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PUNCH-THROUGH RISK ASSESSMENT OF SPUCANS CONSIDERING SOIL SPATIAL CORRELATIONS

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Acomprehensive understanding of the geological conditions at the penetration site is necessary to prevent punch-through accidents of spudcan foundations for the offshore mobile jack-up oil platform.However, the high cost of marine geotechnical survey limits the quantity and area of geological data, which poses great challenges for spudcan site selection and risk assessment. To address this issue, a framework for rapid geological parameter assessment is proposed in this studyto estimate the geological conditions at unsampled area, which are further applied to the punch-through risk analysis of the spudcan.The results show that the maximum relative error between estimatedsoil parameters and the measured soil parameters is 12.9%. The punch-through risk analysis based on estimated soil parameters is in close agreement with that derived from measured parameters.This study provides important assistance for the decision-making of spducan site selection and relocation in the sparse-data areas.

Keywords: Spudcan; Punch-through; Kriging interpolation; Soil Spatial Correlations; Sparse data.

1 Introduction

The offshore mobile jack-up platform has become a widely used structural facility for offshore oil field development in shallow to medium water depths due to the advantages of easy mobility, low cost, and high applicability.However, the restricted survey coverage and sparse geotechnical datasets impose significant constraints on the comprehensive characterization of seabed stratigraphic profiling, thereby elevating the potential risks of punch-through during spudcanpenetration.The punch-through risk of the spudcanalso seriously affects the safety of platform operations (Menzies & Lopez, 2011).

As shown in Fig. 1, the installation of a jack-up platform in a designated sea area requires prior geological exploration(Eslami & Fellenius, 1997; Schneider *et al*., 2008). Completed boreholes are marked by blue dots, while the red dot indicates a planned drilling location. The spudcans were initially planned at W3, W4 and W5. Identified punch-through risks at W5 now require reinstallation planning, necessitating enhanced stratigraphic profiling. However, harsh offshore environments and prohibitive marine drilling costs severely limit borehole sampling density at critical stratigraphic interfaces.In wind power construction, soil parameters from nearby sampled locations are often used to estimate unsampled areas, though this approach neglects soil spatial variability.

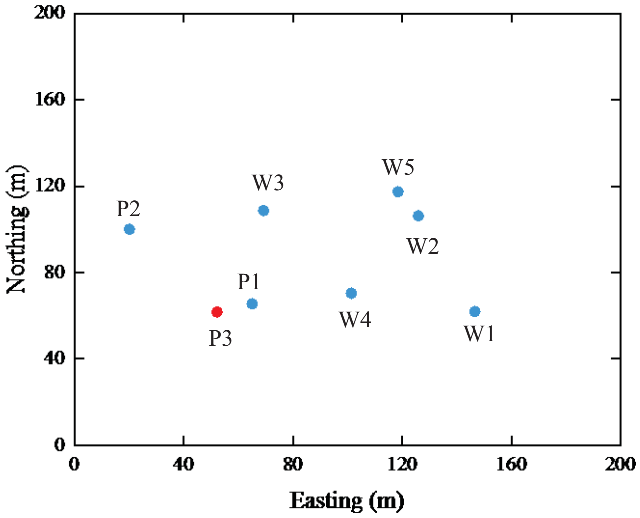


Fig.1 Borehole deployment zones

In this paper,the kriging interpolation method isused in conjunction with historical borehole data to evaluate the geological parameters at unsampled locations. The soil information at the positions of the blue dots in Fig. 1 is utilized to assess the soil information at the position of the red dot (P3). Then, based on the estimated geological parameters, the full penetration resistance profileof the spudcan is predicted to evaluate the punch-through risk.As quantitative evaluation of punch-through risks necessitates site-specific modeling of bearing capacity evolution with penetration depth, current assessment methods are broadly classified into two paradigms: deterministic analysis methods(Lee, *et al.*, 2013; Hu *et al.*, 2014; Zheng *et al.*, 2016; ISO,2023) and probabilistic methods (Marco *et al.*, 2017; Li *et al.*, 2018). Deterministic analysis methodsonly provide a single set of deterministic penetration curves, failing to account forthe uncertainties in seabed conditions and the spatial variability of soil properties.This paper applies probabilistic methods(percentile curves) to characterize the potential range of spudcan penetration behavior.

2 Geotechnical Modeling Considering Soil Spatial Correlations

2.1 *Kriging Interpolation Method*

In this paper, the ordinary Kriging interpolation is used to conduct an interpolation evaluation of the soil in unsampled areas(Li *et al.*, 2016).The relationship is expressed as follows(Dasaka& Zhang, 2012):

$$\hat{z}_0 = \sum_{i=1}^{n} \lambda_i z_i \tag{1}$$

where $\hat{z}_0$ is the estimated value of the spatial attribute at the unsampled location (x_0, y_0); z_i is the spatial attribute value of the known point (x_i, y_i); λ_i is the weighting coefficient of the spatial attributes of the known points. The weighting coefficient is derived from the following Kriging equation:

$$\begin{bmatrix} \gamma_{11} & \cdots & \gamma_{1N} & 1 \\ \vdots & \ddots & \vdots & 1 \\ \gamma_{N1} & \cdots & \gamma_{NN} & 1 \\ 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_N \\ m \end{bmatrix} = \begin{bmatrix} \gamma_{10} \\ \vdots \\ \gamma_{N0} \\ 1 \end{bmatrix} \tag{2}$$

whereγ_{ij} is the semivariogram value based on the separation distance of known points. The function models usually include the spherical model, exponential model, and gaussian model.

The correlation of attributes at different locations is related to distance. The relationship is expressed as follows:

$$\gamma(d_{ij}) = \frac{1}{2} E(z_i - z_j)^2 \tag{3}$$

where d_{ij} is the distance between two points, $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ (Dasaka& Zhang, 2012).

2.2 *Modeling of Unsampled Sites with Neighboring Data*

Fig. 2 shows the soil parameters at the locations of seven groups of boreholes, including soil stratification, clay undrained shear strength, and effective unit weight. The site primarily consists of clay, with minor variations in strength and thickness. Except for P1, the soil within the 0-40 m depth at the other six boreholes is stratified into five layers: three clay layers interbedded with two sand layers. At W5, a 1.5meters thick clay layer with relatively low shear strength is located at the base of the third silty clay layer, posing the punch-through risk. The effective unit weight of the soil ranges from 6 to 10 kN/m^3.

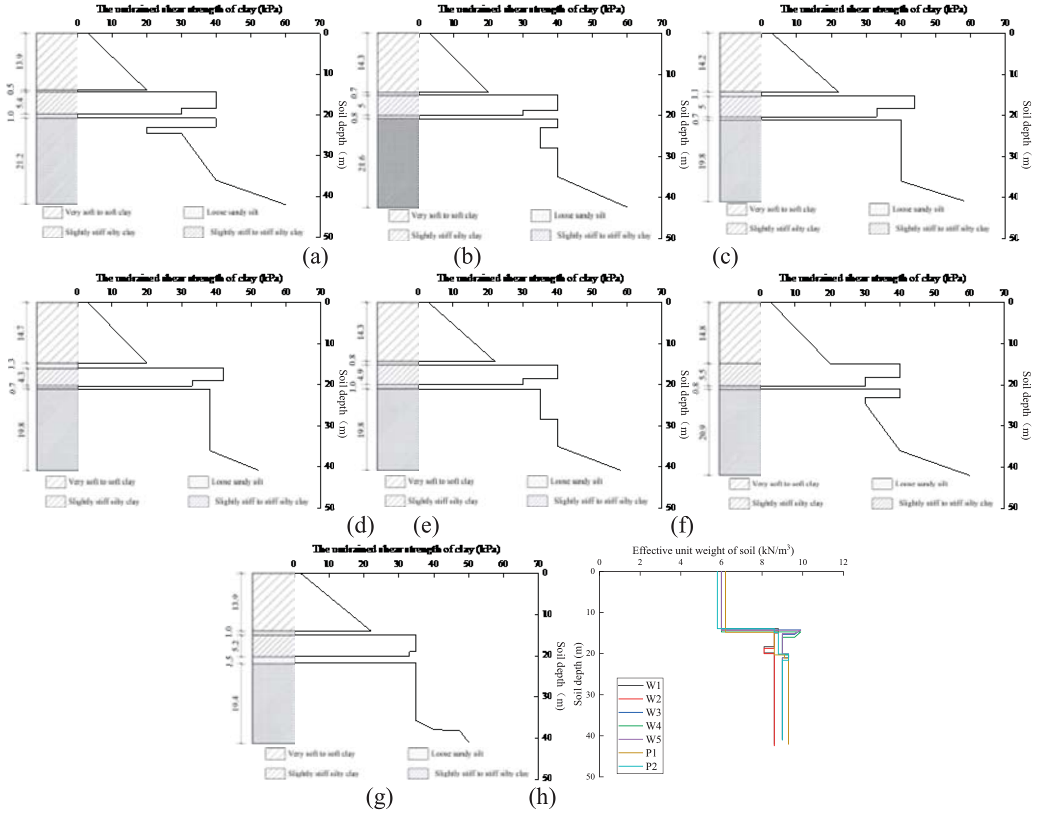


Fig.2. Geotechnical conditions of 7 boreholes of a drilling platform case: (a) W1; (b) W2; (c)W3; (d) W4; (e)W5; (f) P1; (g) P2; (h) the effective unit weight of soil.

The soil parameters at P3 were obtained through Kriging interpolation using data from seven boreholes. Based on Eqs. (1)-(3), interpolation was performed for three parameters: sand location, clay undrained shear strength, and soil effective unit weight. The results are shown in Fig. 3. Fig. 3(a) compares measured and interpolated soil layering, showing consistent soil types and distributions with a maximum relative error of 3.7%. Fig. 3(b) presents clay undrained shear strength, with measured (black) and interpolated (red) values. The peak relative error (12.9%) occurred at 14.2 m depth. Fig. 3(c) displays soil effective unit weight, with measured and interpolated data represented by black and red curves, respectively. The maximum relative error (3.4%) was observed between 20 m and 21 m depth.Fig. 4 shows the variance cloud map of Kriging interpolation, displaying results for sand location, clay undrained shear strength, and soil effective unit weight. Color gradients from blue to red indicate increasing variance. At P3, the soil at a depth of 21.2 m is classified as sand (variance: 0.047), the mean undrained shear strength of clay at 6 m depth is 10.42 kPa (variance: 0.28), and the mean effective unit weight of soil at 6 m depth is 6.1 kN/m³ (variance: 0.0068). Following probabilistic framework proposed by Lacasse and Nadim(1996), this study models sand layer thickness, clay undrained shear strength, and soil effective unit weight at P3 as normally distributed random variables.

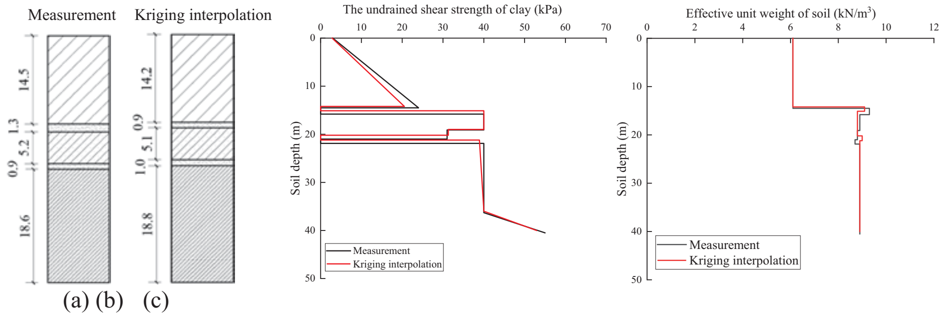
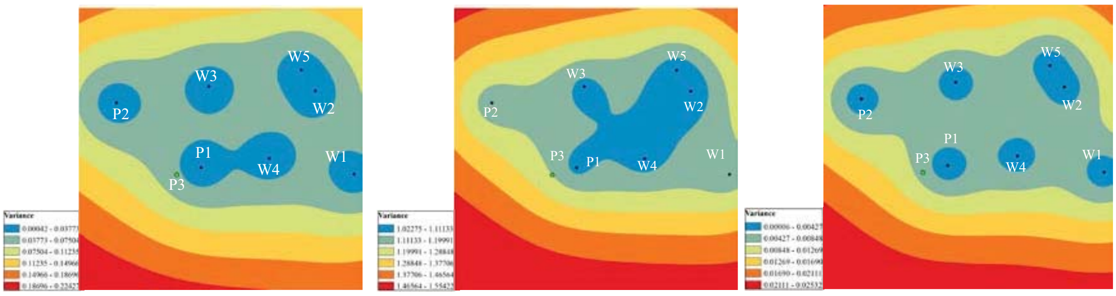


Fig.3Comparison between Kriging interpolation results and measurement results: (a)stratification of soil; (b)the undrained shear strength of clay; (c) the effective unit weight of soil



(a) (b) (c)

Fig.4Spatial distribution of variance by Kriging interpolation: (a) the location of sand; (b) the undrained shear strength of clay; (c) the effective unit weight of soil.

3 Punch-ThroughRisk Analysis

3.1 *ISO Methods for Punch-throughRisk Prediction*

This study employs the ISO (2023)recommended methodology to evaluate the punch-through risk of spudcan during penetration,as shown in Eqs. (4) and (5). For the spudcan installation in sand-over-clay soil, the peak penetration resistance$q_{\text{peak,s}}$ is expressed as:

$$q_{\text{peak,s}} = (1+2\frac{H_s}{D}\tan\alpha_{\text{p}})^2(s_{\text{u}}N_c s_{\text{c}} d_{\text{c}} + q_0 - H_{\text{s}}\gamma_s^{'}) \tag{4}$$

where H_{s} is the thickness of the sandy soil; D is the diameter of spudcan foundation; s_{u} is the undrained shear strength of clay; N_{c} is the bearing capacity factor; s_{c} is the shape factor, $N_{\text{c}}\cdot s_{\text{c}} = 6$;$d_{\text{c}}$ is the depth factor, $d_{\text{c}} = 1 + 0.2(H_{\text{s}}/D)$d1.5; $q_0$is the effective overburden pressure;$\gamma_s^{'}$is the effective weight of sand.

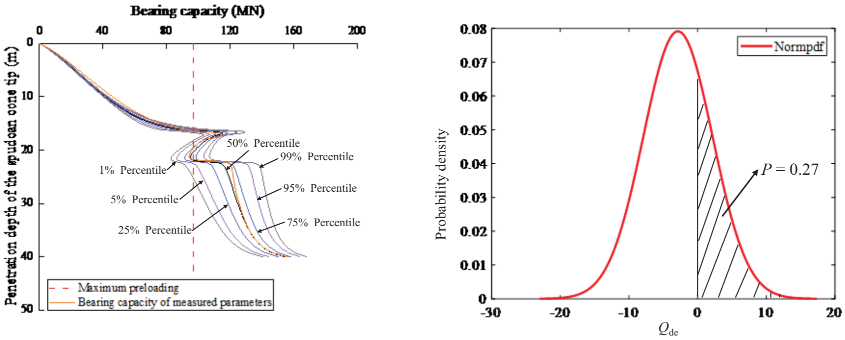
For the spudcan installation in stiff-over-soft clay, the peak penetration resistance $q_{\text{peak,c}}$is be expressed as:

$$q_{\text{peak,c}} = 3\frac{H_c}{D}s_{\text{ut}} + N_c s_{\text{c}} s_{\text{ub}}(1+0.2\frac{H_c}{D}) + q_0 \tag{5}$$

where$H_{\text{c}}$is the thickness of the top-layer soil; s_{ub} is the intact undrained shear strength of bottomlayer soil at layer interface; s_{ut} is the intact undrained shear strength of toplayer soil.

3.2 *Probability Method for Punch-throughRisk Prediction*

This paper adopts the “Bottom-up” method recommended by the ISO (2023) to calculate the bearing capacity of spudcan foundation. Based on the means and standard deviations of the soil parameters (H_{s}, $s_u$and$\gamma_s^{'}$) within the 0-40 m depth range at P3, n random values are generated from their normal distributions and input into Eqs. (4) and (5).Then,N ($N \geq n$) values of bearing capacityof soilare obtained at the corresponding penetration depth.By arranging the N bearing capacity values in ascending order at each penetration depth, the 1th, 5th, 25th, 50th,75th,95thand 99th percentiles are obtained respectively, as presented in Fig.5(a). The 50thpercentile curve aligns closely with the measured parameter curve.At a depth of 21m below the mudline,the 5th and 95th percentile bearing capacities are 85.20 MN and 102.28 MN, respectively, defining a 90% probability interval for bearing capacity of spudcan foundation.When the preloading load is below the ultimate bearing capacity of soft soil layer, there will be no punch-through risk duringthepenetration of spudcan. At P3, a soft soil layer exists at 20-21 m depth.Fig. 5(a) shows the maximum preloading load of 97.1 MN (9900 t).This study defines$Q$as the foundation bearing capacity at 21meters, with$Q_{\text{de}}=Q$ - 97.1. If$Q_{\text{de}} \leqslant 0$, punch-through risk exists.Given that$Q$follows a normal distribution,Q_{de}similarly normally distributed.Fig. 5(b) shows the probability density curve of Q_{de}, with the shaded region ($Q_{\text{de}} > 0$) representing no punch-through failure, covering 27% of the total area. Thus, for a preloading load of 97.1 MN, the punch-through failure probability is 73%.



(a) (b)

Fig.5 The punch-through probability during the penetration of spudcan:(a) a set of percentile curves of bearing capacity; (b)the probability density curve ofQ_{de}

4 Conclusions

This paper employs the existing Kriging interpolation technique to estimate the geological parameters at sparse-data areas. As shown by field case studies, the relative error between the estimated parameters and the actual measured data ranges from a minimum of 0 to a maximum of 12.9%. These estimated parameters are utilized for spudcan punch-through analysis. Through a set of spudcan bearing capacity-depth percentile curves, the probability of punch-through under the maximum preloading load is determined. It provides preliminary guidance for offshore engineers on the measures to be implemented during the installation of spudcan.

Acknowledgements

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