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Three-dimensional numerical parametric study of deformation mechanisms of grouped piled raft foundation due to horizontal loading

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Abstract. In this study, three-dimensional numerical parametric study was conducted to explore deformation mechanisms of grouped piled-raft-foundation due to lateral load in clays. Effects of load intensity, loading angle, soil stiffness, pile diameter, pile spacing and pile length on foundation deformations were explored. It is found that the smallest and largest movements of pile foundation are induced when the loading angles are 0° and 30°~60°, respectively. By increasing loading angle from 0° to 30°~60°, the resultant horizontal movements and settlements increase by up to 20.0% and 57.1%, respectively. Since connection beams can substantially increase integrity of four piled raft foundation, resultant horizontal movements, settlements and bending moments induced in the piled raft foundation decrease by up to 54.0%, 8.8% and 46.3%, respectively. By increasing soil stiffness five times, resultant horizontal movements and settlements of pile foundation decrease by up to 61.7% and 13.0%, respectively. It is indicated that effects of connection beam and soil stiffness on settlements of pile foundation are relatively small. When pile diameter is less than 1.4 m, deformations of piled raft foundation decrease substantially as a reduction in the pile diameter. Two dimensional groups are proposed to develop calculation charts of horizontal movements and settlements of pile foundation. The proposed calculation charts can directly estimate movements of piled raft foundation under arbitrary loading, ground and pile conditions.

Keywords: calculation chart; horizontal load; horizontal movement; pile foundation; settlement; three-dimensional

1. Introduction

Recently, more and more transmission towers are built to meet the increasing demands of electrical power supply (i.e., Savory et al. 2001, Hamada et al. 2010, Huang et al. 2012). Since transmission towers are normally very tall, wind load inevitably induces vibrations in those tall structures, resulting in additional deformation and stress to underground pile foundations (i.e., Fu and Li 2019). To ensure the serviceability and safety of transmission tower, extensive studies have been conducted to explore deformation mechanisms under different ground and environmental conditions.

In literature, extensive research attentions were paid to upper transmission tower and lines (e.g., Bi *et al.* 2023, Dikshit and Alipour 2023). For example, Bi *et al.* (2023) developed a comprehensive wind-induced performance evaluation framework for transmission tower-line system (TTLS). In terms of structural damage, the more favorable layout of TTLS was the orientation of 265°. By conducting model tests and numerical analyses, Shu *et al.* (2018) found that wind load had significant unfavorable effects on resistance of the transmission tower. Fu *et al.* (2019) conducted uncertainty analysis of 230 kV transmission tower, and concluded that failure positions obtained from uncertainty analysis could provide a feasible approach for determining all the potential failure modes. Edgar and Sordo (2017) performed an analytical study to reproduce substantial damages to electrical transmission tower due to Hurricane Wilma. It was found that consistent cyclonic wind speed patterns gave a better estimation of failure modes than traditional non-cyclonic patterns. Using nonlinear static pushover analysis, Mara and Hong (2013) developed capacity curves to form capacity surface of transmission tower under different wind directions.

Currently, interactions between wind and pile foundation were mainly focused on offshore structures (e.g., Wang *et al.* 2022, Shi *et al.* 2023, Zou *et al.* 2022). Wang et al. (2022) carried out centrifuge test and numerical analyses to explore the effects of pile arrangements on lateral responses of pile foundation for offshore turbines in sands.

It was found that the lateral responses of pile foundation were mainly contributed by the first-row pile and the entire failure was controlled by the back-row pile. Using three-dimensional numerical analyses, Jayalekshmi *et al*. (2015) explored deformation mechanisms of tall chimneys with piled raft foundation subjected to wind loads. Responses of chimney were found to be greatly affected by geometrical properties of chimney and foundations. To ensure the safety of the tall chimney, the allowable movements at the base of the chimney were suggested as 1/40th of the chimney height. Dong *et al*. (2023) used finite element model to analyze the effects of pile height, pile tilt angle and prestressed foundation tie beam on the stability of transmission tower bases. It was found that the horizontal movement of tower foundation could be reduced by more than 50% by using inclined piles and prestressed foundation

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tie beams. Chong *et al.* (2019) used finite element method to analyze the effects of pile diameter, embedded length and moment arm distance on deformation mechanisms of offshore monopiles. It was found that different pile geometries produced a distinct evolution of lateral displacement and stress. Because of wind load, additional deformations and stresses would transfer from upper transmission tower to lower pile foundations. However, studies on deformation mechanisms of pile foundation of transmission tower were limited.

To explicitly tackle the above-mentioned challenges, three-dimensional numerical parametric study was conducted to investigate deformation mechanisms of piled raft foundation for transmission tower due to wind load in clays. Effects of wind velocity, loading angle, soil stiffness, pile diameter, pile spacing and pile length on foundation deformations were explored. Based on numerical parametric study, calculation charts were proposed to estimate movements of pile foundation under arbitrary wind, ground and pile foundation conditions.

2. The construction site

2.1 Piled raft supported transmission tower

In this study, deformation mechanisms of a transmission tower constructed in soft clays were analyzed. The height of the transmission tower was 385 m, and the clear distance between north and south towers was 4055 m. Steel pipes filled by C50 concrete were used to construct this ultra height transmission tower. Four individual piled raft foundations were constructed to provide vertical and horizontal supports for this transmission tower. Anchor bolts were used to connect the transmission tower and four piled raft foundations. To increase the integrity of the foundation, concrete beams were adopted to mechanically connect those four individual rafts.

To balance wind load-induced differential deformations, a large scale of piled raft foundation was designed, as shown in Fig. 1. The length, width and height of the piled raft were 18.7, 15.4 and 5.0 m, respectively. Under each concrete raft, 30 concrete piles with a length of 6 5, a diameter of 1.1 m and a spacing of 3.3 m were constructed.

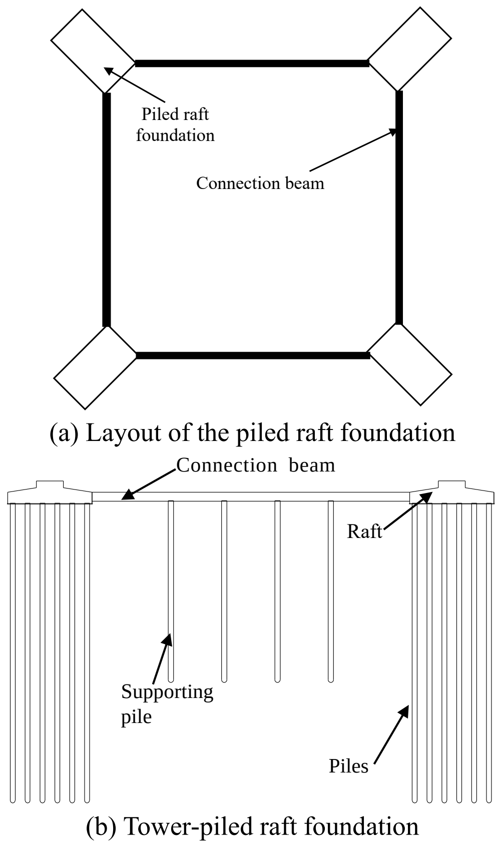


Fig. 1 Layout of the piled raft foundation of transmission tower

Table 1 Geotechnical properties of soil in this site

Soil Type	**Soil Parameter**				
	H (m)	γ (kN/m³)	$E_{s1\text{-}2}$ (MPa)	C (kPa)	φ (°)
Muddy silty clay	14	17.8	3.25	8	24.0
Silty clay	9	18.0	4.75	5	27.0
Fine sand	8	18.6	11.5	5.5	30.0
Silty clay	9	18.6	5.3	9	25.5
Silty clay with sand	4	19.2	7.3	10	26.0
Fine sand	12	19.8	13.5	3	36.0
Coarse sand	24	20.0	15.5	4	36.0

2.2 Geology

The construction site was located at Jiangyin city, which was close to Yangtze rivers. For transmission tower built close to Yangtze River, soil stratum mainly consisted of clay, silty and sand. Thus, soil condition considered in this study was a typical stratum for transmission tower. Table 1 summarized basic mechanical properties of soil located in this site. The thickness of upper two layers (i.e., muddy silty clay and silty clay) was 23 m, underlaid by a fine sand layer with a thickness of 8.0 m. Below this sandy layer, there were another two silty clay layers with thickness of 13.0 m. Another two sandy layers with a thickness of 36 m was located below the silty clay layer. Based on the site investigation, there was no rocks in the soil stratum within top 80 m. Since the length of piles was 65 m, the designed piles could be considered as frictional structures.

Laboratory experiments were conducted to measure geotechnical parameters of each soil layer. As expected, the upper two soil layers had relatively poor mechanical parameters. The constrained compression modulus of these two soils was in a range of 3.25 to 4.75 MPa. By conducting undrained consolidated triaxial tests, the measured effective cohesion and frictional angle of these soils were in a range 5-8 kPa and 24.0°-27.0°, respectively. The underlying fine sand layer had much higher compression modulus (i.e., 11.5 MPa) and internal frictional angle (i.e., 30.0°). Relatively low soil compression modulus (i.e., 5.3-7.3 MPa) and frictional angle (i.e., 25.5°-26.0°)

were observed in the underlying two silty clays. In this construction site, all the bored piles sit on coarse sand layer with good geotechnical properties. The fictional angle of bearing sandy soils was 36.0° and its compression modulus was 15.5 MPa.

3. Three-dimensional numerical parametric study

3.1 Calculation of equivalent lateral loads applied on the foundation

This study aimed to develop a simplified method to predict foundation movements under different ground and wind conditions. In this site, bolts were used to connect upper transmission tower and lower piled raft foundation. Thus, additional loads resulting from wind and self-weight of tower were transmitted to the piles via piled raft. In other words, deformations of pile foundation were controlled by resultant loads at the connection between raft and tower. To simplify three-dimensional transmission tower-soil-pile foundation interaction problems, the upper transmission tower and lower piled raft foundation were analyzed separately.

Fig. 2 shows the numerical model of upper transmission tower established by commercial software Midas. The geometry and dimension of the transmission tower model were the same as that in field. The transmission tower was simulated by truss elements with rod connections, which could only sustain axial loads. Beams elements with fixed connections were used to simulate the columns of the transmission towers. Thus, bending moments could transmit to the pile foundation via beams. Based on the analysis model, the weight of the transmission tower was 3600 ton. By applying a wind under an arbitrary direction, wind load-induced additional loads along the four vertical columns could be obtained. The wind velocity was 35 m/s and direction angle was 0°. As shown in Fig. 2(b), compression and tensile forces were induced in front-row and back-row columns. It was found that wind load-induced additional load at the top of transmission tower was negligible. Accordingly, additional loads increased dramatically as a decrease in the elevation. The maximum loads were always observed at the bottom of the four vertical columns. Thus, it was reasonable to use the computed force at the bottom of the tower to analyze deformations of pile foundation. By applying the calculated internal force at the top of piled raft, movements of individual pile foundation could be obtained.

3.2 Numerical analysis program

Because of wind load-induced horizontal loads, the foundation of transmission tower experienced compression and tension. Thus, deformation mechanisms of transmission tower were expected to be affected greatly by wind with different velocities and angles. The designed grade of wind load for this ultra-high transmission tower was 13, corresponding to a wind intensity of 37.0 to 41.4 m/s. In order to evaluate the effects of wind load on foundation deformation, the designed wind velocity in this study was 0, 5, 10, 15, 20, 25, 30, 35 and 40 m/s, respectively. In reality, wind came from any direction with respect to the transmission tower. In this study, the loading angle was designed as 0°, 15°, 30°, 45°, 60°, 75° and 90°, respectively.

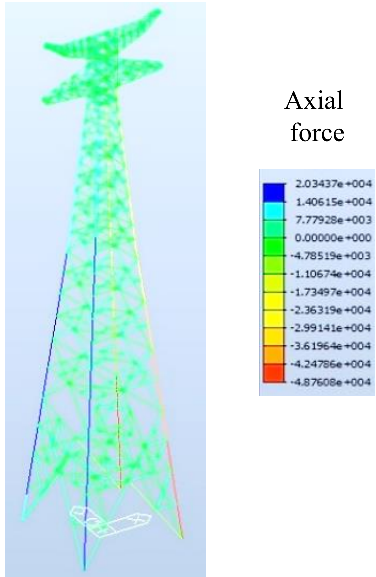


Fig. 2 Distribution of internal force induced in transmission tower

Table 2 Numerical analysis program of basement-soil-box culvert interaction

Wind intensity, (m/s)	Wind direction, (°)	Modulus, (MPa)	Pile diameter, (m)	Pile length, (m)	Pile spacing, (m)
.0 to 15.8	2.0 to 10.0	1.9~11.4	0.5-2.0	45-75	2.3-3.3

To balance wind-induced horizontal loads, four individual piled raft foundations were designed. If concrete beams were used to connect the foundations, the entire foundation could sustain the horizontal loads together. Thus, three-dimensional numerical analyses were conducted to evaluate the contribution of concrete beam for reducing foundation deformations. The height and width of connection beam were 2.0 and 1.6 m, respectively. Since the clear distance between two individual foundation was 75 m, four piles with a diameter of 1.1 m and a spacing of 10 m were used to support each connection beam.

Obviously, the horizontal beaming capacities of pile foundation were controlled by soil properties, pile length, pile diameter and pile spacing. In the area of Yangtze River delta, the majority of upper stratums were clays, underlaid by sandy layers. Normally, the piles used to support transmission tower was penetrated into sandy layers. Thus, pile deformations were expected to be significantly affected by mechanical properties of upper muddy silty and silty clay layers (i.e., thickness of 23 m). In the numerical analysis, compression modulus (E_s) of these two clay layers was designed from 1.9 MPa to 11.4 MPa, corresponding to mechanical properties of muddy soft clay to silty clay. Moreover, the diameter (D_p), length (L_p) and spacing (S_p) of piles were designed in ranges of 0.5-2.0 m, 45-75 m and 2.3-3.3 m, respectively. In total, 150 three-dimensional numerical runs were conducted to develop calculation charts for estimating deformations of pile foundation, as summarized in Table 2.

3.3 Three-dimensional numerical mesh and boundary conditions

Fig. 3 shows the three-dimensional numerical mesh used to analyze deformations of piled raft foundation due to wind load. Since wind came from an arbitrary direction, four piled raft foundation should be simulated in the analysis. To eliminate boundary effects on pile deformation, a large-scale soil model with a length of 220 m, a width of 220 m and a depth of 80 m was established. In total, seven soil layers shown in Table 1 was simulated. Ten-noded tetrahedron elements were used to simulate all soil stratum, while piles and connection beams were modelled by pile and beam elements, respectively. In total, this three-dimensional mesh consisted of 103455 element and 154704 nodes. By increasing the number of elements and nodes 100%, the differences in the maximum lateral and vertical movements of grouped piled-raft were less than 2%. It was indicated that the current mesh density was already fine enough. Roller supports were applied to the four vertical sides of the mesh, while pin supports were applied to the bottom of the mesh. In other words, soil movements perpendicular to the four vertical sides were constrained, while soil movements in all the directions were constrained at the bottom of the mesh. As expected, pile responses were supposed to be affected by pile-soil interface. In this study, a linearly elastic and perfectly plastic model was used to simulate pile-soil interaction. The slippage of pile-soil interface element was controlled by frictional coefficient u (i.e., tanφ_b, where φ_b was 2/3 of internal frictional angle).

3.4 Construction sequences

In this study, the construction sequences adopted in the numerical analysis were listed as follows:

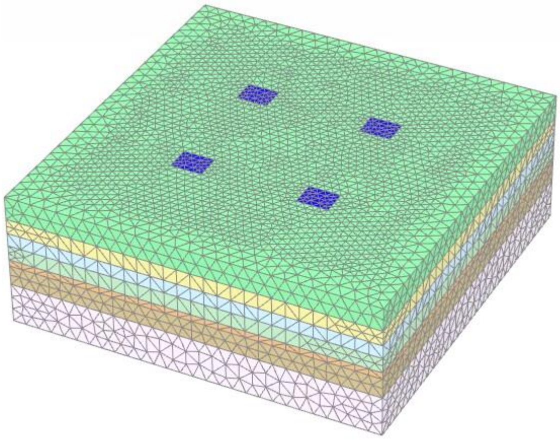
(1) The initial vertical and horizontal stresses were established by applying a coefficient of earth pressure at rest (K_0 = 1-sinφ').

(2) By activating beam and pile elements, construction of concrete rafts, piles and connection beams was simulated.

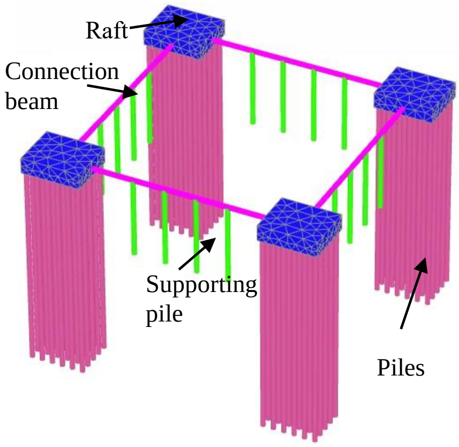
(3) Vertical and horizontal forces were applied at the center of each concrete raft to simulate wind induced additional loads at the connection of raft and transmission tower.

3.5 Constitutive model and model parameters

In this construction site, soil stratum consisted of silty clay and fine sand, which exhibited obvious nonlinear behavior when they were subjected to shearing (Shi *et al.* 2015, 2019, 2023). To capture nonlinear soil behaviors, a widely used hardening soil model (HS model) in literature was adopted to analyze wind-soil-pile interaction problems (Brinkgreve and Broere 2004, Huang *et al.* 2014, Ng *et al.* 2021). By conducting one-dimensional compression test, constrained soil modulus (E_s) of each soil layer was obtained. Moreover, triaxial consolidated shear tests were conducted to obtain internal frictional angle and cohesion. The key parameters of the HS model were secant modulus (E_{50}^{ref}), tangent oedometric modulus (E_{oed}^{ref}) and unloading-reloading modulus (E_{ur}^{ref}). Based on extensive experimental results, the unloading-reloading modulus (E_{ur}^{ref}) was commonly 3 to 6 times of the secant modulus (E_{50}^{ref}) or constrained soil modulus (E_s). Moreover, the modulus stress related power exponent "m" was typically in a range of 0.8-



(a) Three-dimension finite element mesh



(b) Four piled raft foundation

Fig. 3 Layout of the piled raft foundation of transmission tower

Table 3 Soil parameters for hardening soil model (HS)

Soil type	Model parameter			
	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	m
Muddy silty clay	3.25	3.25	19.5	0.90
Silty clay	4.75	4.75	28.5	0.85
Fine sand	11.5	11.5	57.5	0.60
Silty clay	5.3	5.3	31.8	0.80
Silty clay with sand	7.3	7.3	43.8	0.70
Fine sand	13.5	13.5	67.5	0.50
Coarse sand	15.5	15.5	77.5	0.50

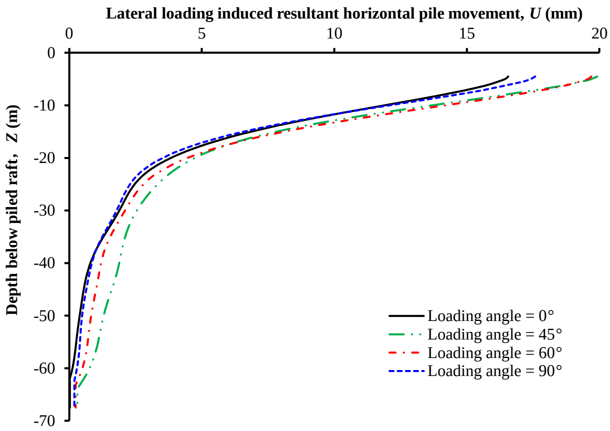


Fig. 4 Lateral loading-induced resultant horizontal pile movement

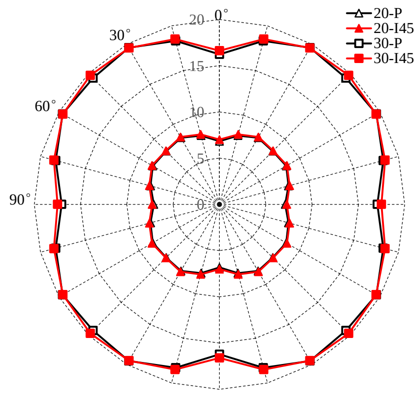
1.0 and 0.5-0.6 for fine- and coarse-grained soils (Brinkgreve and Broere 2004, Ardakani *et al*. 2014, Zheng *et al.* 2018). By using the stress-strain curve from triaxial consolidated shear tests, ratios of E_{ur}^{ref} to E_{50}^{ref} of sand and clay were calibrated as 5 and 6, respectively. In addition, the calibrated soil parameter "*m*" of each soil layer was shown in Table 3. All the soil parameters for the hardening soil model (HS) were summarized in Table 3.

4. Interpretation of computed results

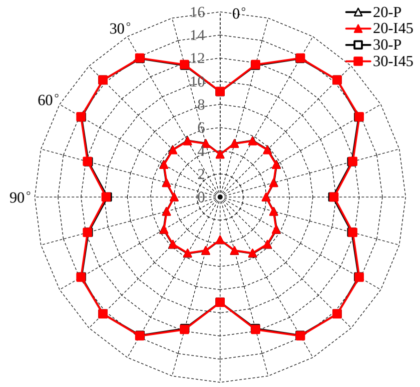
4.1 Effects of foundation layout and loading direction on movements of transmission tower

Fig. 4 shows the effects of loading angle on lateral deformations of piled raft foundations. For each loading angle, the maximum lateral pile movements along the depth are compared. It is found that lateral movements reach the maximum values at the top of the pile, and they decrease rapidly as an increase in the pile depth. When the pile depth is larger than 40 m, negligible lateral movements are induced. It implies that lateral pile movements are supposed to be affected greatly by mechanical properties of upper soft soils. When the loading direction angles are 0º, 45º, 60º and 90º, the maximum lateral movements at the pile top are 16.1, 19.5, 19.3 and 17.1 mm, respectively. Obviously, loading angle of 45º and 60º causes much larger horizontal pile movements than other conditions.

Fig. 5 shows the effects of foundation layout and wind direction on movements of transmission tower. The wind velocities are 20 and 30 m/s, respectively. Notations "P" and "I45" represent parallel and inclined arrangements of the four piled raft foundation. For the case of I45, all the piled raft foundation rotates 45°, as shown in Fig. 1. Obviously, wind load induced movements of piled raft foundation are greatly affected by wind velocity. By increasing wind velocity from 20 to 30 m/s, the resultant horizontal movements and settlements due to wind load in different angles increase by 1.41 and 1.48 times, respectively. Although two foundation layouts are simulated, the differences in the horizontal movements and



(a) Resultant horizontal movement



(b) Settlement

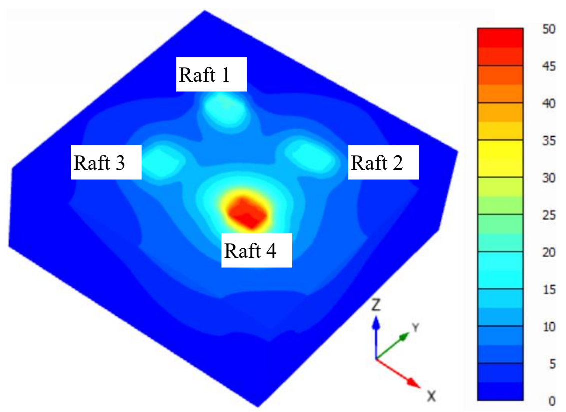
Fig. 5 Effects of foundation layout and loading angle on movements of pile foundation (unit: mm)

settlements are negligible for these two arrangements of pile foundation. Considering the symmetricity, the inclined arrangement of the four piled foundation is a better layout.

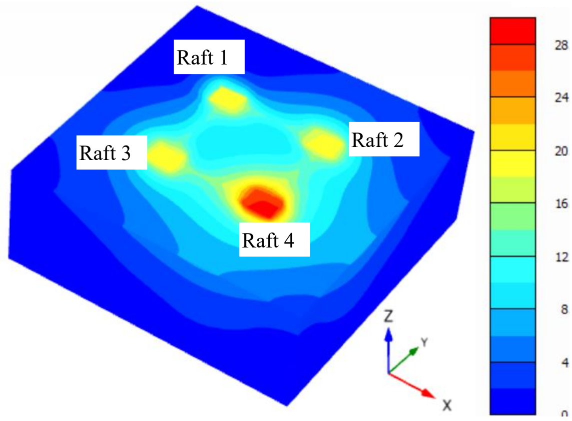
Because of plane symmetry, wind load-induced horizontal movements and settlements are symmetrical. Note that the smallest horizontal movements and settlements are induced when the loading angle is 0°. When the wind velocities are 20 and 30 m/s, wind-load induced the smallest horizontal movements and settlements are in ranges of 7.0-16.6 mm and 3.7-9.1 mm, respectively. However, the horizontal movements and settlements reach the maximum values when the loading angle is in a range of 30°~60°. Accordingly, these two wind velocities induced maximum horizontal movements and settlements are in ranges of 8.4-19.7 mm and 5.8-14.3 mm, respectively. Obviously, the maximum resultant horizontal movements and settlements increase by up to 20.0% and 57.1%, respectively, as loading angle varies from 0° to 30°~60°.To ensure the serviceability and safety of transmission tower, the design of pile foundation for transmission tower should consider the loading angle of 30°~60°.

4.2 Effects of connection beam on movements of pile foundation for transmission tower

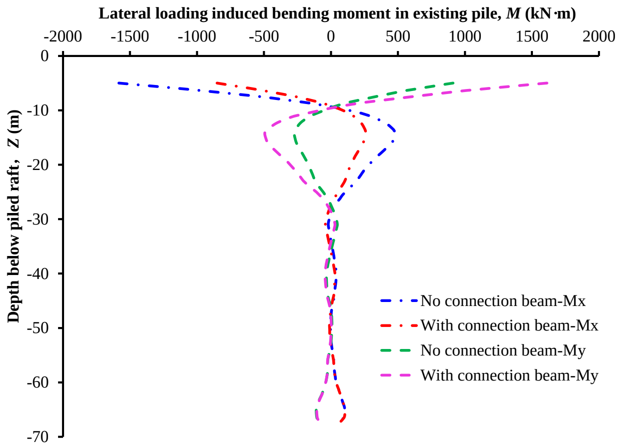
In practice, concrete beams are commonly used to connect piled raft foundation to increase structural integrity. Fig. 6 compares lateral loading-induced resultant horizontal



(a) No connection beam (mm)

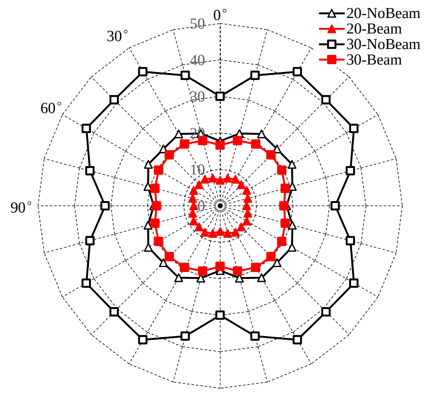


(b) With connection beam (mm)

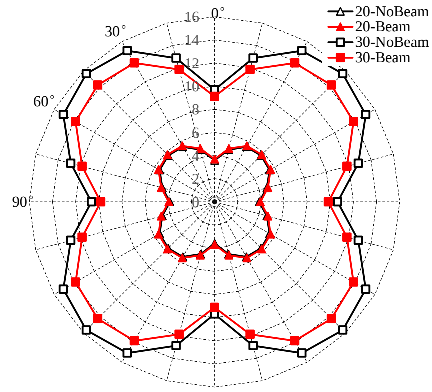


(c) Bending moments

Fig. 6 Lateral load induced soil and pile deformations



(a) Resultant horizontal movement

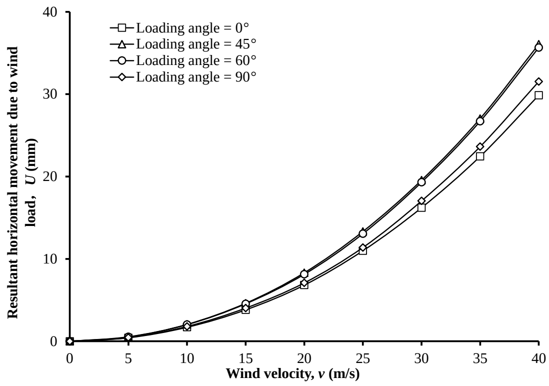


(b) Settlement

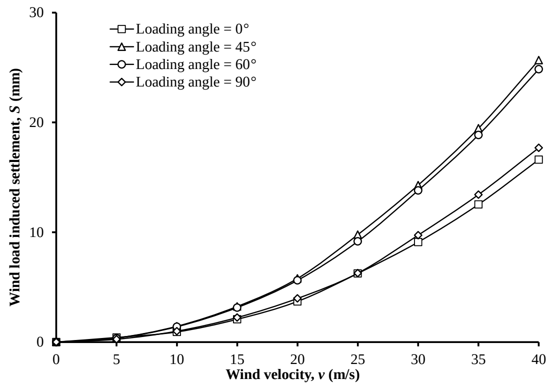
Fig. 7 Effects of connection beam on movements of pile foundation (unit: mm)

soil movements with and without connection beams. In this case, the loading angle is 45° and raft 4 sustains the largest horizontal loads. If these four piled raft foundations are not connected by concrete beams, lateral movements concentrate at the piled raft 4 with a maximum value of 49.9 mm, as shown in Fig. 6(a). By using connect beam, lateral load induced soil movements are sustained by four piled raft foundation together. Thus, the maximum soil movement decreases to 30.2 mm, as shown in Fig. 6(b). Because of lateral load, the maximum bending moments always observed at the pile top, and deceases rapidly with pile depth, as shown in Fig. 6(c). If there are no any connection beams, the maximum bending moments of piles induced in two directions are 1582.7 and 1612.0 kN·m, respectively. The use of connection beam decreases the maximum pile bending moments to 849.5 and 911.0 kN·m, respectively. Obviously, the maximum bending moments of piles decrease by up to 46.3% by using connection beams.

Fig. 7 shown the effects of connection beam on movements of existing piles under different loading directions. Obviously, installation of concrete beams can effectively reduce resultant horizontal movements of piled raft foundation due to lateral load under arbitrary directions. When the wind velocity is 20 m/s, the use of concrete beam can reduce resultant horizontal movements of piled raft foundation by 60.5%~63.0%. Because of the existence of the concrete beam, resultant horizontal movements of pile foundation decrease by 44.6%~54.0% when the wind velocity is 30 m/s. This is because the integrity of the piled raft foundation increases substantially by using concrete beam. All the pile foundation sustains the wind load together. Thus, a rapid decrease in the wind load-induced horizontal movements is observed. However, the effects of concrete beam on foundation settlements are relatively small. When the wind velocities are 20 and 30 m/s, the reductions of foundation settlements by using concrete beams are only up to 2.8% and 8.8%, respectively. Obviously, the resultant horizontal movements of pile foundation are much more sensitive to the concrete beam.

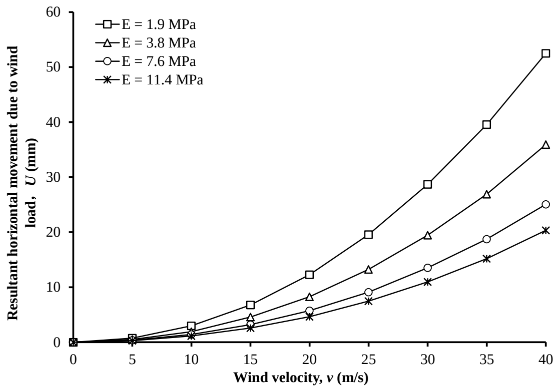


(a) Resultant horizontal movement

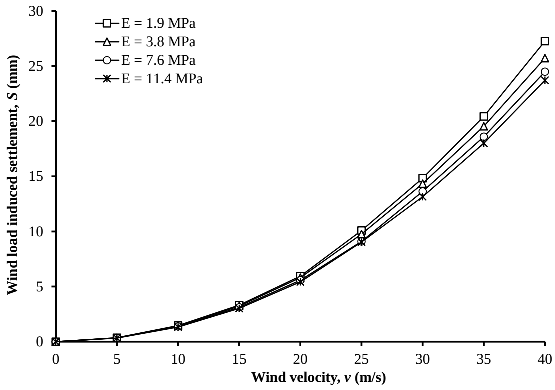


(b) Settlement

Fig. 8 Effects of wind velocity on movements of pile foundation for transmission tower



(a) Resultant horizontal movement



(b) Settlement

Fig. 9 Effects of soil stiffness on movements of pile foun dation for transmission tower

4.3 Effects of load intensity on movements of pile foundation for transmission tower

Fig. 8 shows the effects of wind velocity on movements of pile foundation used to support transmission tower. As shown in Fig. 5, the maximum and minimum movements are observed when the loading angles are 30°~60° and 0°, respectively. For brevity, the computed results under loading angles of 0°, 45°, 60° and 90° are presented. When the wind velocity varies from 0 to 40 m/s, wind with direction angles of 45° and 60° results in almost the same movements of pile foundation. Moreover, movements of pile foundation are quite close when the loading angles of 0° and 90°. Under a given loading angle, both the horizontal movements and settlements of pile foundation increase with wind velocity at an increased rate. As an increase in the wind velocity, the effects of loading angle on the movements of pile foundation are enlarged. When the wind velocity is less than 10 m/s, the resultant horizontal movements and settlements of pile foundation are almost independent of loading angle. However, under a high wind velocity (i.e., 40 m/s), the resultant horizontal movements and settlements of pile foundation increase by 19.4% and 54.5%, respectively, when the wind velocity direction angle changes from 0° to 45°. It is indicated that again the importance of considering loading angle in the design of pile foundation, especially for a transmission tower sustained high wind velocities.

4.4 Effects of soil stiffness on movements of pile foundation for transmission tower

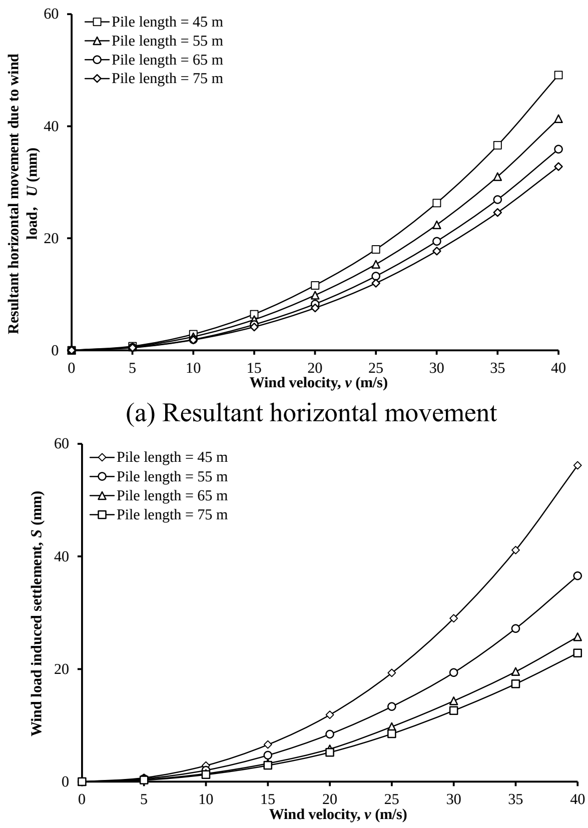
To obtain a conservative estimation of movements of pile foundation, the following sections only present the maximum movements of pile foundation under the loading angle of 45°. As shown in Table 1, there are two soft soils with poor mechanical properties, and movements of pile foundation are supposed to be affected greatly by these two soft soils. In the numerical analysis, the effects of soil stiffness of these two soft clays are analyzed. As shown in Fig. 9, the horizontal movement of pile foundation are significantly affected by stiffness of upper two soils. At a given velocity, the horizontal movements of pile foundation increase rapidly at an increased rate as soil stiffness is reduced. Moreover, the differences in the horizontal movements of pile foundation are enlarged as an increase in the wind velocity. When the wind velocities are 20 and 40 m/s, the incremental horizontal movements of pile foundation are 7.6 and 32.2 mm, respectively. As soil stiffness increases from 1.9 MPa to 11.4 MPa, the horizontal movements of pile foundation decrease by 61.7%. However, effects of soil stiffness on settlements of pile foundation are relatively small. The settlements of pile foundation only decrease by 8.4%~13.0% when soil stiffness increases from 1.9 MPa to 11.4 MPa.

4.5 Effects of pile diameter on movements of pile foundation for transmission tower

Fig. 10 shows the effects of pile diameter on movements of pile foundation for transmission tower. In this section, the wind velocity considered is in a range of 20 to 40 m/s. As expected, pile with a large diameter can provide much more resistances to withstand wind load. However, the effectiveness of reducing movements of pile foundation decreases as an increase in the pile diameter. As the pile diameter varies from 0.5 m to 1.4 m, the resultant horizontal movements and settlements decrease by 33.4%~35.3% and 49.4%~53.5%, respectively. By further increasing pile diameter from 1.4 m to 2.0 m, the resultant horizontal movements and settlements only reduce by up to 15.9% and 8.8%, respectively. Obviously, movements of pile foundation are not sensitive to pile diameter when it is larger than 1.4 m. Under a higher wind velocity, the effects of pile diameter on movements of pile foundation are more notable. When wind velocities are 20 and 40 m/s, reductions in the horizonal movements of pile foundation are 43.1% and 45.9%, respectively, as pile diameter varies from 0.5 m to 2.0 m.

4.6 Effects of pile length on movements of pile foundation for transmission tower

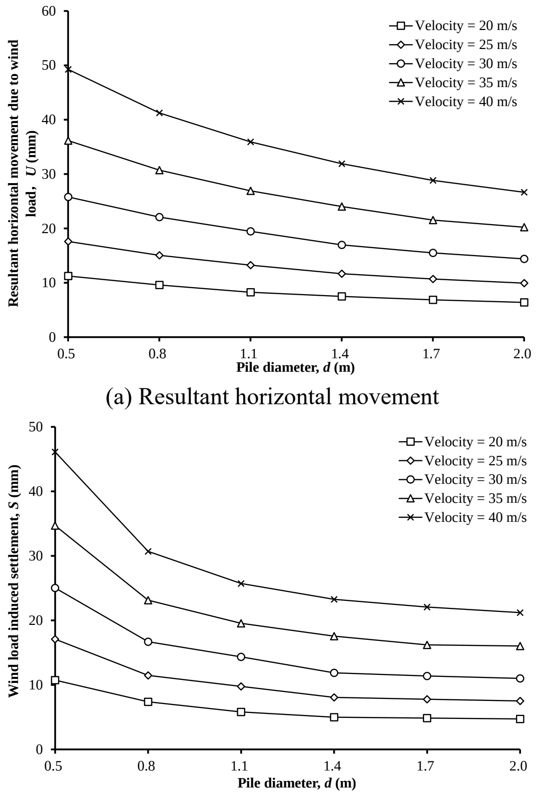
Fig. 11 shows the effects of pile length on movements of pile foundation for transmission tower. In this section, the pile length is in a range of 45 m to 75 m. As expected, the horizontal and vertical resistances decrease as a reduction in pile length.



(a) Resultant horizontal movement

(b) Settlement

Fig. 11 Effects of pile length on movements of pile foundation for transmission tower



(a) Resultant horizontal movement

(b) Settlement

Fig. 10 Effects of pile diameter on movements of pile foundation for transmission tower

Different from soil stiffness, the effects of pile length on vertical settlements of pile foundation are much more notable than the horizontal movements. As the pile length varies from 75 m to 45 m, the wind load induced resultant horizontal movements and vertical settlements increases by 48.4%~58.9% and 127.1%~150.9%, respectively. This is because a shorter pile provides less horizontal and vertical resistances to deform against wind loads. Of all the parameters considered in the numerical study, the wind velocity has the largest effects on responses of grouped piled-raft foundation.

5. Development of calculation chart of movements of transmission tower due to wind loads

Based on previous results, movements of pile foundation are function of wind velocity, soil stiffness, pile length, pile diameter and pile spacing. For the conveniences of designers, it is vital to propose calculation charts to directly estimate movements of pile foundation under various circumstances. As shown in previous sections, movements of pile foundation have inverse relationships with soil stiffness (E_s), pile diameter (D_p) and pile length (L_p), but they have positive correlation with pile spacing (S_p). Thus, a dimensional group, $U\cdot(E_s/P_a)^{0.5}\cdot(D_p/S_p)^{0.5}\cdot(L_p/S_p)^{0.5}$, is proposed to correct

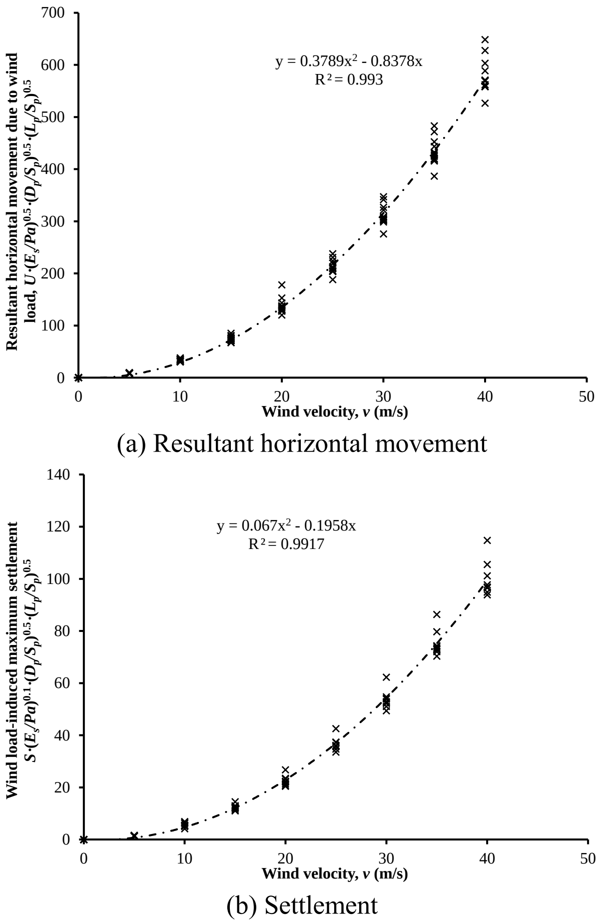


Fig. 12 Calculation chart of movements of pile foundation

resultant horizontal movement (U) with wind velocity (v). Fig. 12(a) shows the relationship between the proposed dimensional group and wind velocity. It is clearly shown that the $U\cdot(E_s/P_a)^{0.5}\cdot(D_p/S_p)^{0.5}\cdot(L_p/S_p)^{0.5}$ increases rapidly as an increase in the wind velocity. By using a polynomial equation, the computed resultant horizontal movements can be reasonably described by following equation (i.e., R^2 value is 0.993):

$$\boldsymbol{y = 0.3789x^2 - 0.8387x} \quad (1)$$

where y is resultant horizonal movements $U\cdot(E_s/P_a)^{0.5}\cdot(D_p/S_p)^{0.5}\cdot(L_p/S_p)^{0.5}$, and x is wind velocity.

By using the same approach, another dimensional group, namely $U\cdot(E_s/P_a)^{0.1}\cdot(D_p/S_p)^{0.5}\cdot(L_p/S_p)^{0.5}$, is proposed to correct settlement of pile foundation (S) and wind velocity (v). Again, the proposed dimensional group of vertical settlement of pile foundation increases rapidly with wind velocity, as shown in Fig. 12(b). By using the polynomial Eq. (2), wind load-induced settlements have a close correlation with the wind velocity with a fitted coefficient (R^2) of 0.9917.

$$\boldsymbol{y = 0.067x^2 - 0.1958x} \quad (2)$$

where y is settlement of pile foundation $S\cdot(E_s/P_a)^{0.1}\cdot(D_p/S_p)^{0.5}\cdot(L_p/S_p)^{0.5}$, and x is wind velocity. Eqs. (1) and (2) captures the effects of soil stiffness, pile diameter, pile spacing, pile length and wind velocity on resultant horizontal movements and settlements of pile foundation for transmission tower. Thus, the proposed calculation charts can directly estimate wind load-induced movements in the pile foundation, which provide guidelines for the design of the pile foundation.

In this study, extensive numerical analyses are conducted to explore the effects of load intensity, loading angle, soil stiffness, pile diameter, pile spacing and pile length on foundation deformations. Thus, conclusions drawn from this study only applies to those conditions. Attentions should be paid when extrapolating these results to a general case.

6. Conclusions

In this study, three-dimensional numerical parametric study was conducted to explore deformation mechanisms of piled raft foundation for transmission tower due to wind load in clays. Effects of wind velocity, loading angle, soil stiffness, pile diameter, pile spacing and pile length on foundation deformations were explored. Based on the computed results, the following conclusions may be drawn:

• It is found that the smallest and largest movements of pile foundation are induced when the wind direction angel are 0° and 30°~60°, respectively. By increasing loading angle from 0° to 30°~60°, the resultant horizontal movements and settlements increase by up to 20.0% and 57.1%, respectively.

• Since installation of connection beam can substantially increase integrity of pile foundation, wind load-induced resultant horizontal movements in the pile foundation decrease by 44.6%~54.0%. However, settlements of pile foundation only reduce by up to 8.8% by installing concrete beams. Obviously, resultant horizontal movements of pile foundation are much more sensitive to concrete beam.

• By increasing soil stiffness from 1.9 MPa to 11.4 MPa, the horizontal movements of pile foundation decrease by 61.7%, but settlements of pile foundation only decrease by 8.4%~13.0%. It is indicated that the effects of soil stiffness on settlements of pile foundation are relatively small.

• As pile diameter varies from 0.5 m to 1.4 m, the resultant horizontal movements and settlements decrease by up to 35.3% and 53.5%, respectively. By further increasing pile diameter from 1.4 m to 2.0 m, the resultant horizontal movements and settlements only reduce by up to 15.9% and 8.8%, respectively. By decreasing pile length from 75 m to 45 m, the resultant horizontal movements and vertical settlements increases by 48.4%~58.9% and 127.1%~150.9%, respectively.

• Based on numerical parametric study, two dimensional groups are proposed to develop calculation charts of resultant horizontal movements and settlements of pile foundation. Polynomial equations can reasonably correct movements of pile foundation and wind velocity. The proposed calculation charts can directly estimate movements of pile foundation under arbitrary lateral load, ground and pile conditions.

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