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Research Article

Analysis of Settlement of Group Pile Foundation in Linear Viscoelastic Soil

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The settlement of a group pile foundation is the result of elastic-plastic settlement of the pile and rheological settlement of the soil. Unfortunately, most research only considers elasto-plasticity settlement of piles or rheological settlement of soils. Classical theories like the Poynting-Thompson model only provide some prediction for the elasto-plasticity behavior of pile groups, which cannot satisfactorily reflect the total settlement characteristics of pile group foundation. In the current paper, we presented a method to study settlement behaviors of pile group foundation in linear viscoelastic soil based on the pile-pile interaction factors, the calculated equation of settlement of single piles and pile groups under vertical loads that are derived, the influence law of pile end resistance, pile spacing, slenderness ratio, elastic modulus ratio, and Poisson ratio on pile end load ratio, and the interaction factors that have been presented. Finally, some typical predictive examples have been presented for a 2×2, 3×3 group pile showing settlement from a field test. It is found that the pile-pile interaction factors increase with the increase of the pile-soil elastic modulus ratio and length-to-diameter ratio but decrease with the increase of the ratio of distance to diameter, and the ratio of distance to diameter has little effect on the interaction factor when pile spacing is more than 10 d (d is the diameter of the pile). The error between the field test results and computed data is 14.9%, the settlement calculated by the present method shows good agreement with the reported results, and the correlativity coefficients R^2 are greater than 0.9223, which signifies that the present method is suitable for the theoretical calculation and prediction of the composite foundation settlement of linear viscoelastic soil when piles are used to strengthen the foundation. The method would provide a unique view to quantitative prediction of the settlement characteristic of group pile foundation.

1. Introduction

Settlement characteristic is a common parameter in group pile foundation design, which plays a crucial role in engineering applications [1]. Several analytical [2], numerical [3], and experimental studies [4] have been made on the group piles that can predict immediate settlements with good accuracy. Mishra and Patra [5] investigated the creep settlement of group piles for line group piles, square group piles, and rectangular group piles undergoing creep settlements over a period of time and the fluctuations of interaction factors on parameters such as pile length to diameter ratio, pile spacing, Poisson's ratio, and modulus ratio. The results of the analysis showed that the load rearrangement due to creep settlements causes about a 5% to 35% increase in base resistance over time. Interaction factors for group piles (2×1, 3×1, 2×2, and 3×2) undergoing creep settlement are about 15% to 55% higher than the interaction factors, considering only the immediate settlements for group pile spacing less than or equal to 5 d. Li et al. [6] proposed a semianalytical solution to analyze the long-term settlement of a single pile embedded in fractional derivative viscoelastic soils under time-dependent loading. Three well-documented cases were used to verify the correctness and reliability of the semianalytical solution, and the results indicate that the dimensionless settlement for fractional derivative viscoelastic models is larger in the early stage and smaller in the later stage than those for conventional viscoelastic models. Kumar et al. [7] investigated the application of relevance vector machines (RVM), generalized regression neural network (GRNN), genetic programming (GP) and adaptive-network-based fuzzy inference (ANFIS) in reliability analysis of settlement of group pile in the normally consolidated clay. The research concludes that the performance of ANFIS is found to be perfect, followed by RVM and GP, giving comparably good performance.

The settlement behavior of a group pile foundation is primarily caused by the material properties of the piles [8–11], the load form of the foundation [12], and soil characteristics [13]. In general situations, it is known that the rheological properties of soils and the elastic-plastic settlement of piles should be considered in practice. Over the last decades, due to the complexity of rheological settlement of soil and the assumption that it only accounts for a small part of the total settlement of group piles, the analysis of group pile settlement in linear viscoelastic soil has been limited, and the research on group pile settlement considering the elastic-plastic settlement of piles is even less. It is however essential to investigate the settlement of linear viscoelastic soil for structures such as high-rise buildings and high-speed railway, bridges, and other important structures because excessive settlements may create severe safety issues.

Based on the interaction factors, the finite element model of the interaction factors of group piles was established by Zhe et al. [14], and the method of calculating the plastic settlement of group piles by data regression is advanced. Several experimental results reveal that the total settlement of a group pile foundation under constant stress is the result of elasto-plasticity settlement of the pile and rheological settlement of the soil. However, the influence of two kinds of settlements on group pile foundations has not yet been elaborated. In this paper, we try to establish a settlement calculation method for group pile foundations by considering the interaction factors between piles. The new method would provide a new insight into settlement analysis and optimization of the bearing capacity of group pile foundations under constant stress.

2. Calculation for Rheological Settlement of Soil Around a Pile

The existing rules for settlement characteristic calculation, such as the Booker and Poulos laws [15], cannot guide the calculation and prediction of settlement characteristics well in soil around piles after decades of research. It is well known that the key process during pile foundation design is determining settlement characteristics. Among them, the generally accepted settlement characteristic theory was proposed by Mattes and Poulos [16].

The settlements of soil around pile can be derived from the settlement characteristic theory as proposed by the Mattes and Poulos [16] and can be generalized as follows:

$$\{\rho\} = \frac{P}{\pi d^2}\left(\frac{c_0}{E_\infty}[I_S]\{r_o\} + \sum_{i=1}^{n}\frac{c_i[I_S]\{r_i\}}{E_\infty\left(1-\left(kE_p\lambda_i/E_\infty\right)\right)}\right), \quad (1)$$

where $[I_s]$ is the displacement influence matrix; E_∞ is the "long-term" elasto-plasticity modulus; $\{r_o\}$ and $\{r_i\}$ are the coefficient matrices; P is the load; c_0 are c_i is the logarithmic settlement rates; E_p is the elastic modulus; λ_i is the eigenvalue parameter; d is the pile diameter; k is the pile-soil elastic modulus ratio; and n is the number of piles.

3. Calculation of Interaction Factors

Figure 1 shows a 2×2 group pile with pile spacing S. The interaction factors among piles are equal to the summation of the interaction effects between the elements of the same pile and the interaction effects between the elements of the adjacent piles [17]. The effect factors of pile-pile interaction factors mainly include pile length, pile diameter, elastic modulus and Poisson's ratio of pile, elastic modulus and Poisson's ratio of soil around pile, pile number and pile spacing. In order to simplify dimensional analysis, only two piles are considered. For other group pile configurations, the dimensional analysis of two piles can be used as an analogy.

According to the three-parameter viscoelastic model and Guo's theory [18], the pile-pile interaction factors can be written as a function of the following main physical quantities:

$$\alpha_{ij} = f\left(P, l_1, d_1, E_{p1}, \nu_{p1}, l_2, d_2, E_{p2}, \nu_{p2}, E_s, \nu_s, S\right), \quad (2)$$

where α_{ij} is the interaction factor of piles; P is the constant load; l_1 and l_2 are the lengths of two piles; d_1 and d_2 are the diameters of two piles; E_{p1} and E_{p2} are the elastic moduli of two piles; E_s is the elastic modulus of soil around the pile; ν_s is Poisson's ratio of soil around the pile; and S is the pile spacing.

Randolph and Wroth [19] pointed out that the Poisson's ratio of the pile has little influence on the capacity and displacement of the pile and thus on the interaction factors of the pile-pile. Therefore, in order to simplify the analysis, the influence of Poisson's ratio of pile is not considered. At the same time, considering that the pile diameter and elastic modulus are basically the same in actual pile foundation engineering, the same pile diameter and length are adopted. Therefore, equation (2) can be simplified as follows:

$$\alpha_{ij} = f\left(P, l, d, E_p, E_s, \nu_s, S\right). \quad (3)$$

According to "Π theorem" [20] (when a physical phenomenon can be described by the functional relationship of n physical quantities, and n physical quantities including m basic dimensions, then a dimensionless group with $n=m$ can be obtained by dimensional analysis, and the characteristics of this phenomenon can be expressed in the form of n-m dimensionless groups), under the action of unit force, six dimensionless groups can be deduced (using d to eliminate the dimensions of l and S, and using E_s to eliminate the dimensions of E_p)

$$\frac{E_s\alpha_{ij}}{d} = f\left(\frac{l}{d}, \frac{E_p}{E_s}, \frac{S}{d}\nu_s\right), \quad (4)$$

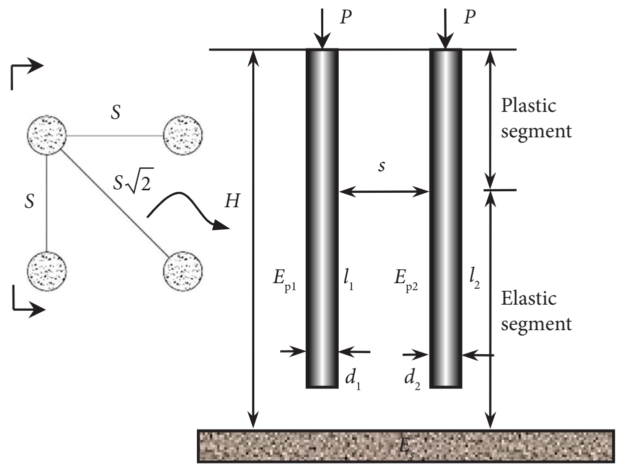

FIGURE 1: A 2 × 2 pile configuration depicting interaction between the piles.

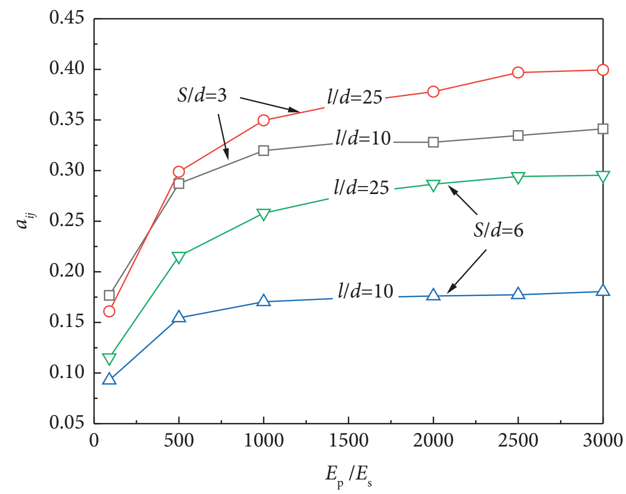

FIGURE 2: Influence of the k on pile-pile interaction factor ($S/d = 3$, $S/d = 6$).

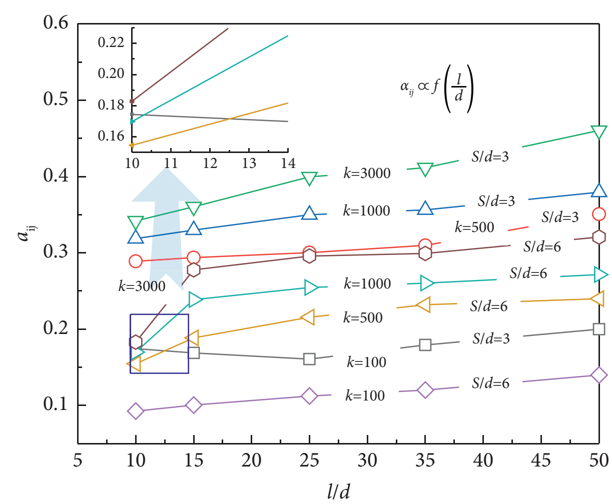

FIGURE 3: Influence of l/d on the pile-pile interaction factor ($S/d = 3$, $S/d = 6$).

where $E_s\alpha_{ij}/d$ indicates the behavior of the pile-pile interaction factors; l/d is the slenderness ratio of pile; E_p/E_s is the modulus ratio between the pile and the foundation soil; S/d is the distance-diameter ratio between two piles; and ν_s is Poisson's ratio of foundation soil.

Equation (4) illustrates that the interaction factors are related to the pile-soil elastic modulus ratio, slenderness ratio, distance-diameter ratio, and Poisson's ratio of the foundation soil. The effects of pile-soil elastic modulus ratio, slenderness ratio, and pile spacing-to-diameter ratio have been statistically analyzed in numerous research studies [21].

3.1. Effect of Pile-Soil Elastic Modulus Ratio on Interaction Factors. It can be observed in Figure 2 that when the pile spacing-to-diameter ratio S/d is constant, the pile-pile interaction factors increase with the increase of the pile-soil elastic modulus ratio k. When k is greater than 500, with the increase of pile-soil elastic modulus ratio, the pile-pile interaction factor has a slight increase.

3.2. Effect of Slenderness Ratio on Interaction Factors. Considering the effect of slenderness ratio on interaction factors, in 3 × 3 group piles with $S/d = 3$ and $S/d = 6$, l/d is 10, 15, 25, 35 and 50 respectively. It can be observed in Figure 3 that when the pile spacing-to-diameter ratio S/d is constant, the pile-pile interaction factors have steady increases with the increase of the length-to-diameter ratio l/d.

3.3. Effect of Pile Spacing-to-Diameter Ratio on Interaction Factors. Considering the effect of S/d on interaction factors, in 3 × 3 group piles with $S/d = 3$ and $S/d = 6$, l/d is 2, 3, 4, 5, 6, 10, and 20, respectively. It can be observed in Figure 4 that when the ratio of elastic modulus of pile to soil is constant, the interaction factors of pile and pile decrease with the increase of the ratio of distance to diameter S/d. The ratio of distance to diameter has little effect on the interaction factor when pile spacing is greater than 10 d, consistent with the reported literature (Guo [22] and Liang et al. [23]).

3.4. Data Regression. The above discussion results show that the length-to-diameter ratio l/d has little influence on the pile-pile interaction factor. Therefore, the function relation of pile-pile interaction factor α_{ij} can be expressed as follows:

$$\alpha_{ij} = f\left(\frac{S}{d}, k\right). \tag{5}$$

According to date regression analysis, the parameters b_1, b_2, and b_3 in the equation can be calculated, respectively, assuming that k is a constant value, as shown in Table 1, and the simplified equation of the pile-pile interaction factor is as follows:

$$\alpha_{ij} = \frac{k}{b_1 + b_2 (S/d)^3 + b_3 \ln (S/d)}. \tag{6}$$

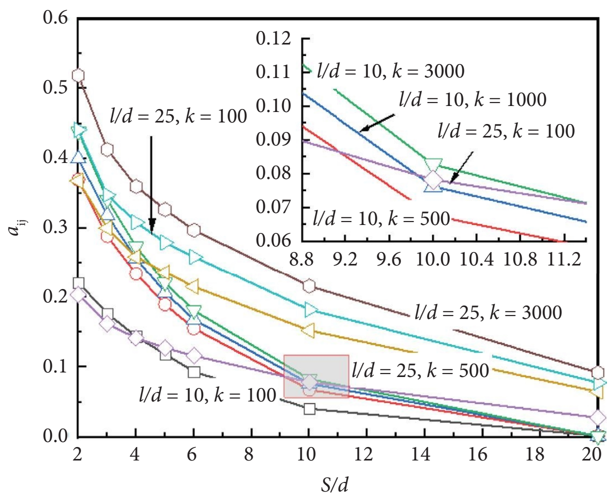

FIGURE 4: Influence of S/d on the pile-pile interaction factor ($l/d = 10$, $l/d = 25$).

4. Calculation of Total Settlement of Group Pile Foundation

We neglected the influence of plastic deformation on the bearing capacity of group piles in the process of analyzing pile-pile interaction factors in the previous section. It should be pointed out that the total settlement of group pile foundation includes both elastic settlement and plastic settlement. Therefore, the deformation calculation of a group pile foundation can be divided into three parts and is expressed as follows:

TABLE 1: Parameters value.

k	b_1	b_2	b_3
100	2.928	0.018	2.081
500	1.603	0.010	1.462
1000	1.550	0.010	1.247
3000	1.315	0.009	1.222

$$S_{pg} = nR_sS_e + nS_p + \{\rho\}, \tag{7}$$

where S_{pg} is the total settlement of group pile foundations; S_e is the elastic deformation part of single pile displacement; R_s is the settlement ratio of group piles; S_p is the plastic deformation part of single pile displacement; $\{\rho\}$ is the rheological settlement of soil around pile; and n is the number of piles.

4.1. Calculation of Elastic Deformation S_e of Single Pile.

In actual engineering, the load-displacement curve of a single pile includes two deformations: elastic deformation and irrecoverable plastic deformation [24] (Figure 5).

According to the pile configuration, the elastic deformation of a single pile can be determined by a load-displacement test. If there is no test data, the elastic deformation of a single pile can be determined through the settlement calculation method of a single pile proposed by Randolph and Wroth [19]. The specific calculation method can be expressed as follows:

$$K_e = \frac{P}{w} = \frac{E_{s1}d}{4(1+\nu)}\,\frac{(4/(1-\nu))(\eta/\zeta) + (4\pi\overline{\rho}/\xi)(l/d)(\tan h(\mu l)/\mu l)}{1 + (8/1-\nu)(\eta_1/\zeta)(1/\pi\lambda)(l/d)(\tan h(\mu l)/\mu l)}, \tag{8}$$

where P is the top load of the pile; w is the top displacement of the pile; E_{s1} is the elastic modulus of the soil at the pile bottom; d is the diameter of the pile; l is the length of the pile; ν is Poisson's ratio of soil; $\eta = E_{s0}/E_{s1}$; and

$$\lambda = 2(1+\nu)\frac{E_p}{E_{s1}};\ \zeta = \frac{E_{s1}}{E_b};\ \overline{\rho} = \frac{\overline{E}_s}{E_b},$$

$$(\mu l)^2 = \left[\frac{2}{(\xi\lambda)}\right]\left(\frac{2l}{d}\right)^2, \tag{9}$$

$$\xi = \ln\left\{[0.25 + (2.5\overline{\rho}(1-\nu) - 0.25)\zeta]\frac{2l}{d}\right\}.$$

The physical meaning of the parameters is shown in Figure 6.

Then, the elastic deformation of a single pile can be obtained

$$S_e = \frac{P_{max}}{K_e}. \tag{10}$$

4.2. Calculation of Settlement Ratio R_s of Group Piles.

The settlement ratio of group piles is greatly influenced by the number of piles n, and increases with the increase of n. Poulos and Davis [25] analyzed the relationship between R_s and n of group piles in homogeneous soil, and found that when the number of piles is large, the relationship between R_s and the square root of the number of piles n is linear. From the point of view of application, for group piles with a large number of piles ($n > 25$), the R_s can be approximately calculated according to the following equation:

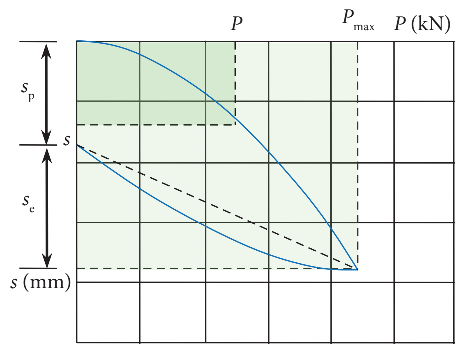

Figure 5: Elastic and plastic deformation of a single pile.

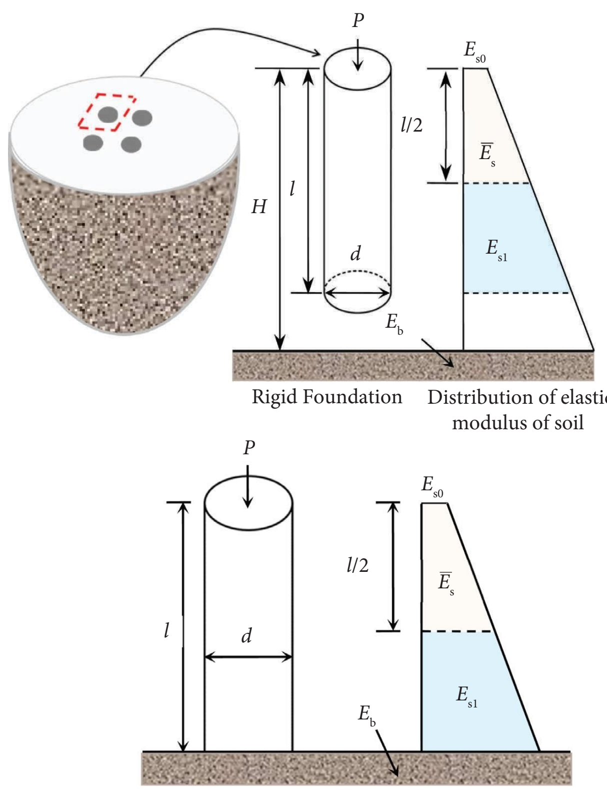

Figure 6: Definition of pile-soil geometric conditions.

$$R_s = R_{25}\left(\sqrt{n} - 4\right) + \left(5 - \sqrt{n}\right)R_{16}, \tag{11}$$

where 16 and 25 are the numbers of piles.

Based on equations (1)–(11), the total settlement of group piles could be derived as follows:

$$\begin{aligned} S_{pg} &= \left[R_{25}\left(\sqrt{n} - 4\right) + \left(5 - \sqrt{n}\right)R_{16}\right]\frac{4nP_{\max}(1+\nu)}{E_{s1}d}\,\frac{1+\psi\left(2\eta_1/\zeta\right)(1/\pi\lambda)(l/d)\phi}{\psi(\eta/\zeta)+\left(4\pi\overline{\rho}/\xi\right)(l/d)\phi} \\ &\quad + nS_p + \frac{P}{\pi d^2}\left(\frac{c_0}{E_\infty}\left[I_S\right]\left\{r_o\right\} + \sum_{i=1}^{n}\frac{c_i\left[I_S\right]\left\{r_i\right\}}{E_\infty\left(1-\left(kE_p\lambda_i/E_\infty\right)\right)}\right), \\ \psi &= \frac{4}{1-\nu}, \phi = \frac{\tanh(\mu l)}{\mu l}. \end{aligned} \tag{12}$$

5. Parametric Studies

5.1. Verify the Rationality of the Proposed Method

5.1.1. Example I. According to the research of O'Neill et al. [26] reported, 11 piles were driven into linear viscoelastic soil. The diameter of the pile is 137 mm, and the buried length of the pile is 13.1 m. Among them, 4 piles are arranged in a 3×3 square and connected with a concrete cap, and the cap is not in contact with the soil below. The pile spacing is $S = 3d$, and the other two piles are 3.7 m on both sides of the center group pile.

Specific parameters: the elastic modulus of soil $E_s = 1.95 \times 10^5$ kPa, Poisson's ratio of soil $\nu = 0.4$, and the elastic modulus of concrete pile $E_p = 2.1 \times 10^8$ kPa. Average load of single pile in group pile is $P = 653$ kN. The load-displacement curve of single pile test is shown in Figure 7. Parameter $S/d = 3$, $E_{\text{p}} = E_{\text{s}} = 1077$. Due to the lack of unloading curve in pile test, the method proposed in this paper is used to define the elastic stiffness of pile: $K_e = 608$ kN/mm, thus $S_e = P/K_e = 1.07$ mm, and $P = 653$ kN. According to the above principle, the settlement of group pile can be calculated as $S = 7.26$ mm. The measured settlement of group pile is 6.63 mm, and the results demonstrate that the error between the field test results and computed data is 14.9%, which signifies that the present method is suitable for the theoretical calculation and predict the composite foundation settlement of linear viscoelastic soil when piles are used to strengthen the foundation.

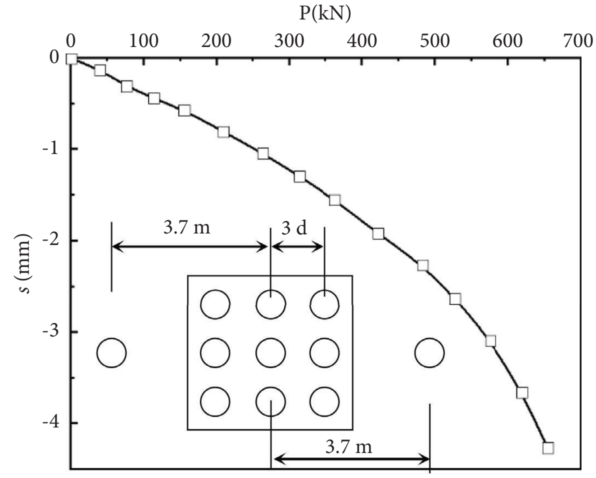

FIGURE 7: Comparison of the capacity of a single model pile.

5.1.2. Example II. In order to further study the settlement characteristics of group piles in linear viscoelastic soil, based on the parameters of the soil layer and piles in a large-scale field group pile test [27] and according to the total settlement calculation method of our paper, the load-settlement curves and group pile settlement-interaction factor curves under different types of group piles, different pile lengths, and different pile spacing (Figure 8) are analyzed. The parameters of pile length, pile spacing, pile cap size, and slenderness ratio are shown in Tables 2, and Table 3 summarizes the soil properties of each soil layer crossed by the test piles.

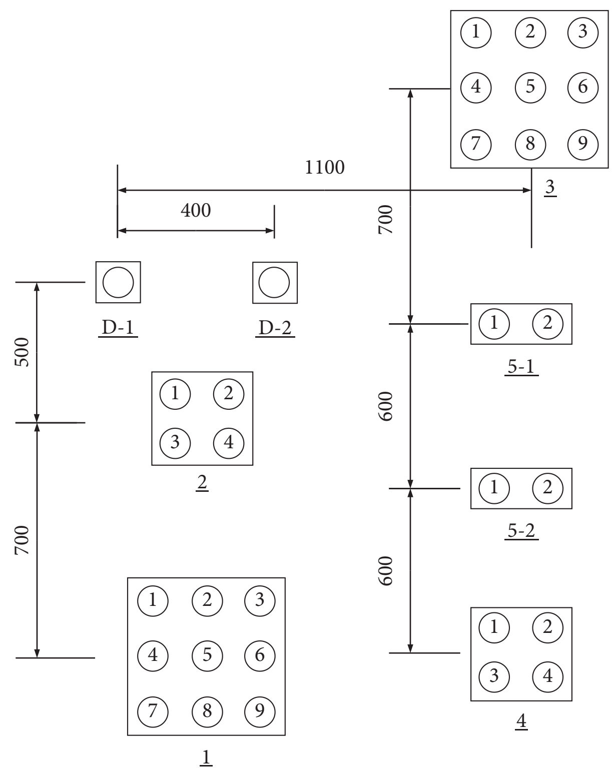

FIGURE 8: Layout plan of test piles and group piles.

Based on the concept of elasticity theory, considering the rheological settlement of soils, we can get the implied interaction factors of group piles as follows:

$$\alpha_{ij} = \Lambda(\lambda L, \Omega) \frac{\ln\left(r_m/s_{\text{pij}}\right)}{\ln\left(2r_m/B\right)} \geq 0, \tag{13}$$

where

$$\Omega = \frac{Q_b}{w_b E_p A_p \lambda} = \frac{4G_b r_s}{1-\nu} \frac{1}{\lambda E_p A_p},$$

$$\lambda = \sqrt{\frac{k}{E_{\text{p}} A_{\text{p}}}}, \tag{14}$$

$$r_m = \left\{0.25 + \left[2.5(1-\nu)\frac{G}{G_L} - 0.25\right]\frac{G_L}{G_b}\right\} L.$$

Based on the interaction factor obtained by equation (13), the load-settlement relationship can be obtained as shown in Figure 9, and the relationship curve between the interaction factor and the settlement of different pile types is shown in Figure 10.

Figure 9 presents the solutions from the present method and Guoliang Dai's, where the present solutions consider the rheological settlement of soils. The total settlement calculated by the present method shows good agreement with the reported results, and the correlation coefficients R^2 are greater than 0.9223.

The relationship between settlement and interaction factor of different pile types is shown in Figure 10 α_{ij}

Table 2: Summary of field tests.

No. of piles	Pile length (m)	Pile spacing	Pile cap sizes (length × width × height; all in metres)	Slenderness ratio (L/B)
D-1	20	—	0.4 × 0.4 × 0.4	50
D-2	24	—	0.4 × 0.4 × 0.4	60
5–2	20	2.5B	1.8 × 0.8 × 0.8	50
5–1	24	3.0B	2.0 × 0.8 × 0.8	60
D-1	20	—	0.4 × 0.4 × 0.4	50
4	20	2.5B	1.8 × 0.8 × 0.8	50
2	24	3.0B	2.0 × 2.0 × 0.8	60
3	20	2.5B	2.8 × 2.8 × 1.2	50
1	24	3.0B	3.2 × 3.2 × 1.2	60

indicates the ratio of the settlement of pile i under load to the settlement of adjacent pile j. For group pile types with different pile lengths (Figure 10(a)), the interaction factor increases and then decreases with the increase in group pile settlement, and the longer the pile length, the smaller the influence on the interaction factor, and the interaction coefficient for the two-group piles L_1 is practically zero. This may be because of the spatial variability of the soil or other variability in the pile installation or pile cap. For the group pile types as shown in Figure 10(b), it is not difficult to see that pile spacing has a larger effect on interaction than pile length. For the 3×3 group pile types, it can be seen from Figure 10(c) that the settlement of the corner pile is the largest and that of the middle pile is the smallest, and the interaction factors are distributed proportionally to pile center-to-center spacing. Similar conclusions can also be drawn from Figure 10(d). Comparing Figures 10(a) and 10(b) with Figures 10(c) and 10(d), it can be seen that when the pile spacing is the same, the interaction factor of the piles in the four group piles is greater than that of the nine group piles.

5.2. Parametric Studies. The calculation method in this paper involves many design parameters, such as pile spacing, slenderness ratio, pile-soil elastic modulus ratio, Poisson's ratio, etc. It is of great significance for optimal design to explore the influence law of each design parameter on the working performance of a group pile foundation. Therefore, the example of group pile foundation in Booker and Poulos [15] is selected for parameter analysis, and the influence laws of pile end resistance, pile spacing, slenderness ratio, elastic modulus ratio and Poisson ratio on pile end load ratio, and interaction factors are studied by the calculation method proposed in this paper.

5.2.1. Pile Spacing. Figure 11 shows the relationship of pile spacing and interaction factor when the ratio of pile spacing to interaction factor is $S/d = 1, 2, 3, \ldots, 19$, the slenderness ratio $l/d = 10$, 50, 100, and the calculation elastic modulus ratio of pile-soil $E_p/E_s = 1000$, Poisson's ratio of soil is 0.5. It can be seen from Figure 11 that the interaction factor decreases with the increase of pile spacing, and the interaction factor decreases with the increase of pile length, but the influence of pile length on the interaction factor can be neglected with the increase of pile spacing.

5.2.2. Slenderness Ratio. Figure 12 shows the relationship between interaction factor and slenderness ratio at different slenderness ratios $l/d = 10, 20, \ldots, 100$, pile spacing, and diameter ratio $S/d = 2$, 3, 4, and 5. It can be seen from Figure 12 that the interaction factor decreases with the increase of slenderness ratio. When slenderness ratio is a constant value, the interaction factor decreases with the increase in pile spacing, which is the same as the conclusion in 5.2.1.

5.2.3. Pile-Soil Elastic Modulus Ratio. Figure 13 shows the relationship between interaction factor and pile-soil elastic modulus ratio at different pile spacing and diameter ratios. It can be seen from Figure 13 that the interaction factor decreases with the increase in pile spacing. When the pile spacing is constant, the interaction factor increases with the increase in the pile-soil elastic modulus ratio, which is consistent with the conclusion of Poulos and Davis [25].

5.2.4. Poisson's Ratio. Figure 14 shows the influence of different Poisson's ratios on the interaction factor. When $S/d = 15$, Poisson's ratio changes from 0 to 0.5, and the interaction factor decreases by 25%. The interaction factor decreases with the increase in pile spacing. At the same time, the larger the group pile spacing, the more obvious it is that the Poisson's ratio affects the interaction factor, and the same conclusion can be found in [28].

TABLE 3: Soil properties.

Soil	Direct shear test, curve-fit strength envelope		One-dimensional consolidation test		Thickness (m)	Unit weight, γ (kN/m^3)	Void ratio, e_0	Plasticity index, I_p	Liquidity index, I_L
	Cohesion (kPa)	Internal friction angle (φ)	α_{1-2} (MPa^{-1})	E_s (MPa)					
Fill	38	17.4	0.30	6.07	2.6	19.2	0.76	16.0	0.42
Clay	50	18.5	0.23	7.65	2.0	19.6	0.71	17.2	0.28
Silt	11	22.5	0.25	7.56	5.6	18.5	0.85	5.8	0.60
Silt intermixed with silty sand	13	23.7	0.20	8.88	7.3	18.8	0.79	5.0	0.64
Soft clay	15	8.3	0.67	3.40	11.6	17.4	1.24	21.7	0.96

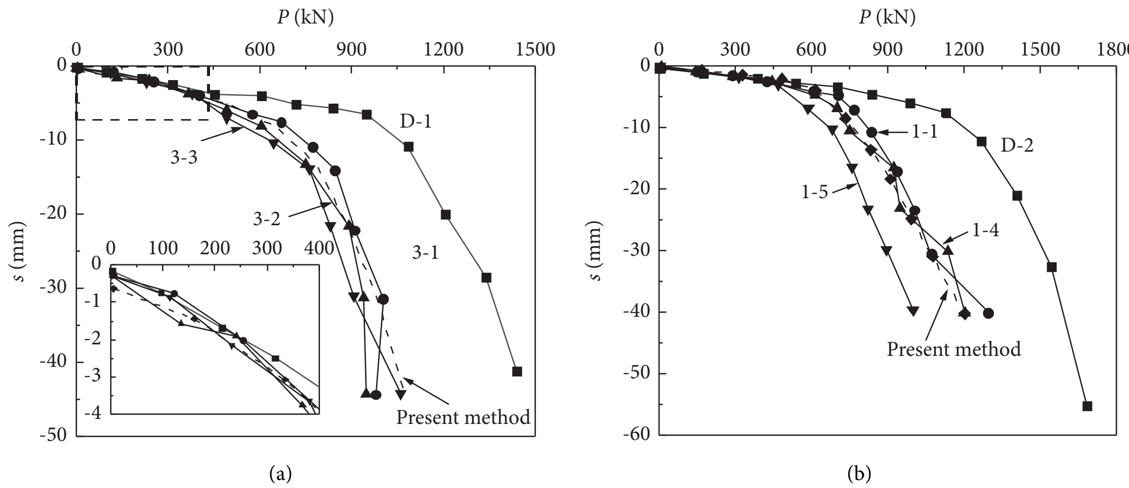

Figure 9: Individual pile load versus group settlement relationship based on the interaction factor. (a) Pile length $L = 20$ m. (b) Pile length $L = 24$ m.

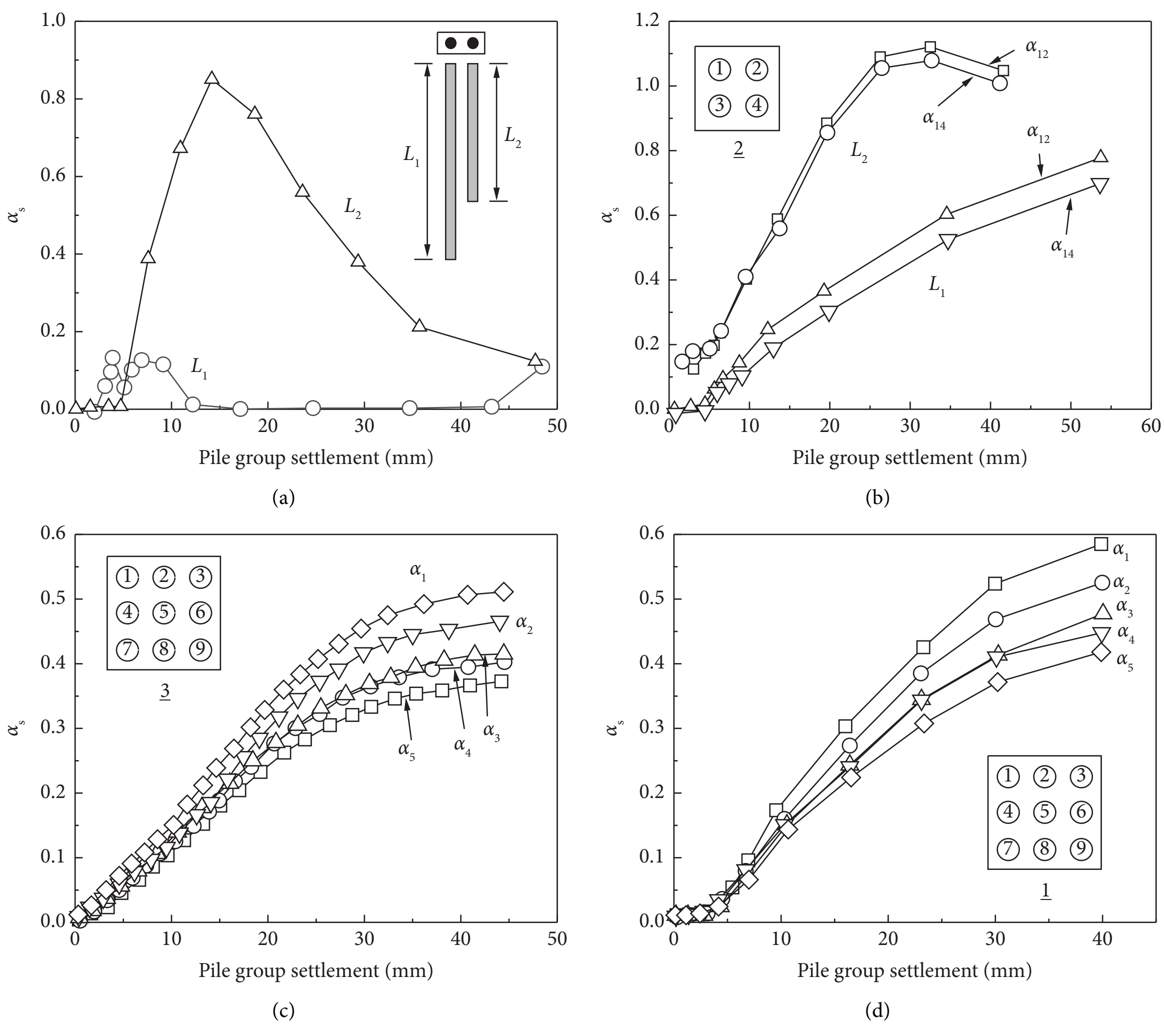

Figure 10: Interaction factor versus settlement for each group pile. (a) Two-group pile with $L_1 = 24$ m and $L_2 = 20$ m, (b) four-group pile with $L_1 = 24$ m and $L_2 = 20$ m, (c) nine-group pile with $L_2 = 20$ m, and (d) nine-group pile with $L_1 = 24$ m.

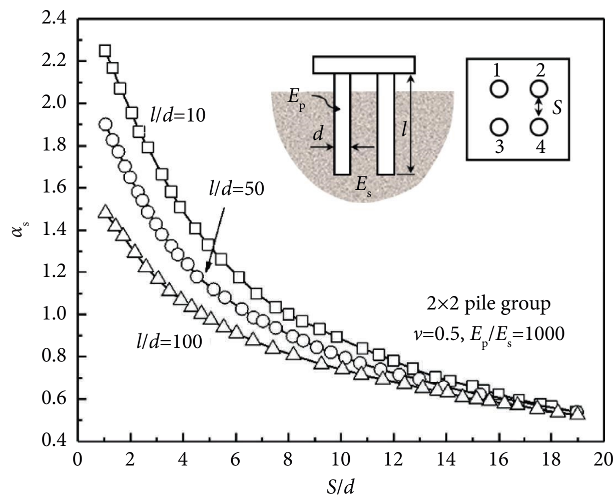

Figure 11: Effect of piles pacing for settlement on interaction factors of 2 × 2 group piles.

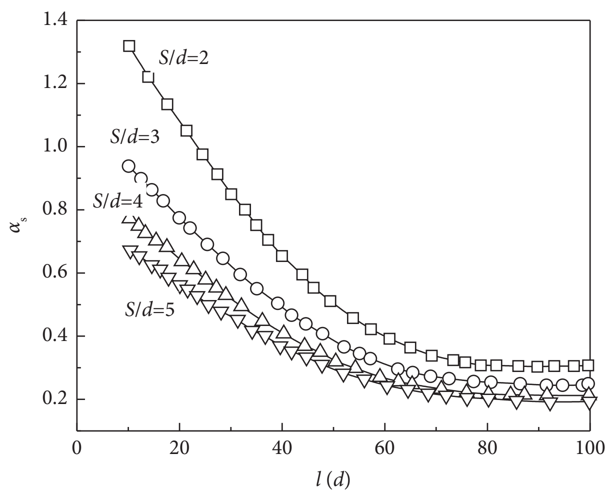

Figure 12: Influence of slenderness ratios l/d on interaction factor α_s.

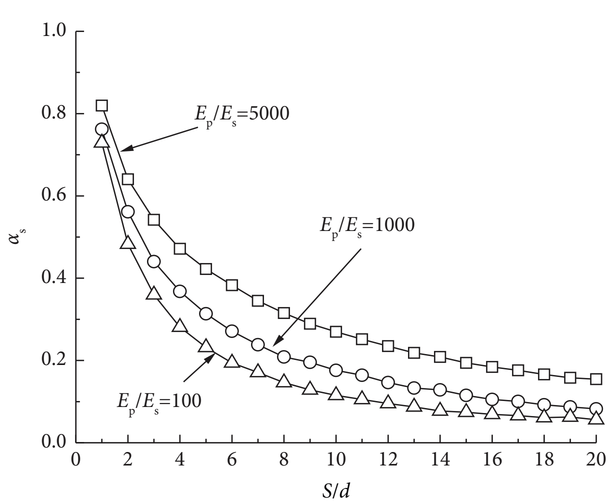

Figure 13: Influence of the pile-soil elastic modulus ratio E_p/E_s on interaction factor α_s.

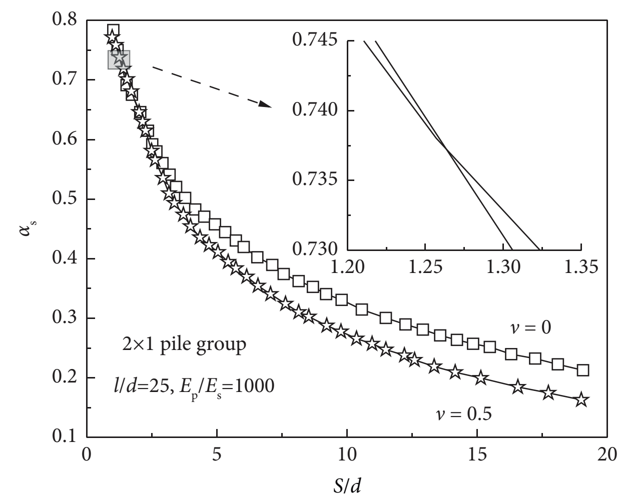

Figure 14: Influence of Poisson's ratio on interaction factor α_s.

6. Conclusions

In the current paper, we present a method to study the settlement behaviors of group pile foundation in linear viscoelastic soil. In this method, the variation of linear viscoelastic soil settlement with pile spacing, length-diameter ratio, elastic modulus ratio, and Poisson's ratio was investigated, and the results were validated through comparison with the field test results. Based on the results, we obtained the following key conclusions:

(1) The pile-pile interaction factors increase with the increase of the pile-soil elastic modulus ratio and length-to-diameter ratio but decrease with the increase of the ratio of distance to diameter, and the ratio of distance to diameter has little effect on the interaction factor when pile spacing is more than 10 d (*d* is the diameter of the pile).

(2) The settlement variation of a group pile foundation in linear viscoelastic soil calculated by the present method is consistent with field test results.

Furthermore, according to the present method, the settlement of a group pile can be calculated at 7.26 mm, while the measured settlement of a group pile is 6.63 mm, and the results demonstrate that the error between the field test results and computed data is 14.9%, which signifies that the present method is suitable for the theoretical calculation and can predict the composite foundation settlement of linear viscoelastic soil when piles are used to strengthen the foundation.

(3) The interaction factor of a group pile can represent the settlement characteristics of a group pile foundation, and with the increase of pile number, the settlement of a group pile is linearly positively correlated with the interaction factor.

(4) The interaction factors-based method can estimate the total settlement of a group pile foundation under constant stress.

It is worth noting that this study only pays attention to the total settlement of group pile foundations under static load, excluding the settlement caused by dynamic load.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] H. Li, X. Li, and X. Qin, "Study on settlement characteristics of deep soft strata by vacuum preloading," in *Proceedings of the IOP Conference Series: Earth and Environmental Science*, vol. 783, no. 1, Zhangjiajie, China, April 2021.

[2] J. J. Xu, X. Xu, and W. J. Yao, "New method for calculating the settlement of single pile and pile group in soft soil area," *Advances in Civil Engineering*, vol. 2020, Article ID 8816704, 9 pages, 2020.

[3] L. Yang, W. Y. Xu, and K. K. Li, "Analysis of the embankment settlement on soft soil subgrade with a cement mixed pile," *Advances in Civil Engineering*, vol. 2021, pp. 1–15, 2021.

[4] R. Cairo and E. Conte, "Settlement analysis of pile groups in layered soils," *Canadian Geotechnical Journal*, vol. 43, no. 8, pp. 788–801, 2006.

[5] A. Mishra and N. R. Patra, "Analysis of creep settlement of pile groups in linear viscoelastic soil," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 43, no. 14, pp. 2288–2304, 2019.

[6] X. m. Li, Q. q. Zhang, and Sw Liu, "Semianalytical solution for long-term settlement of a single pile embedded in fractional derivative viscoelastic soils," *International Journal of Geomechanics*, vol. 21, no. 2, Article ID 04020246, 2021.

[7] M. Kumar, P. Samui, D. Kumar, and W. Zhang, "Reliability analysis of settlement of pile group," *Innovative Infrastructure Solutions*, vol. 6, no. 1, pp. 24–17, 2020.

[8] M. Y. Fattah, M. A. Yousif, and S. M. Al-Tameemi, "Effect of pile group geometry on bearing capacity of piled raft foundations," *Structural Engineering & Mechanics*, vol. 54, no. 5, pp. 829–853, 2015.

[9] M. Y. Fattah, N. M. Salim, and A. M. Al-Gharrawi, "Effect of soil plug removal on the load-carrying capacity of symmetric and non-symmetric pile groups," *Ships and Offshore Structures*, vol. 15, no. 9, pp. 911–933, 2020.

[10] M. Y. Fattah, N. M. Salim, and A. M. B. Al-Gharrawi, "Effect of arrangement of plugged and unplugged pipe pile group on the contribution ratios for friction and end resistance capacity," *Soil Mechanics and Foundation Engineering*, vol. 59, no. 1, pp. 7–14, 2022.

[11] M. Y. Fattah, H. H. Karim, and M. K. M. Al-Recaby, "Investigation of the end bearing load in pile group model in dry soil under horizontal excitation," *Acta Geotechnica Slovenica*, vol. 18, pp. 79–106, 2021.

[12] M. Y. Fattah, H. H. Karim, and M. K. Al-Recaby, "Vertical and horizontal displacement of pile group model in dry soil under horizontal excitation," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 174, pp. 1–53, 2020.

[13] R. R. Al-Omari, M. Y. Fattah, and A. M. Kallawi, "Laboratory study on load carrying capacity of pile group in unsaturated clay," *Arabian Journal for Science and Engineering*, vol. 44, no. 5, pp. 4613–4627, 2019.

[14] H. Zhe, H. Xiao, and T. F. Wu, "Parameters analysis of pile to pile's interaction factors," *Engineering Design of the Ground*, vol. 3, pp. 77–79, 2013.

[15] J. R. Booker and H. G. Poulos, "Analysis of creep settlement of pile foundations," *Journal of the Geotechnical Engineering Division*, vol. 102, no. 1, pp. 1–14, 1976.

[16] N. S. Mattes and H. G. Poulos, "Settlement of single compressible pile," *Journal of the Soil Mechanics and Foundations Division*, vol. 95, no. 1, pp. 189–207, 1969.

[17] H. Noura, M. Salah, and A. Assia, "3D Analysis interaction of piles groups under vertical load," *Selected Scientific Papers - Journal of Civil Engineering*, vol. 16, no. 1, pp. 157–173, 2021.

[18] W. D. Guo, "Visco-elastic load transfer models for axially loaded piles," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 24, no. 2, pp. 135–163, 2000.

[19] M. F. Randolph and C. P. Wroth, "Analysis of deformation ofvertically loaded piles," *Journal of the Geotechnical Engineering Division*, vol. 104, no. 12, pp. 1465–1488, 1978.

[20] R. Bhaskar and A Nigam, "Qualitative physics using dimensional analysis," *Artificial Intelligence*, vol. 45, no. 1-2, pp. 73–111, 1990.

[21] S. Feng, X. Y. Li, F. Jiang, L. Lei, and Z. Chen, "A nonlinear approach for time-dependent settlement analysis of a single pile and pile groups," *Soil Mechanics and Foundation Engineering*, vol. 54, no. 1, pp. 7–16, 2017.

[22] W. D. Guo, *Theory and Practice of Pile Foundations*, CRC Press, Boca Raton, FL, USA, 2012.

[23] F. Liang, Z. Song, and W. D. Guo, "Group interaction on vertically loaded piles in saturated poroelastic soil," *Computers and Geotechnics*, vol. 56, pp. 1–10, 2014.

[24] M. Elshabrawy, M. A. Abdeen, and S. Beshir, "Analytic and numeric analysis for deformation of non-prismatic beams resting on elastic foundations," *Beni-Suef University Journal of Basic and Applied Sciences*, vol. 10, no. 1, pp. 57–11, 2021.

[25] H. G. Poulos and E. H. Davis, *Pile Foundation Analysis and Design*, John Wiley & Sons, New York, NY, USA, 1980.

[26] M. W. O'Neill, R. A. Hawkins, and L. J. Mahar, "Load transfer mechanisms in piles and pile groups," *Journal of the Geotechnical Engineering Division*, vol. 108, no. 12, pp. 1605–1623, 1982.

[27] G. Dai, R. Salgado, W. Gong, and Y. Zhang, "Load tests on full-scale bored pile groups," *Canadian Geotechnical Journal*, vol. 49, no. 11, pp. 1293–1308, 2012.

[28] W. D. Guo and M. F. Randolph, "Rationality of load transfer approach for pile analysis," *Computers and Geotechnics*, vol. 23, no. 1-2, pp. 85–112, 1998.