the existing pile is 9.3 mm. The difference between the analytical solution and the finite element calculation results is less than 5%, and a general consistent trend between analytical solution of lateral displacement of existing pile and finite element simulation results is observed. Therefore, the predicted method offers a conservative solution of lateral displacement of the existing pile under the influence of nearby tunneling activities.

Field measurement

Lee et al. (2004) provides monitoring data on lateral displacement of the existing pile during tunnel construction. The tunnel excavation is carried out in two stages, with a buried depth of 15 m below the ground surface. In the first stage, the excavation diameter of tunnel is 4.5 m. The tunneling-induced soil loss rate is 1.5%. In the second stage, the excavation diameter of tunnel is 8.25 m. The induced soil loss rate is 0.5%. The elastic modulus of soil foundation is 54 MPa, and the Poisson's ratio is 0.5; the diameter, length and modulus of the existing pile are 1.2 m, 28 m and 30 GPa, respectively.

Figure 7 shows the comparison between analytical solution for calculating the lateral displacement of pile and monitoring data results. The calculated lateral displacement trend of the existing pile in the Fig. 7 remains basically consistent with the monitoring data. Pile maximum lateral displacement is 11.25 mm, and pile maximum lateral displacement of monitoring data is 10.1 m, within the allowable range. The reason for these overestimated results may be attributed to fact that tunnel stiffening, which utilized prior to construction and would alleviate adverse impacts on the existing pile, are not related to the results predicted.

From above discussion, the feasibility of analytical solution is validated by comparisons with boundary element simulation, finite element simulation and a well-documented measurement case history. It implies that the proposed analytical solution adopted in the study provides a rapid and reliable solution for estimating responses of the existing pile to adjacent tunneling.

Parametric analyses

For predicting impacts of adjacent tunneling on the existing pile, parametric analyses are demonstrated to validate its effectiveness of the influences of various factors on the existing pile, including clearance distance, tunnel buried depth, excavation tunnel radius, pile diameter and tunneling-induced soil loss rate.

Generally, the tunnel excavation is supposed to pass the pile perpendicularly; It is noted that the tunnel burial depth below the ground surface, tunnel excavation radius, and the induced soil loss rate are 18 m, 3 m, and 1%, and the clearance distance between tunnel centerline and horizontal center of the existing pile is taken as 6 m. The surrounding soil where the tunnel and pile are located is homogeneous, Poisson's ratio and elastic modulus of surrounding soil are 0.5 and 24 MPa, respectively. Besides,

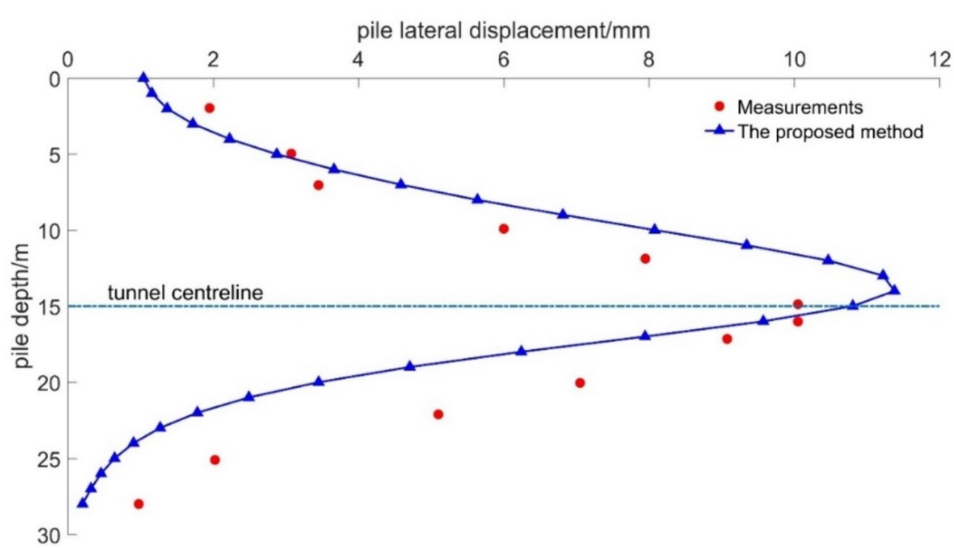
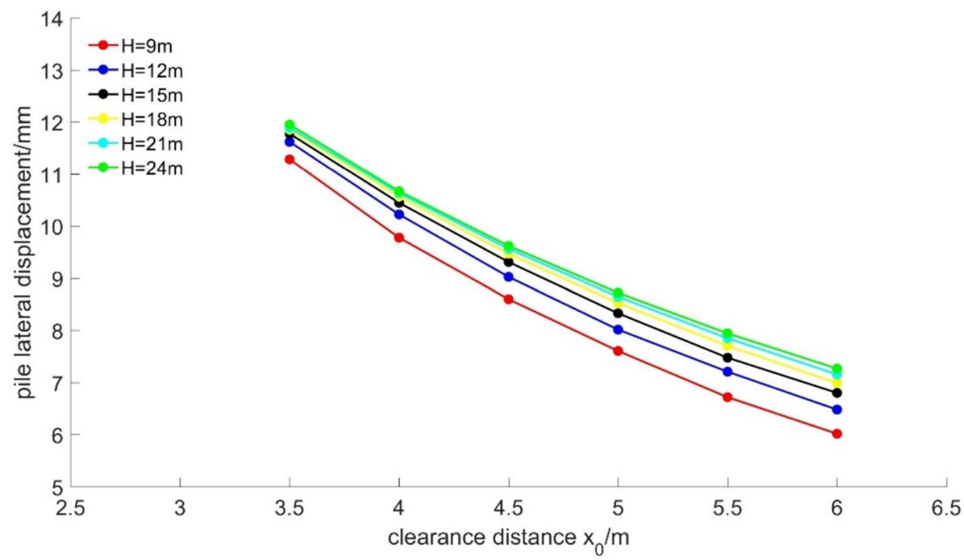


Fig. 7 Comparison of the field measurement and calculated lateral displacement due to tunnel excavation

Fig. 8 Pile maximum lateral displacement with different clearance distance



assumed elastic modulus of pile is 30 GPa, and the diameter and length of the existing pile are taken as 1 m and 25 m, respectively.

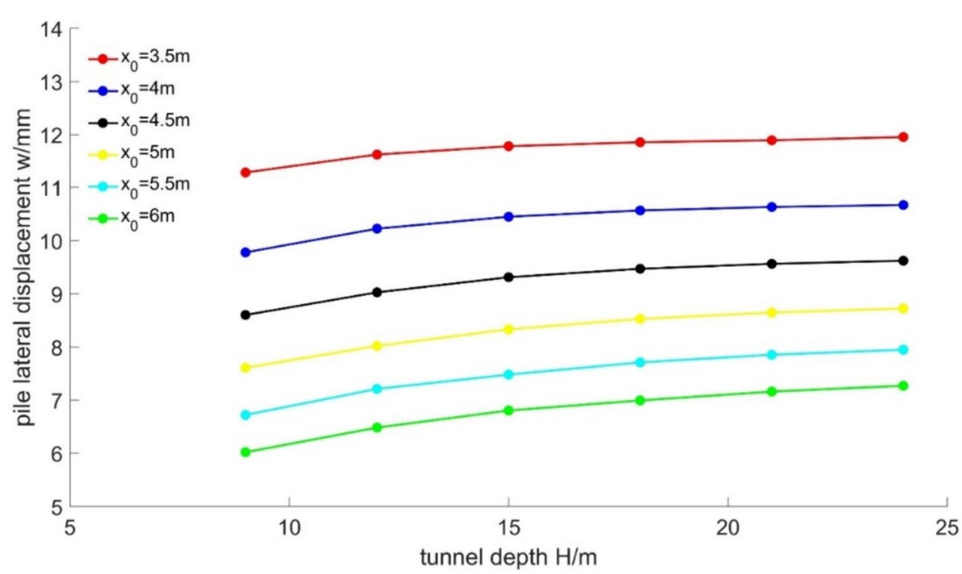
Clearance distance

Figure 8 shows the relationship between variation of maximum lateral displacement of the existing pile and the different clearance distances. Various tunnel buried depths are analyzed to evaluate effects of clearance distances on lateral displacement of the existing pile. At each tunnel buried depth, maximum lateral displacement generated at the intersection point significantly decreases with an increase in the clearance distances. By developing clearance distances from 3.5 to 6 m, the maximum lateral displacement of the existing pile is reduced by up to 39–46%.

Tunnel buried depth

Figure 9 shows the relationship between the maximum lateral displacement of the existing pile and the tunnel buried depth below the ground surface. At each clearance distance, induced lateral displacement increases gradually with an increase in tunnel buried depth. It indicated that increasing the tunnel buried depth will insignificantly alleviate the existing pile lateral displacement induced by adjacent tunneling. It is also showed that a nearer pile endures significantly larger lateral deformation than those of a farther one.

Fig. 9 Pile maximum lateral displacement with different tunnel buried depth



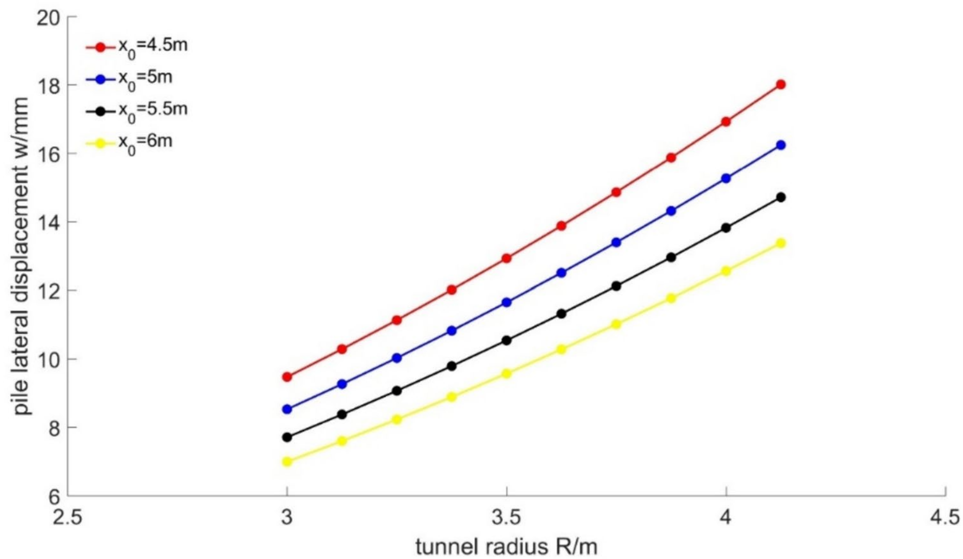


Fig. 10 Pile maximum lateral displacement with different tunnel radius

Tunnel excavation radius

Figure 10 shows maximum lateral displacement of the existing pile due to various tunnel excavation radius. At each excavation radius, the induced maximum displacement of the existing pile increases significantly when the tunnel excavation radius varies from 3 to 4.2 m. At each tunnel excavation radius, induced lateral displacement of farther pile is substantially smaller than that of nearer pile. It appears that discrepancy will be induced by two reasons: less excavation caused by unloading effect on a far pile and large pile-soil stiffness of a far pile. It is observed that trends of lateral displacement of the existing pile are thoroughly parallel to each other.

Pile diameter

Figure 11 shows the relationship between maximum lateral displacement of the existing pile and pile diameter. It is observed that lateral displacement of the existing pile increases gradually with increasing of the pile diameter. It is because that larger pile diameter provides much greater disturbance to the formation. At each pile diameter, by increasing the clearance distance to 6 m, the maximum pile lateral displacement rapidly decreases. From inspection of Fig. 11, increasing pile diameter and clearance distance will both validly reduce lateral displacement of existing pile when subjected to tunnel construction. By further increasing pile diameter, lateral displacement of existing pile of all four clearance distances seem to tend towards parallelism.

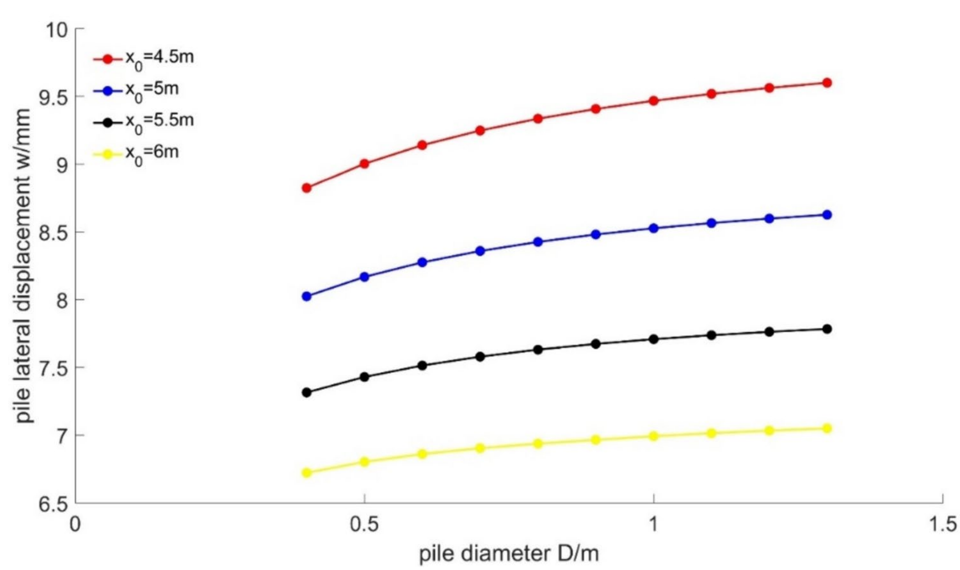


Fig. 11 Pile maximum lateral displacement with different pile diameter

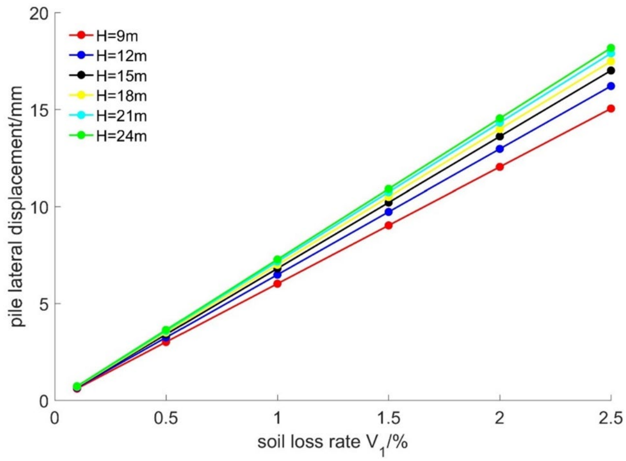


Fig. 12 Pile maximum lateral displacement with different soil loss rate

Soil loss rate

Figure 12 shows the relationship between maximum lateral displacement of pile and soil loss rate. Six tunnel buried depths are applied to estimate the tunneling-induced influence on the existing pile. Due to the larger soil loss rate acting on the pile, at each tunnel buried depth, pile lateral displacement increases linearly with an increase in tunneling-induced soil loss rate, as expected. As the tunnel buried depth is decreased, the maximum pile lateral displacement is remarkably reduced. Moreover, the maximum pile lateral displacement difference between the shallow tunnel excavation and deep tunnel excavation significantly increases with increasing tunneling-induced soil loss rate.

Prediction formula

Development of prediction formula

According to the above discussion, the maximum lateral displacement of the existing pile is approximately linearly increasing with tunnel excavation radius and tunneling-induced soil loss rate. Moreover, induced maximum pile lateral displacement gradually increases with increasing tunnel depth and pile diameter. As the clearance distance is increased, induced maximum pile lateral displacement is significantly reduced. Therefore, a simplified prediction formula can be established to predict maximum lateral displacement of pile due to adjacent tunnel excavation.

$$f = \alpha_1 R^{\alpha_2}(\alpha_3 + \alpha_4 H + \alpha_5 H^2)\alpha_6 x_0^{\alpha_7}(\alpha_8 + \alpha_9 D + \alpha_{10} D^2)V_1 \tag{28}$$

Table 1 Coefficient values of formula (28)

Coefficient	Values
α_1	0.3494
α_2	2.0378
α_3	16.0939
α_4	0.7617
α_5	– 0.0161
α_6	0.6988
α_7	– 1.0281
α_8	0.7079
α_9	0.1146
α_{10}	– 0.0362

In the formula (28), α_1, α_2, α_3, α_4, α_5, α_6, α_7, α_8, α_9, α_{10} are the correlation coefficients. The coefficient values of formula (28) for predicting maximum lateral displacement of pile obtained are shown in Table 1.

Verification of prediction formula

To gain a greater validating of the applicability of the prediction formula previous conducted, the applicability of the prediction formula has been verified by comparison with several published case reports for the problem of tunneling effects on existing pile. As illustrated in Table 2, the values from prediction formula slightly offset towards the results of selected case reports. Nevertheless, general consistent trends are generated by prediction formula and predictions are all within reasonable range, which the deviation rate between predictions and the results of published case reports is less than 10%.

Conclusions

Analytical solution for evaluating the existing pile responses to tunnel construction has been proposed. The crucial conclusions can be presented:

(1) In the proposed model, the horizontal free field soil movement caused by adjacent tunneling at the pile location is estimated using a modified Loganathan's formula. The pile is assumed as an elastic Euler–Bernoulli model resting on Pasternak soil foundation model. The equation of force equilibrium for lateral displacement of a pile subjected to the tunneling-induced horizontal free field soil movement is derived to evaluate the problem of soil-pile interaction. The applicability of analytical solution is validated by Boundary element program, Finite element simulation and a field measurement case.

Table 2 Case verification

No	Type	D/m	L/m	X0/m	R/m	H/m	V_l/%	Predictions /mm	Results of published case reports /mm	Deviation rate between predictions and results of published cases reports /%
1	Finite element (Mu et al. 2012)	1.0	20	4.5	3	20	1.0	9.5512	9.17	4.157
2	Boundary element (Xu and Poulos 2001)	0.5	25	4.5	3	20	1.0	9.1847	9.15	0.379
3	Boundary element (Xu and Poulos 2001)	0.5	25	4.5	3	20	2.5	22.9618	22.28	3.06
4	Boundary element (Xu and Poulos 2001)	0.5	25	4.5	3	20	5.0	45.9236	45.01	2.029
5	Finite element (Mu et al. 2012)	0.8	18	5.5	3	18	1,0	7.5799	7.44	1.88
6	Finite element (Mu et al. 2012)	0.8	20	4.5	3	20		9.4309	9.17	2.845
7	Field measurement (Lee et al. 2004)	0.4	30	8	4	16	1.0	8.7715	8.3	5.68

(2) According to the parametric analyses, the maximum lateral displacement of pile is approximately linearly increasing with tunnel excavation radius and tunneling-induced soil loss rate. Induced pile maximum lateral deformation gradually increases with increasing tunnel depth and pile diameter. As the clearance distance is increased, the induced pile maximum lateral displacement is significantly reduced.

(3) A prediction formula for estimating maximum lateral displacement parameter of pile due to tunnel excavation is provided. The applicability of proposed formula has been verified through published cases, which the deviation rate between predictions and the results of published case reports is less than 10%.

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Chiang KH, Lee CJ (2007) Responses of single piles to tunneling-induced soil movements in sandy ground. Can Geotech J 44(10):1224–1241. https://doi.org/10.1139/T07-050

Franza A, Marshall AM (2017) Centrifuge modelling of tunneling beneath axially loaded displacement and non-displacement piles in sand, american society of civil engineers geotechnical frontiers 2017, 576–586, March 12–15. Orlando Florida USA. https://doi.org/10.1061/9780784480441.060

Gokuldas S, Banerjee S, Nimbalkar SS (2020) Effects of tunneling-induced ground movements on stability of piled raft foundation: three-dimensional finite-element approach. Int J Geomech 20:04020104. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001726

Jacobsz SW, Bowers KH, Moss NA, Zanardo G (2006) The effects of tunneling on piled structures on the CTRL. Proceedings of the 5th international conference of TC 28 of the ISSMGE, the Netherlands, 15–17 june 2005, 115–121.

Jongpradist P, Kaewsri T, Sawatparnich A, Suwansawat S, Youwai S, Kongkitkul W, Sunitsakul J (2013) Development of tunneling influence zones for adjacent pile foundations by numerical analyses. Tunn Undergr Space Technol 34:96–109. https://doi.org/10.1016/j.tust.2012.11.005

Lee CJ (2012) Numerical analysis of the interface shear transfer mechanism of a single pile to tunneling in weathered residual soil. Comput Geotech 42:193–203. https://doi.org/10.1016/j.compgeo.2012.01.009

Lee SH, Sl K, Lee JH, Chang BS (2004) Two-parameter beam-column model and back analysis for flexible earth retaining walls. Comput Geotech 31:457–472. https://doi.org/10.1016/j.compgeo.2004.06.002
Liu C, Zhang Z, Regueiro RA (2014) Pile and pile group response to tunneling using a large diameter slurry shield—Case study in Shanghai. Comput Geotech 59:21–43. https://doi.org/10.1016/j.compgeo.2014.03.006
Loganathan N, Poulos HG (1998) Analytical prediction for tunneling-induced ground movements in clays. J Geotechn Geoenviron Eng 124(9):846–856. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:9(846)
Loganathan N, Poulos HG, Stewart DP (2000) Centrifuge model testing of tunneling-induced ground and pile deformations. Geotechnique 50(3):283–294. https://doi.org/10.1680/geot.2000.50.3.283
Lu H, Shi J, Ng CWW, Lv Y (2020) Three-dimensional centrifuge modeling of the influence of side-by-side twin tunneling on a piled raft. Tunn Undergr Space Technol 103:103486. https://doi.org/10.1016/j.tust.2020.103486
Lueprasert P, Jongpradist P, Jongpradist P, Suwansawat S (2020) Numerical investigation of tunnel deformation due to adjacent loaded pile and pile-soil-tunnel interaction. Tunn Undergr Space Technol 70:166–181. https://doi.org/10.1016/j.tust.2017.08.006
Mu L, Huang M, Finno RJ (2012) Tunneling effects on lateral behavior of pile rafts in layered soil. Tunn Undergr Space Technol 28:192–201. https://doi.org/10.1016/j.tust.2011.10.010
Ng CWW, Lu H (2014) Effects of the construction sequence of twin tunnels at different depths on an existing pile. Can Geotech J 51(2):173–183. https://doi.org/10.1139/cgj-2012-0452
Ng CWW, Lu H, Peng SY (2013) Three-dimensional centrifuge modelling of the effects of twin tunneling on an existing pile. Tunn Undergr Space Technol 35:189–199. https://doi.org/10.1016/j.tust.2012.07.008
Pasternak PL (1954) On a new method of analysis of an elastic foundation by means of two foundation constants. Gosudarstvennoe Izdatelstvo Literaturi po Stroitelstvu i Arkhitekture, Moscow
Sagaseta C (1987) Analysis of undrained soil deformation due to ground loss. Geotechnique 37(3):301–320. https://doi.org/10.1680/geot.1987.37.3.301
Selemetas D, Standing JR (2017) Response of full-scale piles to EPBM tunneling in London clay. Geotechnique 67(9):123–136. https://doi.org/10.1680/tue.63778.123
Simic-Silva PT, Martínez-Bacas B, Galindo-Aires R, Simic D (2020) 3D simulation for tunneling effects on existing piles. Comput Geotech 124:103625. https://doi.org/10.1016/j.compgeo.2020.103625
Sohaei H, Namazi E, Hajihassani M, Marto A (2020) A Review on tunnel–pile interaction applied by physical modeling. Geotech Geol Eng 38(4):3341–3362. https://doi.org/10.1007/s10706-020-01240-6
Song G, Marshall AM (2020) Centrifuge study on the influence of tunnel excavation on piles in sand. J Geotechn Geoenviron Eng 146(12):04020129. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002401
Soomro MA, Hong Y, Ng CWW, Lu H, Peng S (2015) Load transfer mechanism in pile group due to single tunnel advancement in stiff clay. Tunn Undergr Space Technol 45:63–72. https://doi.org/10.1016/j.tust.2014.08.001
Soomro MA, Ng CWW, Liu K, Memon NA (2017) Pile responses to side-by-side twin tunneling in stiff clay: effects of different tunnel depths relative to pile. Comput Geotech 84:101–116. https://doi.org/10.1016/j.compgeo.2016.11.011
Tanahashi H (2004) Formulas for an infinitely long Bernoulli-Euler beam on the Pasternak model. Soils Found 44:109–118. https://doi.org/10.3208/sandf.44.5_109
Vesić AB (1961) Bending of beams resting on isotropic elastic solid. J Eng Mech Div 87(2):35–53. https://doi.org/10.1061/JMCEA3.000021
Wei Z (2023) Simplified method for evaluating mechanical interactions between tunnel and soil due to adjacent excavation. Tunn Undergr Space Technol 139:105205. https://doi.org/10.1016/j.tust.2023.105205
Wei Z, Jiang Y, Yin M, Yang X (2022) Simplified theoretical solution of horizontal deformation of pile caused by tunnel excavation. J Central South Univ (science and Technology) 53(10):4106–4114
Williamson MG (2014) Tunneling effects on bored piles in clay. University of Cambridge, UK
Xu KJ, Poulos HG (2001) 3-D elastic analysis of vertical piles subjected to "passive" loadings. Comput Geotech 28:349–375. https://doi.org/10.1016/S0266-352X(00)00024-0
Yoo C (2013) Interaction between tunneling and bridge foundation—a 3D numerical investigation. Comput Geotech 49:70–78. https://doi.org/10.1016/j.compgeo.2012.11.005
Zhang Z, Huang M, Xu C, Jiang Y, Wang W (2018) Simplified solution for tunnel-soil-pile interaction in Pasternak's foundation model. Tunn Undergr Space Technol 78:146–158. https://doi.org/10.1016/j.tust.2018.04.025
Zhang Y, Ding C, Lu H, Ji W (2022) Effects of large-scale twin tunnel excavation on an existing pile group: three-dimensional centrifuge modeling. Soil Mech Found Eng 58(6):500–506. https://doi.org/10.1007/s11204-022-09772-0
Zhang J (2006) Study on soil deformation analysis induced by shield tunnel. Zhejiang University,
Zidan AF, Ramadan OMO (2015) Three dimensional numerical analysis of the effects of tunneling near piled structures. KSCE J Civ Eng 19(4):917–928. https://doi.org/10.1007/s12205-014-0741-6