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Lateral responses of piles due to excavation-induced soil movements

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ABSTRACT: Lateral soil movements induced by excavation of a deep foundation pit may adversely affect nearby pile foundations. In this paper, a simple analysis method is proposed for computing lateral responses of passive pile groups subject to excavation induced lateral soil movement. Based on a two-stage method, the Winkler model is adopted for simulating the pile-soil interaction, combined with finite difference method in the case of multi-layered soils. A specified free-field soil movement profile is used as input. Then, the governing equation for a pile group is obtained considering the shielding effect in pile groups by the simplified Mindlin's equation. Comparisons are made between the observed behavior of centrifuge model tests and those computed by the proposed method. The present method can in general give a satisfactory prediction of the lateral response of passive pile groups. However, the major limitation is the assumption of linear elastic soil springs, which provides only an upper bound estimate.

1 INTRODUCTION

Deep excavations for basements and other underground facilities are unavoidable in big cities. The lateral soil movements resulting from excavations will impose additional bending moments and deflections on nearby piles, which may lead to structural distress or failure (Pan *et al.* 2002, Goh *et al.* 2003). Developing reliable and simple methods to estimate the behavior of piles next to excavations is urgent in practical engineering.

Available methods of analysis can be broadly classified into complete three-dimensional method and two-stage method. The former, which is carried out by a finite element analysis, can consider complex pile-soil interaction and the whole construction process (Goh *et al.* 2002, Miao *et al.* 2005). However, it is computationally expensive and the accuracy depends on the accuracy of the constitutive soil models, which are currently under a stage of calibration with results from physical tests (Juirnarongrit & Ashford 2006). Furthermore, it is more suited to obtain a benchmark solution or to obtain solutions of detailed analysis for final design, rather than as a preliminary routine design tool (Kitiyodom & Matsumoto 2002).

Comparatively, the simplified two-stage method appears to be a more attractive choice. The known free-field soil movement is a prerequisite (Goh *et al.* 1997). As a wealth of experience accumulations on estimation of the soil deformation resulting from excavation have been obtained by engineers, the two-stage method can give a satisfactory result to guide construction and design. In the works of Poulos (Poulos & Chen 1997, Chen & Poulos 1997, 1999), a combined finite element method and boundary element method was used to analyse piles adjacent to an excavation. However, most of their works are focused on single passive piles and the surrounding soil is modelled as an elastic continuum. Issues such as group effect due to pile-soil-pile interaction and the effect of non-homogeneous soils are not well-understood. Further research is clearly required.

This paper describes a simplified two-stage numerical procedure for analyzing response of piles in group subjected to excavation-induced lateral soil movements. A numerical model, considering of non-homogeneous soils, is achieved using the finite difference method and the concept of shielding effects is introduced to analyse the pile-soil-pile interaction. The assessment is performed by comparing the results from the presented method with those from centrifuge model tests and the predicted results of centrifuge tests by Leung (Leung *et al.* 2000, Leung *et al.* 2003).

2 ANALYSIS METHOD

According to the two-stage method, the analysis can be decomposed into two components (Poulos & Chen 1997). First, the free-field soil movement (without the presence of piles in the substratum) is obtained by measurement or calculation. Second, the acquired soil movement is imposed on a nearby pile to calculate its response. The flexural bending of the pile is modelled by an elastic beam while the complex phenomenon of pile-soil interaction is modeled by linear elastic soil springs based on the Winkler model. The lateral deflection equation for a single pile is formulated. Then, considering the restriction of soil movement due to pile-soil-pile interaction, the shielding effect between two piles is imposed using simplified Mindlin's elastic solution for a lateral point load in an elastic half-space. At last the response of group piles is obtained with superposition theorem.

2.1 *Free-field soil movement induced by the construction of deep foundation pit*

Analysis methods for estimating free-field soil movement include an empirical method, a finite element method and an analytical method. As a means to verify the validity of the two-stage method, supposed free-field soil movement or that from in-situ measurement can be adopted. Bigot *et al.* (1982) clearly showed that the displacement-based method of analysis provides very good predictions of bending moment profiles and pile deflections if the measured free-field soil displacement is used as input, or if an accurate prediction of soil movement can be made.

2.2 *Analysis of a single pile*

As an approximate method, the nonlinear springs which represent the actual pile-soil interaction and tension cracks developed around piles are not taken into account. In other words, the following hypotheses are adopted:

1. the pile is represented by an elastic beam based on a Winkler subgrade reaction model;
2. the complex phenomenon of pile-soil interaction is modeled using linear elastic soil springs and no crack appears between pile and surrounding soils;
3. the effect of axial load on the pile is ignored.

The linear elastic soil spring is represented through a modulus of subgrade reaction, which is defined as

$$k_z = -\frac{p}{y} \tag{1}$$

where k_z has the units of force/length^2, p = soil reaction per unit-length of pile, in unit of force/length, y = the relative displacement between pile and surrounding soils. Vesic (1961) analyzed an infinite horizontal beam in an elastic foundation and compared the results with those obtained by the use of subgrade-reaction theory, which related the modulus of subgrade reaction k_z to the elastic parameter E_s and ν_s of the soil mass, as follow in:

$$k_z = \frac{0.65E_s}{\left(1-\nu_s^2\right)}\sqrt[12]{\frac{d^4E_s}{E_pI_p}} \tag{2}$$

where E_pI_p is pile rigidity.

Then, the governing differential equation of single pile is given by:

$$\frac{d^4U_t(z)}{dz^4} + 4\lambda^4\left[U_t(z) - h_x(z)\right] = 0 \tag{3}$$

in which $U_t(z)$ is the lateral deflection of pile caused by excavation; $h_x(z)$ is the free-field soil movements due to excavation; and λ is written as

$$\lambda = \sqrt[4]{\frac{k_z}{4E_pI_p}} \tag{4}$$

The equation (3) can be solved either by finite difference method or by analytical method. The analytical method has been undertaken by the authors before, and can only be applied for homogeneous soils. In order to consider the influence of non-homogeneous soils, the numerical finite difference method is adopted in this paper.

The total pile length L is divided into n cells and the length of each cell is δ, with a node in each cell, which is $0, 1, \ldots n-1, n$. In addition to n real cells, there are four additional imaginary cells (two at each end of the pile and additional nodes of $-2, -1, n+1, n+2$) to implement boundary conditions.

The basic differential equation (3) can be written in the finite difference form for any real cell i, as

$$U_{t,i-2} - 4U_{t,i-1} + (6 + 4(\lambda_i\delta)^4)U_{t,i} - 4U_{t,i+1} + U_{t,i+2} = 4(\lambda_i\delta)^4 h_{x,i} \tag{5}$$

The different boundary conditions at the top and tip of the pile provide four different additional equations (Poulos & Davis 1990).

With free-head pile exerted load H and bending moment M, equations are as follow:

$$-U_{t,-2} + 2U_{t,-1} - 2U_{t,1} + U_{t,2} = \frac{2H}{E_pI_p}\delta^3 \tag{6}$$

$$U_{t,-1} - 2U_{t,0} + U_{t,1} = \frac{M}{E_pI_p}\delta^2 \tag{7}$$

With fixed pile head, the equations are

$$U_{t,1} - U_{t,-1} = 0 \quad , \qquad U_{t,0} = 0 \tag{8}$$

When deflection and rotation of pile head is possible, the equation is changed corresponding to the relevant boundary condition.

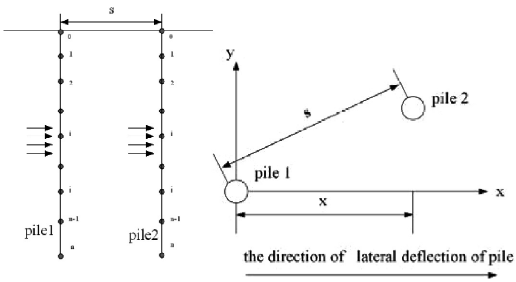

Figure 1. Computation model for two passive piles.

Similarly, the equations for cell $n-1$, n can also be acquired, based on their boundary conditions.

Substituting the equations of boundary conditions into equation for nodes 0, 1, $n-1$ and n, the $n+1$ unknowns, which represent the deflection of pile in $n+1$ nodes, can be solved by the whole system of $n+1$ simultaneous equations. The rotation, shear force and bending moment of the pile can be obtained from deflection based on the theory of material mechanics.

2.3 *Interaction between two piles*

In general, piles do not follow exactly the free-field soil movement at the pile location and the soil profile is also altered by pile. The hindered free-field soil movement affects nearby piles, the amount of which depending on the relative stiffness between pile and surrounding soils. This is called shielding effect.

The problem of interaction between two piles is depicted in Figure 1, where two piles with pile spacing s are represented. By discretizing each pile into n cells with a node in each cell, the free-field soil movement in arbitrary node i at the position of pile 1 is $h_{s1,i}$ and the deflection of pile 1 caused is $U_{p1,i}$. The corresponding lateral soil deflection is $U_{s1,i}$, where $U_{p1,i}$ is identical to $U_{s1,i}$ based on compatibility of lateral displacement between pile and soil. The lateral soil displacement in node i due to shielding effect of pile 1 is then expressed as

$$\Delta U_{s1,i} = h_{s1,i} - U_{s1,i} \tag{9}$$

The corresponding lateral soil shielding displacement in any node j at the position of pile 2 due to soil displacement in node i at the position of pile 1, is

$$h_{s21,ij} = \xi_{ij} \cdot \Delta U_{s1,i} = \xi_{ij} \cdot \left[h_{s1,i} - U_{s1,i}\right] \tag{10}$$

where ξ_{ij} is the attenuation function of the lateral shielding movement based on the simplified Mindlin's equation as follows (Poulos & Davis 1990). Suppose the load in arbitrary node i at the position of pile 1 is $k_{zi} U_{s1,i} \delta$ from Winkler subgrade model in the case of active piles. Based on Mindlin's equation, the corresponding soil displacement in arbitrary node j at the position of pile 2(without the presence of pile 2) due to load at node i is

$$U_{s2,j} = \frac{U_{s1,i} k_{zi} \delta}{16\pi G(1-\nu)} \left\{ \frac{3-4\nu}{R_1} + \frac{1}{R_2} + \frac{x^2}{R_1^3} + \frac{(3-4\nu)x^2}{R_2^3} + \frac{2 z_i z_j}{R_2^3}\left(1 - \frac{3x^2}{R_2^2}\right) + \frac{4(1-\nu)(1-2\nu)}{R_2 + z_i + z_j}\left(1 - \frac{x^2}{R_2\left(R_2 + z_i + z_j\right)}\right)\right\} \tag{11}$$

where $R_1^2 = s^2 + (z_j - z_i)^2$, $R_2^2 = s^2 + (z_j + z_i)^2$, z_i and z_j is the depth of cell i, j, x is the distance between two piles in the direction of lateral soil deflection. The coefficient ξ_{ij} can be therefore written as

$$\xi_{ij} = \frac{U_{s2,j}}{U_{s1,i}} \tag{12}$$

With the superposition theorem, the lateral soil shielding displacement in any node j at the position of pile 2 is

$$h_{s21,j} = \sum_{i=1}^{n} h_{s21,ij} = \sum_{i=1}^{n} \xi_{ij} \cdot \Delta U_{s1,i} = \sum_{i=1}^{n} \xi_{ij} \cdot \left(h_{s1,i} - U_{s1,i}\right) \tag{13}$$

The lateral equilibrium equation of pile 2 due to shielding effect of pile 1 is written as

$$\frac{d^4 U_{t21}(z)}{dz^4} + 4\lambda^4\left[U_{t21}(z) - h_{s21}(z)\right] = 0 \tag{14}$$

where $U_{t21}(z)$ is the corresponding lateral deflection of pile 2. The equation can also be solved by finite difference method in the same way.

2.4 *Pile group analysis*

For the usual case of a group of n piles, the total response of a single pile in the group(i.e. the total displacement and the total internal force) is written as the sum of two components:

1 displacement due to excavation-induced free-field soil movement.
2 shielding displacement resulting from pile-to-pile interaction (shielding effect) which decreases the response of single pile caused by excavation.

Considering the arbitrary pile i in the group, the total displacement of the pile head could be obtained by superposition

$$U_{ti} = \sum_{j=1}^{n} U_{tij} \tag{15}$$

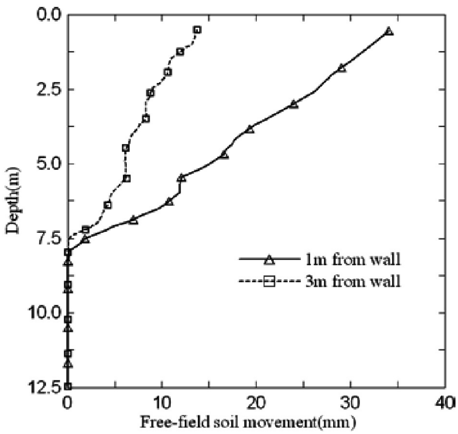

Figure 2. Lateral soil movement induced by excavation.

where U_{tii} represents the response of pile i due to excavation-induced free-field soil movement, and $U_{tij}(i \neq j)$ represents the shielding displacement of pile i due to the existence of pile j.

3 VERIFICATION BY COMPARISON WITH CENTRIFUGE MODEL TESTS AND FEM ANAYSIS

3.1 *Experiments*

Only very limited field data are available so far, especially in the case of pile groups. Leung *et al.* (2000, 2003) have published a series of centrifuge model tests on unstrutted deep excavation in dense sand and its influence on an adjacent single pile and pile group foundation behind the retaining wall.

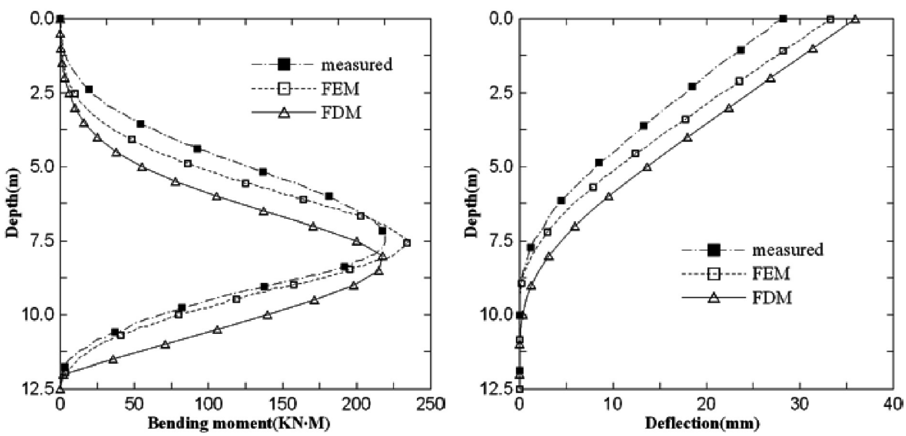

Figure 3. Comparison of free-head pile response for pile located 1 m behind wall.

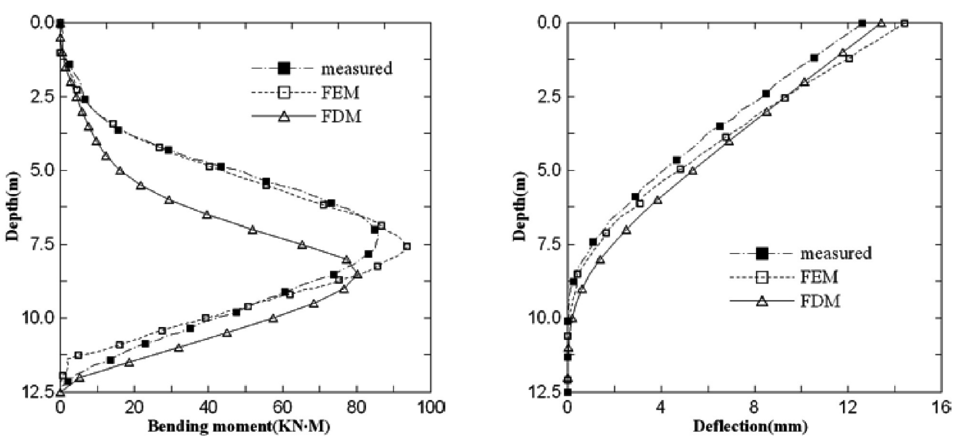

Figure 4. Comparison of free-head pile response for pile located 3 m behind wall.

Due to approximate assumption about linear elastic soil springs in the present simplified method, cases in which soil experienced failure are not taken into account. The predicted results by Leung in the case of single pile with finite element method are also shown herein.

3.2 *Analysis of single piles*

Two tests for single free-head pile located at 1 and 3 m behind the retaining wall and two tests for restraint head (fixed deflection-free rotation head and fixed deflection-fixed rotation head) at 3 m behind the retaining wall are presented here. The prototype square pile has a width of 0.63 m and a length of 12.5 m with $E_pI_p = 220 \times 10^3$ kNm. The free field soil displacement profiles with depth at the location of the pile are instrumented and shown in Figure 2. $Es = 6z$ (in MPa, z is the depth below ground surface, in m) is applied for the analysis as suggested by Leung *et al.* (2000). Figures 3–4 show comparisons between the measured and predicted bending moments and deflection profiles along a free-head pile located at 1, 3 m from the wall. Figures 5–6 give the results for the case of head restraint. FE analysis by Leung *et al.* (2000) gives a relatively better estimation than the present method, especially at the position of the maximum bending moment. The reason maybe the assumption of linear elastic soil springs along the pile. The soil around the long pile up to a depth less than 4 times the pile diameter may have reached limited soil pressures, even experiencing very small displacement (Pan *et al.* 2002). In Leung's works, the ultimate soil pressures acting on pile were introduced to consider this effect,

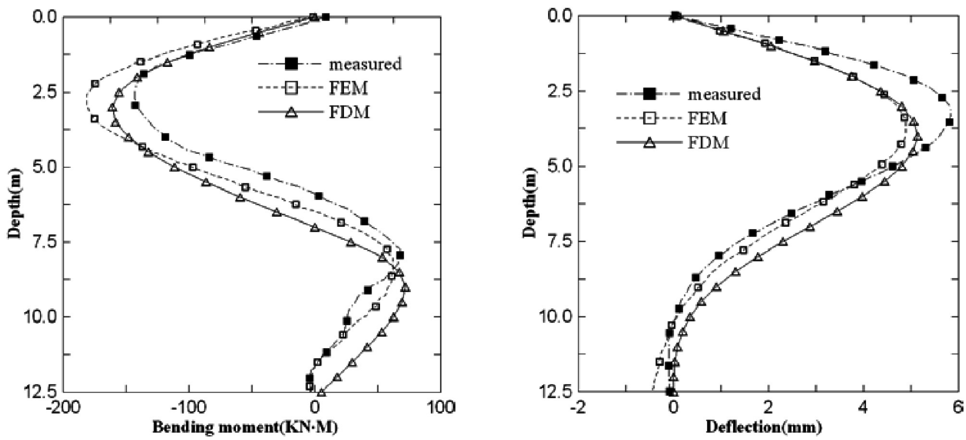

Figure 5. Comparison of fixed (deflection)-free(rotation) head pile response.

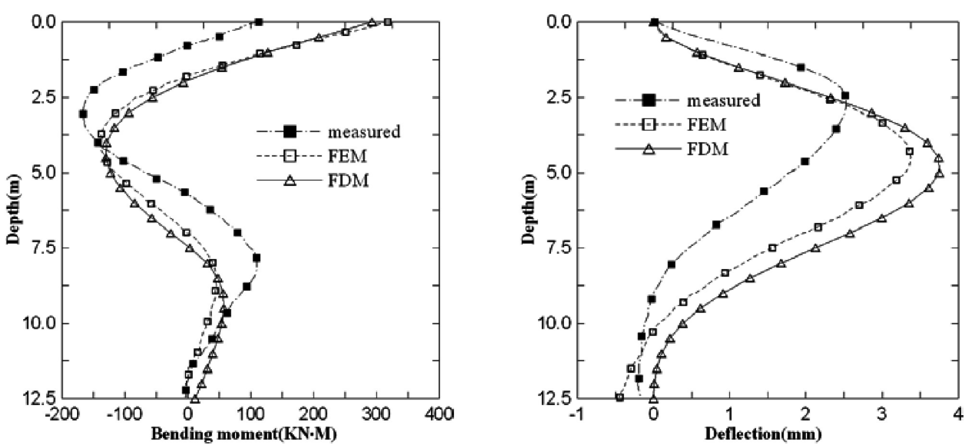

Figure 6. Comparison of fixed (deflection)-fixed(rotation) head pile response.

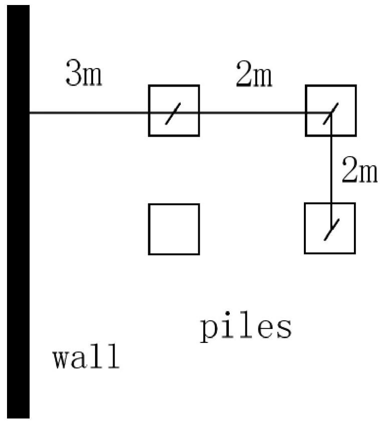

Figure 7. Configuration of pile group.

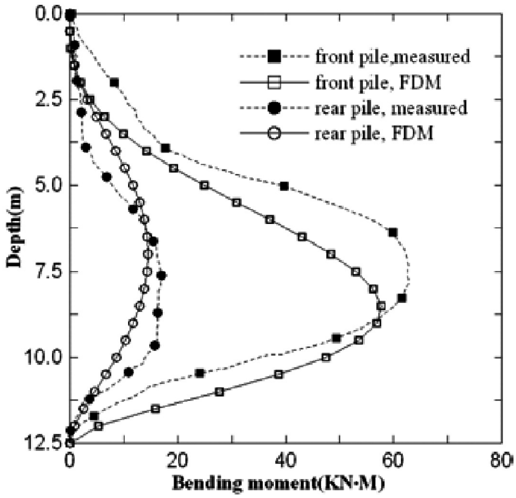

Figure 8. Comparison of free head pile group.

while they are not taken into account in the presented method. However, the simplified method still gives reasonable estimation with little computational effort and it can be used with some confidence in the preliminary design.

3.3 *Analysis of pile group*

17 group-pile tests with different number of piles and different configures are shown in Leung *et al*. (2003). Due to the limited length of this paper, only 2 typical pile groups are described here. The prototype square pile has a width of 0.48 m and a length of 12.5 m with $E_pI_p = 240 \times 10^3$ KNm^2. The pile cap with a thickness of 0.55 m is placed above the ground, which can be treated as rigid cap. Pile groups with four piles in free-head and capped-head are described here, the configuration of which are shown in Figure 7. The predicted results by the present simplified method are compared with the data from centrifuge tests in Figures 8–10. The calculated results provide reasonable approximation to the centrifuge tests data for free-head and capped-head pile groups. The discrepancy between the predicted and measured bending moment profiles is seem to be small along the upper portion of the pile, while it is relatively large along the lower portion of piles. However, deflections of capped-head piles show the tendency that the front pile is dragged back by the rear file through connection of pile cap.

4 CONCLUSIONS

This paper presents a numerical analysis with finite difference method for studying the behavior of piles subjected to excavation-induced lateral soil movement in non-homogeneous soils. Response of a single pile is determined by imposing the known free-field soil movement profile to the passive pile. The Mindlin's

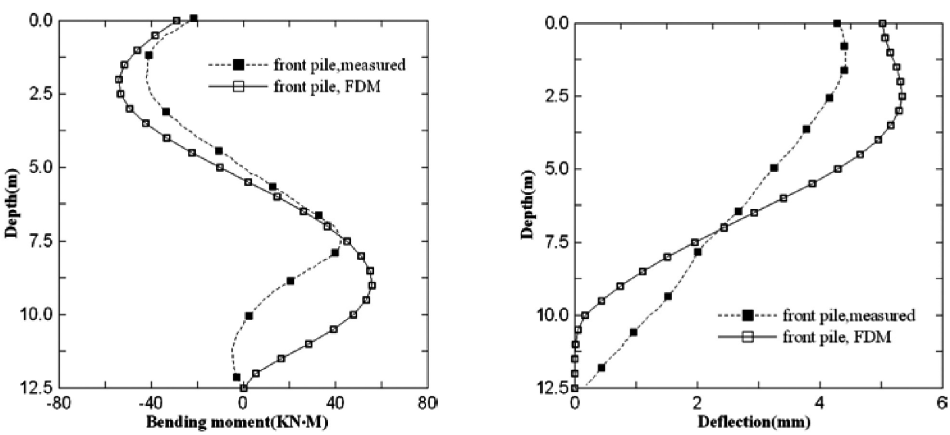

Figure 9. Comparison of front pile in capped head pile group.

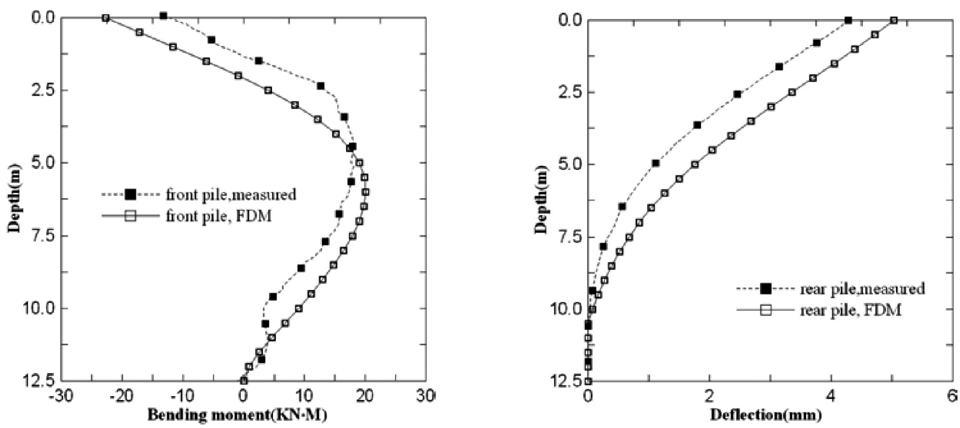

Figure 10. Comparison of rear pile in capped head pile group.

equation is employed to calculate the shielding effect of passive pile groups due to pile-soil-pile interaction. Comparisons with centrifuge model tests confirm that the method provides reliable estimates in simple way.

However, the major limitation of the method is the assumption of linear elastic soil springs, which provides only an upper bound estimate of the maximum bending moments and pile deflections. Hence, the analysis considering the nonlinear effect is still needed in order to decisively assess the responses of piles due to excavation-induced lateral soil movements.

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