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Experimental and Numerical Study of Pile-to-Pile Interaction Factor in Sandy Soil

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Abstract

In structures to support large vertical and horizontal loads, piles are usually used in the form of closely spaced group. The piles in a group are not only affected by their individual loads transmitted from the pile cap, but also by additional loads transferred through the soil from the interference of neighboring piles. This group interaction influences the group stiffness, load-transfer mechanism and group settlement. In order to predict the response characteristics of pile groups, the interaction factors calculated using Mindlin's solution based on the theory of elasticity has been widely applied. The pile-to-pile interaction factor is defined as the ratio of displacements or rotations of an unloaded receiver pile to those of neighboring loaded source pile due to soil deformation. In this paper, a series of centrifuge model tests were carried out to examine the effect of soil relative density and pile spacing and pile tip condition on the interaction factor between two adjacent piles. Based on the results, soil relative density has a significant effect on the interaction between piles and thus it must be considered in the calculation of interaction factor. For this purpose, a correction to the Randolph and Wroth equation based on the test results was proposed in which the effect of soil relative density is contemplated. With an increase in the pile spacing, the value of interaction factor for all cases decreased. Compared to the effect of pile shaft, pile tip condition has a little effect on the interaction factor. The obtained results were also compared with those from a three-dimensional finite element analysis and a good agreement between the measured and the calculated results was observed.

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Keywords: pile-to-pile interaction factor; soil relative density; pile tip; centrifuge test; finite element method;

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Nomenclature

α_{ij}	Pile-to-pile interaction factor
D	Pile diameter (m)
t_p	Pile wall thickness (m)
S	Pile spacing (m)
D_r	Soil relative density
D_{50}	Particle mean diameter (m)
C_u	Soil uniformity coefficient
G_s	Soil specific gravity
e_{max},e_{min}	Soil maximum/minimum void ratio
E	Modulus of elasticity (MPa)
ν	Poisson's ratio
γ	Unit weight (kN/m^3)
c	Soil cohesion (kPa)
ϕ	Soil internal friction angle
ψ	Soil dilatancy angle
μ	Interface friction coefficient

1. Introduction

The majority of high-rise buildings and heavy structures are supported by pile groups or piled rafts (not only a single pile) to carry the applied load to stronger soil layer. Although it would be helpful to use a single pile capacity and deformation to predict the overall capacity and settlement of a pile group, it is also necessary to take into account the group effects. Thus, the pile-to-pile interaction factor α_{ij} for statically loaded vertical piles was introduced by Poulos [1] with regard to the group effects. The pile-to-pile interaction factor is defined as,

$$\alpha_{ij} = \frac{\text{displacements or rotations of an unloaded receiver pile } (i) \text{ due to soil deformation}}{\text{displacements or rotations of neighboring loaded source pile } (j)} \tag{1}$$

For pile groups and piled rafts in clay, the capacity of individual piles within a group may be lower than for equivalent isolated piles. For pile groups in sand, however, the capacity of each pile is usually taken as an isolated pile capacity [2] but providing a framework for calculating the pile-to-pile interaction factor results in controlling the settlement requirements in design process.

Several researchers have proposed different methods to determine this interaction factor. Randolph and Wroth [3] used shear displacement method for calculating interaction factors in order to determine the settlement of a pile group. El Sharnouby and Novak [4] presented flexibility coefficients and interaction factors to facilitate the analysis of pile group under vertical load by an analytical method. Mandolini and Viggiani [5] developed a program based on back analysis of field data to determine the pile group settlement considering the nonlinear behaviour of pile-soil interface and interaction factors. Polo and Clemente [6] used finite element method to show the interaction factors for different parameters in design charts. Recently, some other methods such as different analytical methods [7,8], experimental methods [9,10], hybrid load-transfer method [11], boundary element method [12] and finite element method [13,14] were also used to consider the pile-to-pile interaction factor in the analysis of pile groups and piled rafts.

In this study, based on the results of 100g centrifuge tests and three-dimensional finite element analyses, the value of pile-to-pile interaction factor α_{ij} was examined and the predicted values were compared with that from different approaches. From the regression analysis, a modification to the equation presented by Randolph and Wroth [3] has been made.

2. Experimental setup and test procedure

Full-scale field tests to consider the behaviour of piled raft foundation is costly and time-consuming and thus simulation of in-situ condition using model tests such as centrifuge tests would be helpful. The observations from the model can be converted to the prototype scale using the well-known scaling factors.

2.1. Testing equipment

The model tests were conducted in the IUST 14g-ton geotechnical centrifuge at Iran University of Science and Technology. The maximum capacity of this centrifuge with a 1 m radius is 140kg for centrifugal acceleration of 100g. The soil container was made from Plexiglas with steel frame, having inside dimensions of 0.60 m $\times$ 0.20 m in plan and 0.18 m in depth. Two model piles with the diameter of $D = 10mm$ and the wall thickness of $t_p = 0.5mm$ made of aluminium pipe ($E = 7 \times 10^4\ MPa$) were placed at different spacing (Fig 1a). The box and model dimensions were selected such that the effects of boundary and particle size is minimized. The loading was applied to the piles through weight mass on the top of piles. The settlements of soil and piles were measured by means of three LVDTs (Fig. 1b).

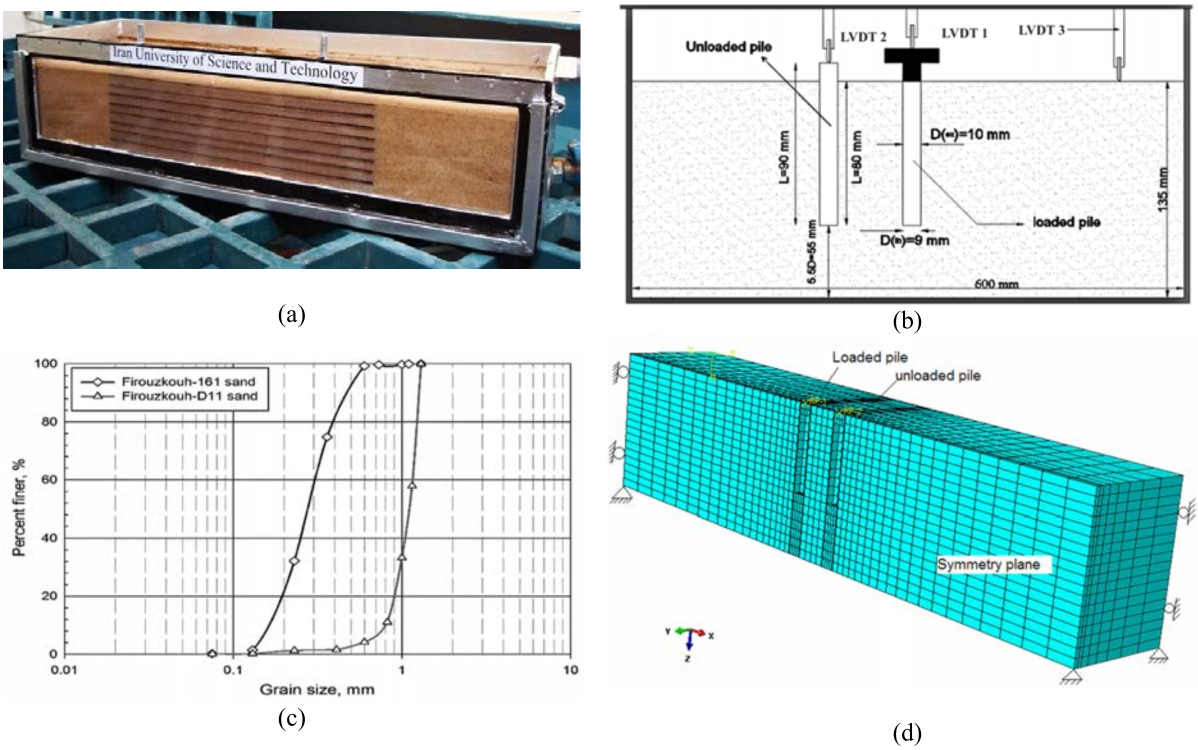

Fig. 1. (a) test box (b) experimental setup (c) Grain-size distribution of Firouzkouh-161 sand (d) FE mesh.

2.2. Test program and testing parameters

To determine the pile-to-pile interaction factor in sand, thirty-three centrifuge tests were conducted with a nominal acceleration of 100g. As it will be discussed, the effects of soil relative density (D_r=23%, 40%, 56%, 78%), pile center to center spacing (S / D =3, 5, 7, 9, 12) and pile tip condition (open-ended or close-ended) on the interaction factor were investigated. Firouzkouh-161 sand with a particle mean diameter of $D_{50} = 0.3mm$ and the uniformity coefficient of $C_U = 2.58$ was used for all centrifuge tests (Table 1 and Fig. 1c). The dry sand samples with a certain relative density were prepared in layers by pluvial deposition technique to achieve enough compaction. By conducting some control tests, the effect of centrifugal acceleration on the soil relative density was determined and these variations were considered in model preparation.

Table 1. Material properties [15].

Material		G_s	e_{max}	e_{min}	F.C. (%)	E (MPa)	Poisson's ratio, ν	γ (kN/m^3)	c (kPa)	$\phi(°)$	$\psi(°)$
Firouzkouh-161 sand		2.658	0.97	0.55	0.2	-	-	-	-	-	-
in Numerical model	Sand	-	-	-	-	20	0.20	18	0.3	32	2
	Pile	-	-	-	-	25000	0.15	24	-	-	-

3. Numerical analysis

In order to verify the effectiveness of centrifuge tests, the obtained results were compared to that from three-dimensional finite element analysis.

3.1. FE mesh and boundary condition

Fig. 1(d) shows a typical 3D finite element mesh used in the numerical analysis. The foundation was modelled on the prototype scale to simulate the real condition. The pile and soil were discretised by means of eight-node quadrilateral wedge elements and each mesh comprised of about 9000 elements. At the pile-soil interface, a relatively fine mesh was used to accurately consider the stress/strain gradients. To minimize the boundary effects, the distance from boundaries to the pile edge and tip were considered greater than the pile length (Taghavi Ghalesari and Rasouli, 2014). The lateral boundaries were just allowed to move downward to simulate the settlements and the bottom of the model was fixed in three perpendicular directions.

3.2. Modelling procedure

Because the piles are in elastic state under working load conditions, they were modelled by linear elastic model. The soil (Firouzkouh-161 sand) was modelled with Mohr-Coulomb model and material properties are listed in Table 1. The interactions with the soil at the pile skin were modelled by using thin-layer interface elements with the same material properties as soil [16]. For close-ended piles, at the soil-pile tip interface, the tangential and contact interactions were considered using interface friction coefficient of $\mu = 0.35$. Further information about the foundation modelling procedure and interface modelling technique which are used in this study can be found in Taghavi Ghalesari et al. [13] and Barari et al., [17]. After applying the gravity loading and initial equilibrium, the vertical load was applied to the pile head.

4. Comparative results and discussion

The effects of soil relative density, pile spacing and pile tip condition on the pile-to-pile interaction factor were considered in Fig. 2 and a comparison between the results of present experimental and numerical analysis was carried out. As illustrated in Fig. 2(a), in most cases, the interaction factor increases with increasing soil relative density but after $D_r = 56\%$ a slight increase was observed. For very close or wide-spaced piles, the effect of soil relative density was minimized. Fig. 2(b) shows the effect of pile tip condition on the pile-to-pile interaction factor, α_{ij} . From these figures, it is found that pile tip condition (open-ended or close-ended) has no considerable effect on the interaction factor, especially for wide-spaced piles.

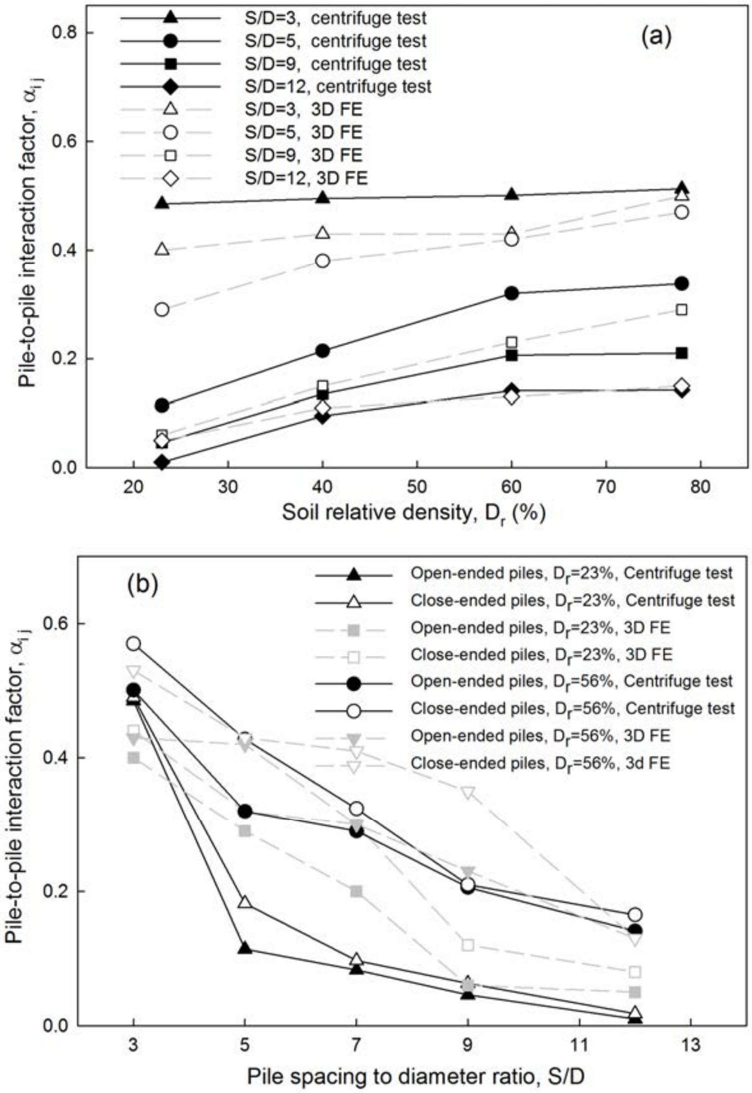

Fig. 2. The effect of (a) soil relative density and (b) pile tip condition on the interaction factor.

According to Fig. 3, when the pile distance (S) increases, the interaction factors decrease. This reduction is more obvious for piles in soils with lower relative densities. This is due to the fact that in loose sand the relative displacement at the pile-soil interface is much more than that in dense sand and thus the interaction effects will decrease. The values of pile-to-pile interaction factor from centrifuge tests and 3D FE analyses were compared to the values from Randolph and Wroth [3], Mandolini and Viggiani [5] and Polo and Clemente [6] in Fig. 3. It can be observed that regardless to the pile tip condition, the obtained interaction factors from Randolph and Wroth approach are in good agreement with that obtained from the present analysis, especially for soils with relative density higher that 50%. Their approach seems a little conservative because the effect of sliding between soil and pile was neglected and based on Mylonakis and Gazetas [11] this sliding should be taken into account. Mandolini and Viggiani [5] proposed two equations for estimating interaction factor and thus a range of values was depicted. The values of interaction factor from experimental and numerical analysis vary in this range. As shown in Fig. 3(a), the method proposed by Polo and Clemente [6] is relatively conservative for open-ended piles. From the results of experimental and numerical analysis and by means of regression analysis, a modification to the Randolph and Wroth equation was proposed, taking into account the effect of soil relative density as a logarithmic function.

$$\alpha_{ij} = \frac{Ln(\frac{r_m}{S})}{Ln(\frac{r_m}{r_0})} + (\frac{d_b}{\pi S}) + 0.211Ln(D_r) + 0.128 \tag{2}$$

where $r_m = 2.5L(1-0.5\nu)$, L is pile length, r_0 is the radius of pile, d_b is the diameter of pile tip, S is pile spacing and ν is soil Poisson's ratio. This equation with $R^2 = 92\%$ and RSME=0.05 shows a good performance in determining the pile-to-pile interaction factor.

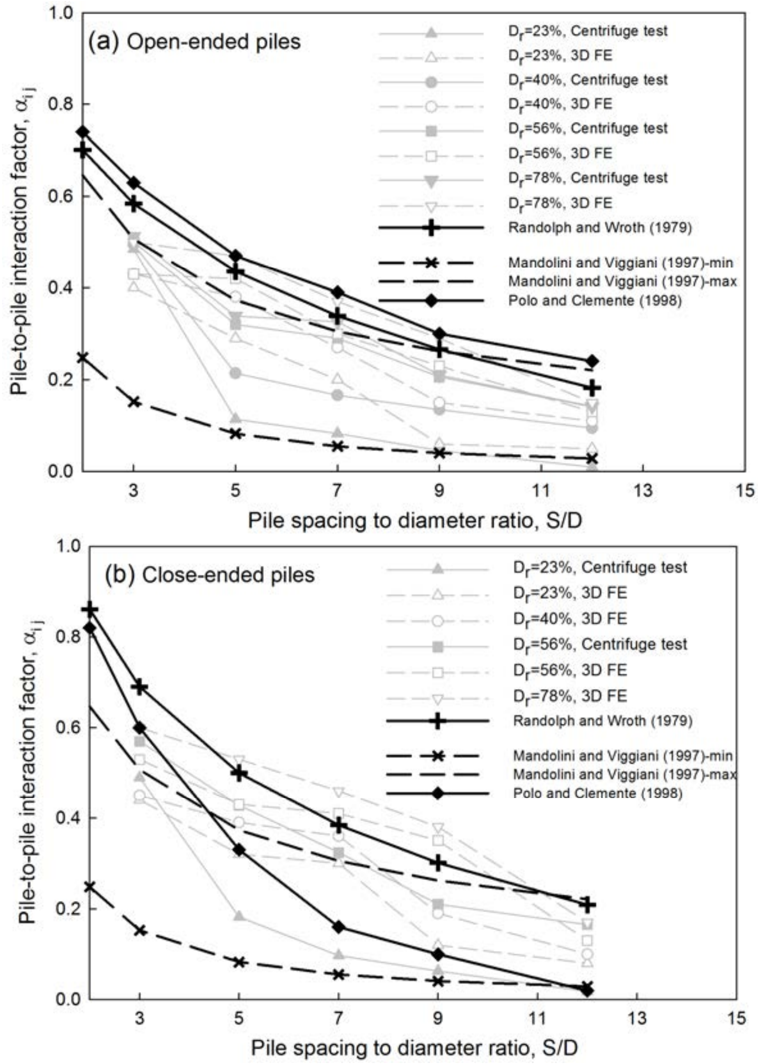

Fig. 3. Comparison between the results from present analysis and those from Randolph and Wroth [3], Mandolini and Viggiani [5] and Polo and Clemente [6] for (a) open-ended (b) close-ended piles.

5. Conclusions

Based on the results of experimental and 3D FE analyses, the effect of soil relative density and pile spacing and pile tip condition on the pile-to-pile interaction factor was examined and the obtained results were compared with the existing method. Eventually, a correction to the Randolph and Wroth equation was proposed with great accuracy.

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