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EFFECT OF ANISOTROPY SPATIAL VARIABILITY OF MULTI-LAYERED SOIL ON THE BEARING CAPACITY OF OFFSHORE SINGLE PILE COMPOSITE FOUNDATION

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The bearing capacity of offshore single pile composite foundations is significantly influenced by spatially variable soil properties and the presence of different soil layers during pile installation. Previous research has primarily focused on the effects of isotropic or transversely anisotropic spatial variability of soil on the bearing capacity and failure mechanisms of piles embedded in a single homogeneous soil layer. However, practical offshore sites often consist of multiple soil layers, where soil properties can exhibit pronounced rotated anisotropy due to complex geological processes. The impact of such rotated anisotropic spatial variability on the bearing capacity of offshore single pile composite foundations embedded in multiple soil layers remains poorly understood.This study systematically investigates the effects of rotated anisotropic three-dimensional spatial variability of soil properties on the bearing capacity of offshore single pile composite foundations embedded in two distinct soil layers. A three-dimensional random finite element method is employed to simulate the pile-soil interaction under vertical static loads. The study examines the influence of the scale of fluctuation (´), the rotated anisotropy angle, and the coefficient of variation (COV) of soil parameters including elastic modulus (*E*), cohesion (*c*), and internal friction angle (Æ) on the failure mechanism and the characteristic bearing capacity of the pile. The result shows that the rotated anisotropy of the upper-layer soil generally exerts a more significant effect on the pile's bearing capacity compared to the lower-layer soil, especially when the horizontal scale of fluctuation is large. These findings highlight the critical importance of considering rotated anisotropy spatial variability in the design and analysis of offshore single pile composite foundations.

Keywords: spatial variability; rotated anisotropy; offshore pile composite foundation; vertical bearing capacity; Monto Carlo Simulation;

1. Introduction

The pile foundation is widely used in offshore geotechnical fields for transforming the loads from the supporting offshore structures such as offshore platforms and wind turbine (Li et al., 2024; Zhao et al., 2024) into the soils and/or bedrocks and providing the bearing capacity. The bearing capacity of pile is significantly affected by the properties of soils installing the piles under the vertical loads.In past decades, many efforts have been made to study the pile-soil response and failure mechanisms under vertical loading. (Hazzar et al. 2017; Franza et al. 2021; Chen et al. 2020). However, these studies mainly focus on the investigation of the effects of 3D spatial variability of soil properties on failure mechanisms of different pile foundations (e.g., monopole foundation, piled-raft foundations, etc.) subjected to various loading conditions (e.g., vertical loading, lateral loading, multi-directional loading, seismic loading, etc.), among which the spatially variable soil properties are frequently modelled with the isotropic and/or transverse anisotropy random fields (Kawa and Pula 2020; Johari et al. 2021; Zhou et al. 2022; Choudhuri and Chakraborty 2024; Li et al. 2024).

Few effort has been made to investigate the influence of transverse anisotropy and/or rotated anisotropy on the failure mechanism and bearing capacity of the offshore single pile composite foundation. In addition, the practical offshore site may contain multiple soil layers; however, the existing studies often assumed that the pile is embedded into a single-layer soil. How the transverse anisotropy and/or rotated anisotropy of spatial variable soil properties affect the failure mechanism and bearing capacity of the offshore single pile composite foundation remains unclear. This study systematically investigates the influence of transverse and/or rotated anisotropy spatial variability of soil properties on the bearing capacity of an offshore single pile composite foundation embedded in two layered soils based on 3D stochastic finite element model.

2. Method

2.1. Setting of the 3D finite element model

This study used the ABAQUS 2021 to establish the three-dimensional finite element analysis model. The elastic-perfectly plastic Mohr-Coulomb constitutive model is a widely used as the material model to describe the behavior of soils. Fig. 1 shows the established 3D finite model of the full-length single pile composite foundation. Since this model is symmetric, only half of it is shown in Fig. 1 for clear observation of the internal pile-soil structure. The 3D model is with a length of 10.5 m, a width of 10.5 m and a depth of 11 m. The upper layer of soft clay has a thickness of 4 m, and the lower layer of sandy clay has a thickness of 7 m. The length and width of the 3D model is large enough compared with the diameter of pile so that the effects of boundary constraint on the estimation of bearing capacity can be neglected. The soil elements on the boundary of the 3D model is subjected to displacement constraints in the corresponding horizontal direction, while the bottom elements of soils are constrained in both the horizontal and vertical directions. The top surface is free to move. The pile is with a diameter of 0.6 m and a length of 8 m. The pile penetrates into the entire soft clay layer and is embedded into the sandy clay with a depth of 4 m. The tangential behavior of the pile-soil interface is defined by the penalty friction formulation, with a friction coefficient of 0.25. The normal behavior is modeled as hard contact, allowing separation after contact. The bottom surface of the cushion layer is in contact with the top of the pile, and the top surface is in contact with the bearing plate. To prevent numerical non-convergence caused by relatively sliding among the bearing plate, cushion, and pile, the interfaces between the bearing plate and cushion as well as the cushion and pile are set to be bonded. A stepwise vertical static load with each step being 25 kN is applied to the bearing plate with a size of 1.2m × 1.2m. When the final load step is applied, the load is approximately 139 kPa.

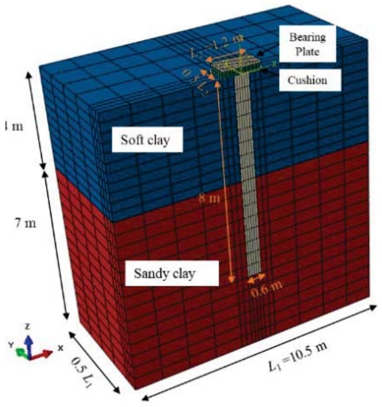


Fig. 1 Three-dimensional model and mesh.

2.2 *Simulation of rotational anisotropy random field*

Suppose that the transverse anisotropy random field is rotated counter-clock wisely with an angle of β_x around the *x*-axis. The autocorrelation function corresponding to rotation around the *x*-axis can be expressed as:

$$\begin{cases} \rho_x = \exp\left(-2\dfrac{|\tau_x|}{\delta_x}\right) \\ \rho_{yz} = \exp\left[-2\left(\dfrac{|\tau_y\cos\beta_x - \tau_z\sin\beta_x|}{\delta_y} + \dfrac{|\tau_y\sin\beta_x + \tau_z\cos\beta_x|}{\delta_z}\right)\right] \end{cases} \quad (1)$$

where $^{2}{}_{x}$ ranges from to 0° to 180°. Based on Eq. (1), the corresponding separable auto-correlation matrices for x direction $\boldsymbol{R}_x$,and yz direction $\boldsymbol{R}_{yz}$ can be assembled. Let $\boldsymbol{L}_x$ and $\boldsymbol{L}_{yz}$ denote the lower triangular Cholesky decomposition matrices of $\boldsymbol{R}_x$ and $\boldsymbol{R}_{yz}$, respectively. The 3D normal random field $\boldsymbol{X}$can be simulated as $\boldsymbol{X}= \boldsymbol{L}_{yz}\mathbf{U}\boldsymbol{L}_{yz}{}^{\mathrm{T}}$ where $\boldsymbol{U}$is a matrix contain standard normal independent random variables. The lognormal random field of $\boldsymbol{Y}_E$

soil parameters is simulated by $\boldsymbol{Y}_E = \exp(\mu_{\ln E}+\sigma_{\ln E}\boldsymbol{X})$ where $\mu_{\ln E}$ and $\sigma_{\ln E}$ denote the mean and standard deviation of E in the normal space. The process is repeated for other parameters to obtain the lognormal random field of other parameters.

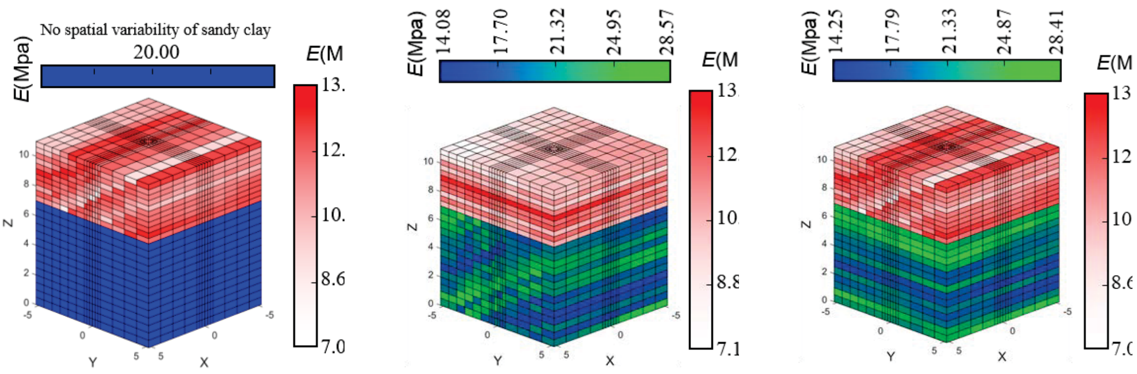
4. Effect of rotated anisotropy spatial variability of soft clay and sandy clay

This section further investigates the influence of rotated anisotropy spatial variability on the bearing capacity of the single pile composite pile foundation. The mean of COV of E, c and φ are summarized in Table 1. Table 1 also shows the parameters of cushion, bearing plate and pile. The COV of these parameters, autocorrelation function and the scale of fluctuation for the soft clay and sandy clay are assumed to be the same (i.e., $\mathrm{COV}_E = 0.1$, $\mathrm{COV}_c = 0.2$, $\mathrm{COV}_\varphi= 0.1$, $'_h = 100$ m and $'_v = 1$ m). However, rotation angles for the two soil layers can be different.

Table 1 Materials parameters of cushion, bearing plate, pile and different layers of soil

Parameter	Symbol	Soft clay	Sandy clay	Cushion	Bearing plate	Pile	Unit
Young's Modulus	E	10	20	16.7	2×10^5	2.5×10^4	MPa
Poisson's ratio	½	0.25	0.28	0.25	0.18	0.22	——
Weight	³	1850	1950	1800	7850	2400	kg/m^3
Cohesion	c	20	22	5.5	——	1000	kPa
Friction Angle	Æ	20	25	21	——	30	°

This section investigates the effect of rotated anisotropy spatial variability of soft clay and sandy clay on the bearing capacity of the single pile composite foundation. Fig. 2 shows the typical realizations of rotated anisotropy random field of the two soil layers for $'_h = 100$. For simplification, only the lognormal random field of Young's Modulus E is shown. The rotated anisotropy random field provides a more reasonable description of soil that has experienced geological movement and the nature horizontal decomposition has been rotated. It is particularly applicable to underground involving inclined sedimentary layers or fractured rock and soil masses, offering a more accurate modeling of the soil properties for analysis.

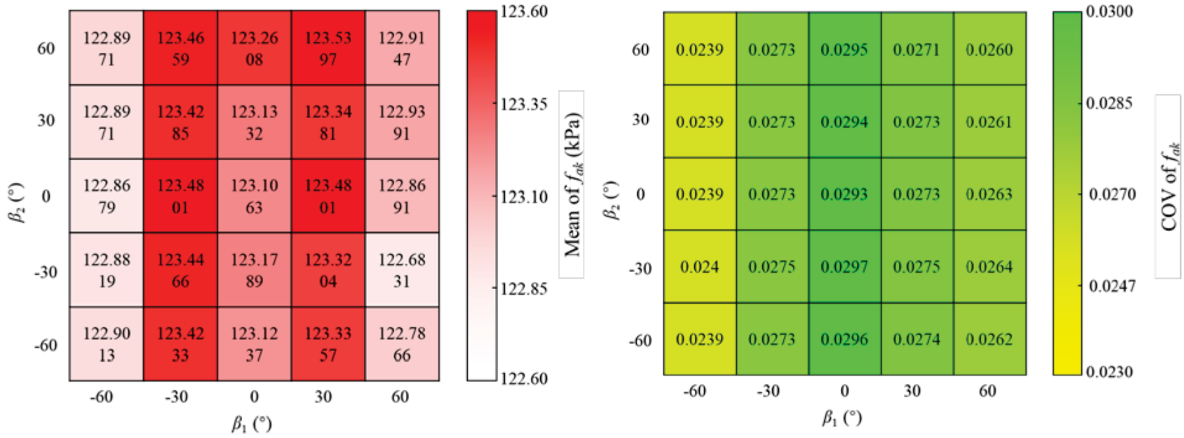


(a) (b) (c)

Fig. 1. Typical realizations of anisotropy random field of E: (a) Spatial variability of single-layer soil with $^2{}_1$=30 ° ; (b) Spatial variability of double-layer soils with $^2{}_1$=0°and $^2{}_2$=30°; (c) Spatial variability of double-layer soils with $^2{}_1$=30° and $^2{}_2$=0°

Fig. 24 shows mean and COV of f_{ak} for various combinations of the rotation angles $^2{}_1$ and $^2{}_2$. The $\delta_h = 100$ m and $\delta_v = 1$ m are used in this section. It is seen that $^2{}_2$ has samller effect on the mean of f_{ak} compared with $^2{}_1$.For the same $^2{}_2$, the mean of f_{ak} obtains the largest value in the 30° or –30° of $^2{}_1$. Rotationof the random fields of soft clay does not always increase the mean of f_{ak}. The mean value of f_{ak} reaches its maximum for $^2{}_1$ = 30° and $^2{}_2$ = 0°. The mean value of f_{ak} reaches its minimum for $^2{}_1$ = 60° and $^2{}_2$ = –30°. For the same $^2{}_2$, the COV of f_{ak} increases from –60° to 0° and decreases from 0° to 60° for $^2{}_1$. For the same $^2{}_1$, $^2{}_2$ has minor effect on the COV of f_{ak}. It is clear that the

COV of f_{ak} is also more sensitive to the rotation angle of β_1. The small influence of β_2 might be because only part of the pile is embedded into the sandy clay and thus the sandy clay provides less resistance to the load transmitted from the pile.



β_2 (°)	-60	-30	0	30	60
60	122.8971	123.4659	123.2608	123.5397	122.9147
30	122.8971	123.4285	123.1332	123.3481	122.9391
0	122.8679	123.4801	123.1063	123.4801	122.8691
-30	122.8819	123.4466	123.1789	123.3204	122.6831
-60	122.9013	123.4233	123.1237	123.3357	122.7866

β_2 (°)	-60	-30	0	30	60
60	0.0239	0.0273	0.0295	0.0271	0.0260
30	0.0239	0.0273	0.0294	0.0273	0.0261
0	0.0239	0.0273	0.0293	0.0273	0.0263
-30	0.024	0.0275	0.0297	0.0275	0.0264
-60	0.0239	0.0273	0.0296	0.0274	0.0262

(a) Mean of f_{ak} (b) COV of f_{ak}

Fig.24 The variation of the mean and COV of f_{ak} for various β_1 and β_2

5. Conslusions

The rotated anisotropy of the upper soft clay (i.e., β_1) has the larger influence on the mean and COV of f_{ak} compared with the rotated anisotropy of the sandy clay (i.e., β_2). This might be because only part of the pile is embedded into the sandy clay and thus the sandy clay provides less resistance to the load transmitted from the pile. For the same β_2, the mean value and OCV of f_{ak} are not monotonically with the increasing β_1. The mean value of f_{ak} reaches its minimum for $\beta_1 = 60°$ and $\beta_2 = -30°$. The COV of f_{ak} reaches its minimum for $\beta_1 = 0°$ and $\beta_2 = -30°$.

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