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Effect of pile-cap connection on behavior of torsionally loaded pile groups*

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Abstract: To evaluate the responses of fixed and pinned pile groups under torsion, a method is presented to analyze the nonlinear behavior of free-standing pile groups with rigid pile caps. The method is capable of simulating the nonlinear soil response in the near field using p-y and τ-θ curves, the far-field interactions through Mindlin's and Randolph's elastic solutions, and the coupling effect of lateral resistance on torsional resistance of the individual piles using an empirical factor. Based on comparisons of the solutions for fixed- and pinned-head, 1×2, 2×2, and 3×3 pile groups subjected to torsion, it was found that pile-cap connection significantly influences the torsional capacity of pile groups and the assignment of applied torques in the pile groups. In this study, the applied torques for the pinned-head pile groups are only 44%~64% of those for the corresponding fixed-head pile groups at a twist angle of 2°. Such a difference is mainly due to the change of the lateral resistances of individual piles in the groups.

Key words: Pile group, Pile foundations, Torsional response, Pile-cap connection, Nonlinear analysis
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INTRODUCTION

Grouped piles are usually used as foundations for offshore platforms, bridge bents and tall buildings. Because of eccentric lateral loading on these structures from wind and wave actions, ship impacts, or high-speed vehicles, the grouped piles may be subjected to significant torsional loads. In the past, researchers focused on studying the behavior of single piles under torsion (Poulos, 1975; Randolph, 1981; Chow, 1985; Guo and Randolph, 1996; Laue and Sonntag, 1998; Zhang and Kong, 2006; Hu *et al.*, 2006). In recent years, attention has been paid to the behavior of pile groups under torsion. Zhang and Tsang (2005) studied the behavior of a torsionally loaded 2×2 bored pile group using a 3D finite difference method. Kong (2006) and Kong and Zhang (2007b) reported a series of centrifuge model tests to investigate load shearing mechanisms and pile-soil-pile interactions in three-diameter spaced, 1×2, 2×2, and 3×3 pile groups subjected to torsion. From these studies, it was found that a pile group subjected to torsion simultaneously mobilizes lateral and torsional resistances of the individual piles, as shown in Fig.1a, and that the torsional resistances resist up to 50% of the applied torque when the pile-cap connection is fixed. In addition, Kong and Zhang (2007b) noted that when the pile-cap connection became weak, the torsional capacity of a pile group decreased significantly, and that the torsional contribution, which was the sum of the torsional resistances of the individual piles in the pile group, to the group torsional capacity increased.

Kong (2006) proposed a numerical approach to analyze the response of pile groups subjected to torsion. The approach is capable of simulating several attributes of torsionally loaded pile groups observed from experimental studies; namely, (1) nonlinear behavior of soil adjacent to piles in pile groups subjected to torsion, (2) pile-soil-pile interactions, and (3) the coupling effect of lateral loading on torsional response, which is referred to as the deflection-torsion coupling effect. A program, NATLPG, was developed

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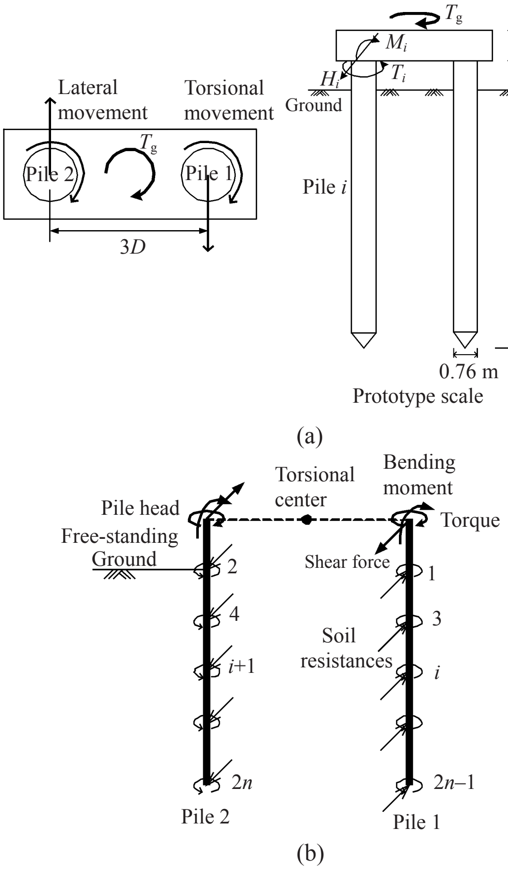


Fig.1 (a) Movements and resistance forces in a pile group subjected to torsion and (b) discretization of piles in the approach

using Mathematica 5 for the proposed approach.

To further study the effect of pile-cap connection on the response of pile groups subjected to torsion, in this paper, the program, NATLPG, is extended to analyze the behavior of torsionally loaded pile groups under different constraint conditions of pile-cap connection. In numerical analysis or preliminary design of group pile foundations, pile-cap connection is commonly assumed to be fixed or pinned. For pile groups subjected to torsion, a fixed-head connection can be considered as the constraint condition where the pile-cap connection can sustain both bending moments and torques without pile-head rotation and twist; a pinned-head connection is the constraint condition where the connection can only sustain torques without pile-head twist. This study focuses on comparing different responses of fixed- and pinned-head pile groups subjected to torsion and different paths along which the applied torque is transferred in the pile groups.

METHOD OF ANALYSIS

The problem of a pile group subjected to torsion in soil is shown in Fig.2. The soil-pile system in Fig.2 can be decomposed into two domains; namely, (1) the pile domain, i.e., the group piles subject to external loads, $\{\boldsymbol{Q}\}$, and pile-soil interaction forces acting on the piles, $\{\boldsymbol{P}_{\rm p}\}$; and (2) the soil domain, i.e., the soil mass acted on by a system of pile-soil interaction forces, $\{\boldsymbol{P}_{\rm s}\}$, at the boundary of the pile-soil interface. As shown in Fig.2, each pile in the pile group is subjected to a lateral load, a bending moment and a torsional load at the pile head. The pile domain and the soil domain interact with each other through the pile-soil interaction forces and the compatibility of the deformations of the soil and pile domains. Young's modulus of these piles should strictly be equal to the difference between the actual Young's modulus of the piles and that of the soil at the corresponding depth, but for practical purposes it is assumed to be the actual Young's modulus of the piles.

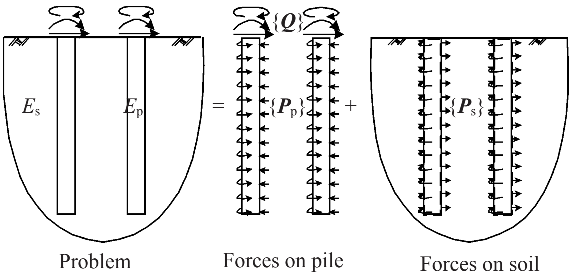


Fig.2 Pile-soil-pile interactions

The pile shafts are assumed to be vertical, linear elastic, and obey the small deformation assumption. The pile cap is rigid and not in contact with the ground. In this approach, each pile is modeled by a number of discrete beam elements (Fig.1b). Based on the finite element method, the load-deformation relationship is written as

$$[\boldsymbol{K}_{\rm p}]\{\boldsymbol{W}_{\rm p}\} = \{\boldsymbol{Q}\} + \{\boldsymbol{P}_{\rm p}\}, \tag{1}$$

where $[\boldsymbol{K}_{\rm p}]$ is the global stiffness matrix of all elements of the group piles; $\{\boldsymbol{W}_{\rm p}\}$ is the vector of deformations at the pile nodes.

It is assumed that the nonlinear behavior of a pile group subjected to torsion is due to the nonlinear soil response in the near field. The near-field soil is simulated by a series of independent nonlinear springs, as shown in Fig.3a. Each spring represents the relationship between the load at a point along the pile in the group and the associated soil deformation at the point. The far-field interactions (i.e., pile-soil-pile interactions) are assumed to be linear elastic. In the present approach, a "lumped" formulation in which the soil stiffness is lumped at the pile nodes is adopted (Fig.1b). Correspondingly, the pile-soil interaction forces are also condensed at the pile nodes. This simplification is adequate in most practical problems. Thus, the soil deformation at node i due to its own loading as well as loadings at other nodes, ϖ_{si}, can be obtained by superposition:

$$\varpi_{si}=\sum_{j=1}^{n} f_{ij}P_{sj}, \tag{2}$$

where f_{ij} is the flexibility coefficient, denoting the deformation at node i due to a unit load at node j; P_{sj} is the pile-soil interaction force acting on the soil at node j; and n is the total number of nodes. It is assumed that P_{sj} includes a lateral force and a torsional force, denoted as H_{sj} and T_{sj}, respectively. The soil deformation at node i, ϖ_{si}, then includes a lateral component, ϖ_{si}^{H}, and a torsional component, ϖ_{si}^{T}. Correspondingly, the flexibility coefficient, f_{ij}, is divided into four parts, denoted as f_{ij}^{HH}, f_{ij}^{TH}, f_{ij}^{HT} and f_{ij}^{TT}. Therefore, Eq.(2) is decomposed as:

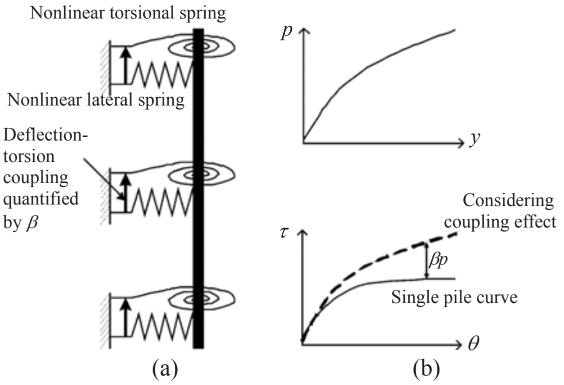


Fig.3 Modeling of nonlinear soil response and deflection-torsion coupling effect

(a) Soil spring model; (b) p-y and τ-θ curves

$$\begin{Bmatrix}\varpi_{si}^{H}\\ \varpi_{si}^{T}\end{Bmatrix}=\sum_{j=1}^{n}\begin{bmatrix}f_{ij}^{HH} & f_{ij}^{HT}\\ f_{ij}^{TH} & f_{ij}^{TT}\end{bmatrix}\begin{Bmatrix}H_{sj}\\ T_{sj}\end{Bmatrix}, \tag{3}$$

where f_{ij}^{HH} is the lateral component of the soil deformation at node i due to a unit lateral force at node j; f_{ij}^{TH} is the torsional component of the soil deformation at node i due to a unit lateral force at node j; f_{ij}^{HT} is the lateral component of the soil deformation at node i due to a unit torsional force at node j; f_{ij}^{TT} is the torsional component of the soil deformation at node i due to a unit torsional force at node j.

In terms of sources of loading, the soil deformation at a node consists of the one due to the forces at the node and the one due to the forces at other nodes. So ϖ_{si}^{H} and ϖ_{si}^{T} are each divided into two components:

$$\begin{cases}\varpi_{si}^{H}=\varpi_{sii}^{H}+\varpi_{ai}^{H}=(f_{ii}^{HH}H_{si}+f_{ii}^{HT}T_{si})\\ \qquad\qquad +\displaystyle\sum_{j=1,j\neq i}^{n}(f_{ij}^{HH}H_{sj}+f_{ij}^{HT}T_{sj}),\\ \varpi_{si}^{T}=\varpi_{sii}^{T}+\varpi_{ai}^{T}=(f_{ii}^{TH}H_{si}+f_{ii}^{TT}T_{si})\\ \qquad\qquad +\displaystyle\sum_{j=1,j\neq i}^{n}(f_{ij}^{TH}H_{sj}+f_{ij}^{TT}T_{sj}),\end{cases} \tag{4}$$

where ϖ_{sii} represents the soil deformation at node i due to forces at the same node; ϖ_{ai} represents the added soil deformation at node i due to forces at nodes other than i; f_{ii}^{HH} represents the lateral component of soil deformation at node i due to a unit lateral force at the same node; f_{ii}^{TT} is the torsional component of soil deformation at node i due to a unit torsional force at the same node; f_{ii}^{TH} is the torsional component of soil deformation at node i due to a unit lateral force at the same node; f_{ii}^{HT} is the lateral component of soil deformation at node i due to a unit torsional force at the same node. Eq.(4) can be written in a matrix form

$$\{\boldsymbol{W}_{s}\}=[\boldsymbol{F}_{s}]\{\boldsymbol{P}_{s}\}, \tag{5}$$

where $\{\boldsymbol{W}_{s}\}$ is the vector of soil deformation; $[\boldsymbol{F}_{s}]$ is the soil flexibility matrix; $\{\boldsymbol{P}_{s}\}$ is the vector of pile-soil interaction forces acting on the soil.

Inherent in the load-transfer approach for modeling near field soil response in a pile is the assumption that the soil reactions are uncoupled; namely, the displacement at a particular node will only affect the soil reaction at that node. Thus, f_{ii}^{HH}, f_{ii}^{TT}, f_{ii}^{TH} and f_{ii}^{HT} are used to model the soil response in the near field, whereas the values of the flexibility coefficients f_{ij}^{HH}, f_{ij}^{TH}, f_{ij}^{HT} and f_{ij}^{TT} for nodes *i* and *j* (*i*≠*j*) at the same pile are zero. f_{ii}^{TH} and f_{ii}^{HT} reflect the interaction effects between the lateral force and torsional force in an individual pile. The former effect is called the deflection-torsion coupling effect by Kong (2006). Fig.3 illustrates the deflection-torsion coupling effect. The arrows pointing to the torsional springs in Fig.3a represent the effect of the lateral subgrade reaction on the torsional shear resistance. Kong (2006) found that the latter effect is minor in the pile group tests only subjected to torsional loading. However, Hu *et al.*(2006) observed from their centrifuge tests on drilled shafts under a combination of lateral and torsional loading that the lateral resistance of the pile decreases as the torque increases to large values. In the present approach, f_{ii}^{HT} is set as zero. Kong (2006)'s tests modeled closely-spaced, closed-end pipe pile groups jacked into sand, hence this approach may be more suitable to simulate jacked or driven pile groups subjected to torsion.

In this study, f_{ii}^{HH} and f_{ii}^{TT} are calculated by nonlinear *p-y* and *τ-θ* curves (Fig.3b):

$$f_{ii}^{HH}=\frac{1}{k_{hi}\delta}, \tag{6}$$

$$f_{ii}^{TT}=\frac{2}{\pi}\frac{1}{k_{\theta i}D^2\delta}, \tag{7}$$

where k_{hi} and $k_{\theta i}$ are the soil subgrade reaction moduli with respect to *p-y* and *τ-θ* curves, respectively; *D* is the pile diameter; *δ* is the pile segment length. A coupling coefficient, *β*, is introduced to quantify the deflection-torsion coupling effect in an individual pile instead of f_{ii}^{TH},

$$\beta=-f_{ii}^{TH}p_{\mathrm{a}}D\delta/\varpi_{\mathrm{s}ii}^{T}, \tag{8}$$

where p_{a} is the atmospheric pressure. Then, $\varpi_{\mathrm{s}ii}^{T}$ in Eq.(4) is rewritten as

$$\varpi_{\mathrm{s}ii}^{T}=\frac{f_{ii}^{TT}}{1+\left(\dfrac{\beta}{p_{\mathrm{a}}D}\right)\dfrac{H_{\mathrm{s}i}}{\delta}}T_{\mathrm{s}i}. \tag{9}$$

In Eq.(9), *β* quantifies the contribution of lateral subgrade reaction (condensed as $H_{\mathrm{s}i}$) to the increase in torsional shear resistance (condensed as $T_{\mathrm{s}i}$) at the soil-pile interface. The physical meaning of *β* is schematically represented in Fig.3b.

f_{ij}^{HH}, f_{ij}^{TH}, f_{ij}^{HT} and f_{ij}^{TT} (*i*≠*j*, and *i* and *j* at different piles) reflect different pile-soil-pile interactions among piles in torsonally loaded pile groups. f_{ij}^{HH} is the lateral component of soil deformation at node *i* on a pile due to a unit lateral force at node *j* on another pile; f_{ij}^{TT} represents the torsional component of soil deformation at node *i* on a pile due to a unit torsonal force at node *j* on another pile; f_{ij}^{HT} represents the lateral component of soil deformation at node *i* due to a unit torsional force at node *j* on another pile; and f_{ij}^{TH} is the torsional component of soil deformation at node *i* due to a unit lateral force at node *j* on another pile. Both Poulos (1975) and Kong (2006) found that the interaction between two torsionally loaded, three-diameter spaced piles, if any, is negligible; f_{ij}^{TT} is therefore set as zero in this paper. Other coefficients are calculated using elastic solutions.

f_{ij}^{HH} is obtained from Mindlin (1936)'s solutions for the influence of a unit lateral point force in a homogeneous, isotropic elastic half-space. This technique has been used by Leung and Chow (1987) for the analysis of laterally loaded pile groups. However, for the case of a pile group subjected to torsion, the angle between the lateral loads on two arbitrary piles could be of any value, so a more general solution to lateral interaction between two piles is developed, which is

$$f_{ij}^{HH}=u_j\cos\gamma_{ij}+v_j\sin\gamma_{ij},\quad i\neq j, \tag{10}$$

where u_j and v_j are the soil displacements at node *j* on a pile in the same direction and in the perpendicular direction of the unit force at node *i*, respectively; γ_{ij} is the angle between the directions of the two lateral forces at node *i* and node *j*.

f_{ij}^{HT} is calculated using Randolph (1981)'s analytical solution for torsionally loaded single piles. Randolph (1981) treated the soil as independent horizontal layers and obtained the relationship between the torsional shear stress on the soil-pile interface at a particular depth and the circumferential soil displacement at a point at the same depth. In the present approach, assume that the adjacent piles near a pile subjected to torsion follow exactly the free-field soil displacement. Given a unit torque at node *i*, the induced soil displacement at node *j* on another pile at the same depth with node *i*, which is f_{ij}^{HT}, can be calculated using Randolph (1981)'s solution

$$f_{ij}^{HT}=\frac{\sin\psi}{4\pi G_{\mathrm{s}}s\delta},\qquad i\neq j,\tag{11}$$

where G_{s} is the shear modulus of soil; s is the center-to-center spacing between the two piles; ψ is the angle between the line jointing nodes *i* and *j* and the direction of the lateral loading at node *j*. When nodes *i* and *j* are not in the same depth, f_{ij}^{HT} is zero. Then, based on the reciprocal theorem, f_{ij}^{TH} is equal to f_{ji}^{HT}.

The flexibility matrix $[\boldsymbol{F}_{\mathrm{s}}]$ in Eq.(5) is inverted to give the following stiffness relationship for the soil

$$\{\boldsymbol{P}_{\mathrm{s}}\}=[\boldsymbol{K}_{\mathrm{s}}]\{\boldsymbol{W}_{\mathrm{s}}\},\tag{12}$$

where $[\boldsymbol{K}_{\mathrm{s}}]=[\boldsymbol{F}_{\mathrm{s}}]^{-1}$ is the soil stiffness matrix. Equilibrium of the interaction forces acting on the pile-soil interface yields

$$\{\boldsymbol{P}_{\mathrm{s}}\}=-\{\boldsymbol{P}_{\mathrm{p}}\}.\tag{13}$$

Assuming no separation between the soil and the piles, the compatibility of the deformations of the soil and the piles yields

$$\{\boldsymbol{W}_{\mathrm{s}}\}=\{\boldsymbol{W}_{\mathrm{p}}\}.\tag{14}$$

Using Eqs.(1), (13), and (14), the load-deformation relationship of the pile-soil system is expressed as

$$([\boldsymbol{K}_{\mathrm{p}}]+[\boldsymbol{K}_{\mathrm{s}}])\{\boldsymbol{W}_{\mathrm{p}}\}=\{\boldsymbol{Q}\}.\tag{15}$$

Since nonlinear *p-y* and τ-θ curves are used, $[\boldsymbol{K}_{\mathrm{s}}]$ in Eq.(15) will vary with soil displacement, and an iteration technique has to be used to solve the simultaneous equations.

CONSTRAINT CONDITIONS OF PILE-CAP CONNECTION

Two types of constraint conditions of pile-cap connection, fixed and pinned, are employed in the response analysis of torsionally loaded pile groups. In the case of a fixed pile-cap connection, the rotation of all the pile heads in the vertical plane should be zero and the twist of all the pile heads should be equal to that of the pile cap. The pile-head lateral displacement of an individual pile is equal to the twist angle of the pile group times the distance from the pile to the torsional center of the group. The torsional force equilibrium of the pile cap requires:

$$\sum_{I=1}^{n}(T_I+H_I s_I)=T_{\mathrm{g}},\tag{16}$$

where T_I and H_I are the pile-head torque and shear force on pile *I*; s_I is the distance between the torsional center of the pile group to pile *I*; T_{g} is the applied torque on the pile cap.

In the case of a pinned pile-cap connection, the differences from the former case are that the rotation of all the pile heads in the vertical plane does not have to be zero and the pile heads cannot resist bending moments.

NUMERICAL ANALYSIS AND COMPARISON

Centrifuge model tests

In this study, the pile and soil parameters for Kong and Zhang (2007b)'s centrifuge model tests are employed to investigate the effect of pile-cap connection on behavior of 1×2, 2×2, and 3×3 pile groups subjected to torsion. In the centrifuge model tests, aluminum model piles 19 mm in diameter and 300 mm in length were employed. The model piles were connected to aluminum pile caps at three-diameter spacing. The tests were conducted at 40*g*, thus the model pile groups simulated three-diameter spaced, closed-end pipe pile groups with an outside pile diameter of 0.76 m and an embedded pile length of 10.8 m, as shown in Fig.1a. The flexural stiffness and torsional rigidity of an individual pile are 220.5 MN·m^2 and 169.9 MN·m^2, respectively; the pile Poisson's ratio is 0.3. The pile cap is 1.2 m thick and 1.2 m above the ground surface (Fig.1a). The model tests were conducted in Leighton Buzzard sand. A sand raining technique introduced by Kong and Zhang (2007a) was employed in the sample preparation. Two dry soil densities (13.76 and 14.83 kN/m^3) were prepared for the tests, with relative densities of 35% for the loose sand and 75% for the dense sand.

Before starting the centrifuge, each of the pile groups was first jacked into the sand bed to 90 mm using a pile jacking device. After the centrifuge was gradually accelerated to 40*g*, the pile group was jacked at 1 mm/s to the final embedment depth of 270 mm. Then, the pile group was torsionally loaded in increments using two horizontal actuators. At each load level, the load was kept constant until no further variations in twist angle were observed.

Two types of pile-cap connections were simulated in the tests. In most of the tests, the pile-cap connection was fixed-headed. This fixity was sufficient to sustain the mobilized torques and bending moments at small twist angles. In the test of 2×2 pile group in dense sand, the model piles and the model group cap were connected by screws only, which was insufficient to sustain large bending moments, so the pile-cap connection was considered flexible. Details of the pile group tests have been described by Kong and Zhang (2007b).

Simulation results

Two sets of soil parameters are required in the present approach. One is the soil subgrade reaction parameters for calculating f_{ii}^{HH} and f_{ii}^{TT}; the other is the soil modulus, Poisson's ratio, and shear modulus of soil for calculating f_{ij}^{HH}, f_{ij}^{HT} and f_{ij}^{TH}.

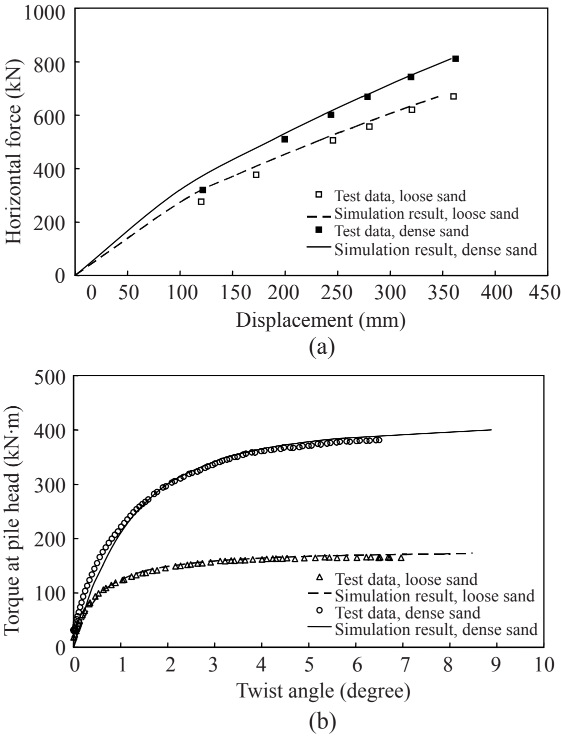
Kong (2006), based on the results of laterally loaded and torsionally loaded single pile tests in sand (Kong and Zhang, 2007a; Zhang and Kong, 2006), proposed a series of exponential *p*-*y* curves, hyperbolic *τ*-*θ* curves, and hyperbolic toe torsional resistance curves for piles in sand:

$$p/D = kA_0\lambda_z(z/D)^{0.5}(y/D)^{0.5}, \tag{17}$$

$$\tau = AB\theta/(A\theta + B), \tag{18}$$

$$T_\mathrm{t} = A_\mathrm{t}B_\mathrm{t}\theta_\mathrm{t}/(A_\mathrm{t}\theta_\mathrm{t} + B_\mathrm{t}), \tag{19}$$

where k is a fitting coefficient; z is the embedded depth; A_0 is a factor related to soil density and soil stress states; λ_z is a reduction factor for considering the effect of ground surface; T_t is the toe torsional resistance; θ_t is the local twist angle of the pile toe; A and A_t are the initial slopes of the hyperbolic *τ*-*θ* curve and toe resistance curve, respectively; and B and B_t are the ultimate shaft torsional shear stress and toe torsional resistance, respectively. Kong (2006) reported details of the proposed load-transfer curves. Fig.4 compares the simulated and measured horizontal force-displacement curves and torque-twist angle curves for the single piles.



(a)

(b)

Fig.4 Comparison of single pile tests and numerical analyses
(a) Laterally loaded single pile tests; (b) Torsionally loaded single pile tests

The shear modulus of soil is a key parameter for pile group interactions. It is calculated from the soil modulus and Poisson's ratio. The values of soil modulus proposed by Poulos (1971) are 0.9~2.1 MPa for loose sand, 2.1~4.1 MPa for medium dense sand, and 4.1~9.7 MPa for dense sand. In this study, the employed soil moduli for the loose and dense sands are 2.1 MPa and 5.0 MPa, respectively. For the soil Poisson's ratio, Budhu (2000) suggested typical values from 0.15 to 0.25 for loose sand and from 0.25 to 0.35 for dense sand. In this study, the Poisson's ratios of 0.2 and 0.3 are used for the loose and dense sands, respectively. Values of coupling coefficient β of 0.4 and 0.8 proposed by Kong (2006) are used for the loose and dense sands, respectively.

Fig.5 shows the applied torque-twist angle curves of fixed- and pinned-head 1×2, 2×2, and 3×3 pile groups. In the investigated twist angles up to 8º, no peak torque is observed from all the applied torque-twist angle curves. This is different from the results of torsionally loaded single piles shown in Fig.4b, in which the torsional resistance of the single pile is substantially mobilized at a torsional angle of 4º in both loose and dense sands. Such a difference is related to more complicated loading conditions of the group piles (Fig.1a), as well as the pile-soil-pile interactions among the group piles. The detailed difference of the load-transfer mechanisms between a single pile and a pile group subjected to torsion has been discussed by Kong and Zhang (2007b).

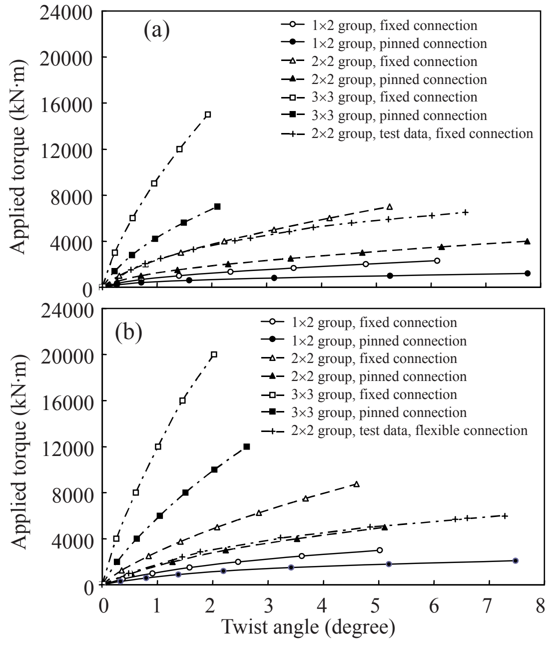


Fig.5 Torque-twist angle curves of 1×2, 2×2, and 3×3 pile groups. (a) Loose sand; (b) Dense sand

The torsional resistances of the fixed-head pile groups in Fig.5 are much larger than those of the corresponding pinned-head pile groups, which is consistent with the observation from the centrifuge model tests by Kong and Zhang (2007b). The ratios of the applied torques for the pinned-head pile groups to those for the corresponding fixed-head pile groups at a twist angle of 2° are summarized in Table 1. The minimum and maximum ratios in Table 1 are 0.44 and 0.64, respectively. The former is for the 3×3 pile group in the loose sand and the latter is for the 1×2 pile group in the dense sand. It is also found from Table 1 that the ratios decrease with group size and increase with soil density. The effect of group size comes from an increase of the average distance from the piles in a group to the torsional center of the group. The effects of group size and soil density will be detailed later.

Table 1 Ratios of applied torques for pinned and fixed pile-cap pile groups at a twist angle of 2°

Pile groups	Ratios of applied torques for pinned and fixed pile-cap pile groups	
	Loose sand	Dense sand
1×2 pile group	0.53	0.64
2×2 pile group	0.50	0.59
3×3 pile group	0.44	0.50

The calculated torques and shear forces at individual pile heads in the fixed- and pinned-head 2×2 pile groups are compared in Fig.6. In Fig.6a, the pile-head torques on the pinned-head pile group are slightly smaller than those on the fixed-head pile group in both the loose and dense sands, especially at large twist angles. Such a difference is due to the fact that the mobilized lateral soil resistance on a free-head pile is smaller than that on a fixed-head pile. The mobilized lateral soil resistances enhance the torsional resistances on the pile through the deflection-torsion coupling effect quantified by β in the present approach.

Fig.6b compares the pile-head shear forces in the fixed- and pinned-head 2×2 pile groups. The shear forces in the pinned-head pile group in the loose and dense sands are only 35% of those in the fixed-head pile group at a twist angle of 2°. The comparison in

Fig.6 demonstrates that the significant difference of torsional responses between fixed and pinned pile-cap pile groups is from mobilization of both torsional resistances and shear forces of the individual piles in the groups, with the component from the shear forces of the individual piles dominating.

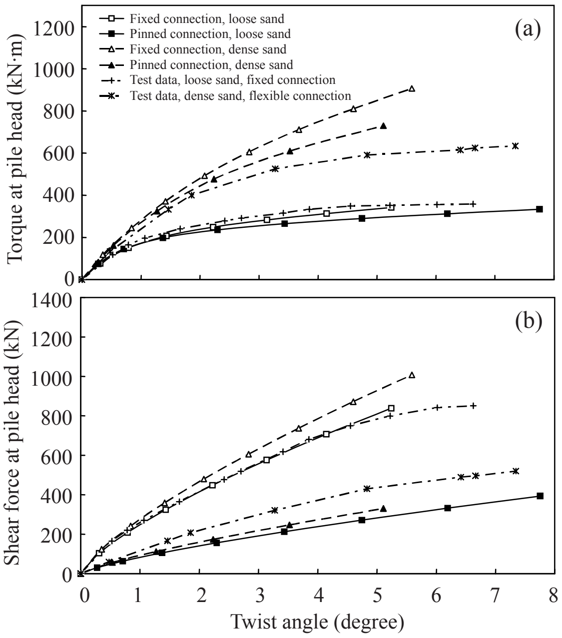


Fig.6 Torsional resistances (a) and shear forces (b) of individual piles in 2×2 pile group

In addition, the relative density of sand has a more significant influence on the torsional resistances than on the lateral resistances. In Fig.6a, a 110% increase in relative density results in approximately the same percentage of increase in the torsional resistance at a twist angle of 2°; while in Fig.6b, the same increase in relative density only results in about 15% increase in the shear forces at the same twist angle. Such difference suggests that the contribution from the lateral resistances of piles in a group to resist applied torque is relatively low in the dense sand. This explains that, as the lateral resistances of the piles in a group decrease to a certain percentage due to the change from a fixed-head pile-cap connection to a pinned-head connection, the decrease of the group torsional resistance is relatively low in the dense sand. The ratios for the dense sand in Table 1, therefore, are larger than those for the loose sand.

As shown in Fig.1a, the sustained torque by pile i in the group is shared by the torsional resistance, T_i, and the lateral contribution from the shear force, H_i. Fig.7 shows the variation of the percentages of the torsional resistances to the sustained torques with twist angle for representative piles in the 1×2, 2×2, and 3×3 pile groups. All the curves in Fig.7 decrease after a twist angle of about 1°; while at small twist angles, the curves may increase with twist angle. As shown in Fig.6, the pile-head torques increase faster at small twist angles; while the pile-head shear forces continue to increase in the whole range of twist angles. The above attributes of the pile-head torques and shear forces suggest that the torsional resistances take larger proportions of the sustained torques at small twist angles and the proportions decrease at large twist angles. Because of symmetry of the 1×2 and 2×2 pile configurations, the percentages in Fig.7 also represent the torsional contribution to resist the total applied torque. The percentages of torsional contribution to resist the applied torque in the 3×3 pile groups are shown in Fig.8. The torsional resistance percentages in Fig.8 also reach the maximum at a twist angle of about 1°.

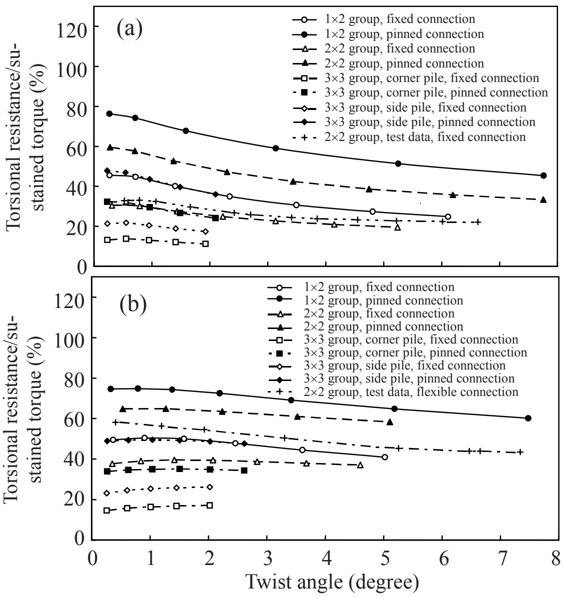


Fig.7 Percentages of torsional resistance in sustained torque
(a) Loose sand; (b) Dense sand

As shown in Fig.7, the contribution of the torsional resistances from the piles at different locations in the groups is different. The percentage of the torsional resistance in Fig.7 decreases with the distance from the piles to the torsional center of the pile groups,

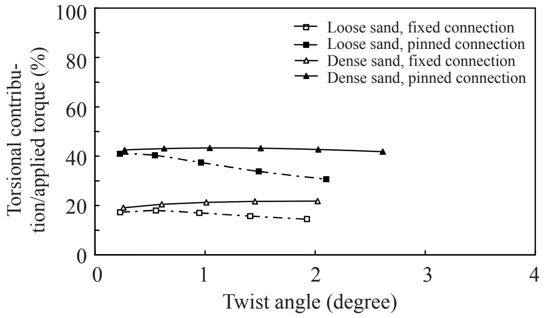


Fig.8 Percentages of torsional contribution in applied torque in 3×3 pile group

which are 1.5*D*, 2.12*D*, 3*D*, and 4.24*D* for the piles in the 1×2 and 2×2 pile groups, and the side piles and the corner piles in the 3×3 pile groups, respectively. Comparing curves in Fig.7 for 1×2 and 2×2 pile groups in the loose and dense sands with corresponding curves in Fig.8, the percentage of the torsional contribution to the applied torque also decreases with group size. Correspondingly, the percentage of the lateral contribution to resist the applied torque, which is equal to the sum of the shear force on each pile in a group times the distance from the pile to the torsional center of the group divided by the applied torque, increases with group size. As shown in Fig.6b, when the lateral resistances of the group piles decrease due to the change of pile-cap connection from fixed to pinned connection, the loss of group torsional resistance from the decrease of the lateral contribution becomes more significant with group size. Therefore, the ratios in Table 1 decrease with group size.

From Figs.7 and 8, it is clear that pile-cap connection also influences the assignment of applied torques in a pile group, i.e., the load sharing mechanism. For a pile group configuration, the percentages of the torsional resistance to the sustained torque and the torsional contribution to the applied torque in the pinned-head pile groups are larger than those in the fixed-head pile groups. In the investigated range of twist angles, the percentages to the sustained torques for the fixed-head pile groups (Fig.7) are in a range of 15%~50%; while those for the pinned pile-cap pile groups are in a range of 25%~75%. The percentages to the applied torques for the fixed-head 3×3 pile groups in the loose and dense sands (Fig.8) are only up to 20%; while those for the pinned-head 3×3 pile groups reach up to 42%. This is because, as shown in Fig.6, different pile-cap connections (fixed and pinned) significantly influence the lateral resistances of piles in a group but only slightly influence the torsional resistances of piles in the group. In addition, the results in Figs.7 and 8 clearly demonstrate that the mobilized torsional resistances of piles in both fixed- and pinned-head pile groups play an important role in resisting the applied torque, especially at small twist angles up to 1°.

Comparisons with test results

The test results of the 2×2 pile group reported by Kong and Zhang (2007b) are employed to compare with the corresponding simulation results. The results of the 2×2 pile group with a fixed pile-cap connection in the loose sand are shown in Figs.5a, 6, and 7a. In these figures, the simulation results for the fixed-head 2×2 pile group in the loose sand fit the test data well, especially at small twist angles. It proves that the proposed approach is capable of simulating the response of pile groups under torsion. More comparisons for other group configurations with fixed pile-cap connection are detailed by Kong (2006).

The results of the 2×2 pile group with the flexible cap-pile connection in the dense sand are shown in Figs.5b, 6, and 7b. The test curves in Fig.5b, 6, and 7b are all between the simulation curves for fixed-head connection and those for pinned-head connection, but closer to the latter. It means that the flexible connection used in the model test might be neither fixed nor pinned, but a constraint condition in between. In addition, the test pile-head torque curve in Fig.6a fits the simulation curves for fixed- and pinned-head connections in the dense sand well at small twist angles up to 2°, but exhibits differences at large twist angles. It implies that the flexible connection might have twisted under large applied torques. Further work is needed to study the effect of partial pile-head fixity on bending moments and torques.

CONCLUSION

In this paper, two ideal constraint conditions of pile-cap connection, fixed and pinned, are analyzed to investigate the effect of pile-cap connection on the torsional response of pile groups jacked into sand. For pile groups under torsion, the fixed pile-cap connection is the constraint condition where the pile-cap connection can sustain both bending moments and torques without the pile-head rotation and twist; the pinned connection is the constraint condition where the connection only sustains torques without pile-head twist. A nonlinear approach is developed in this study to model nonlinear soil response and major pile-soil-pile interactions and coupling effect in a pile group. Based on the comparison of the responses of fixed- and pinned-head 1×2, 2×2, and 3×3 pile groups subjected to torsion, the following conclusions are drawn:

Pile-cap connection significantly influences the capacity of pile groups under torsion. In this study, the torsional resistances for the pinned-head pile groups are only 44%~64% of those for the corresponding fixed-head pile groups at a twist angle of 2°. The torsional resistance ratios between pinned- and fixed-head pile groups decrease with group size and increase with soil density.

The significant difference in the group torsional resistances between fixed- and pinned-head pile groups is mostly from the change of the lateral resistances of the individual piles in the groups. The pile-head shear forces for the pinned-head pile groups are only 35% of those for the corresponding fixed-head pile groups, while the pile-head torques are just slightly smaller for the pinned-head pile group than for the corresponding fixed-head pile group.

Pile-cap connection also influences the sharing of applied torque in a pile group. For each pile group configuration, the percentage of the torsional resistance in a pinned-head group pile is larger than that in an equivalent fixed-head group pile. In the investigated range of twist angles up to 8°, the percentages of the torsional resistance to the sustained torque for the fixed-head pile groups are in a range of 15%~50%; while those for the pinned-head pile groups are in a range of 25%~75%. The mobilized torsional resistances of piles in both fixed- and pinned-head pile groups play an important role in resisting the applied torque.

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