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# Research Progress on Prediction of Spudcan Penetration for Jack-up

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## Abstract

**Under complex stratigraphic conditions (hard soil layer overlying soft soil layer, also known as the "eggshell" formation), the influence of the underlying soft soil may cause a jack-up drilling platform to experience rapid settlement of the spudcan foundations after penetrating the upper hard layer during the preload phase. This phenomenon can lead to platform tilting beyond the range of its self-leveling capability, resulting in spudcan punch-through incidents. Such incidents may cause severe structural damage to the platform, leading to significant economic losses and posing serious threats to personnel safety. This paper focuses on a comprehensive review of research progress in the prediction of spudcan punch-through for offshore jack-up platforms. The mechanisms of spudcan punch-through and the critical stratigraphic conditions leading to such failures are systematically described. The existing research progress, both domestic and international, is summarized, and the advantages and limitations of current prediction approaches are critically analyzed. Furthermore, forward-looking preventive measures against punch-through are proposed, which are of great importance for ensuring the operational safety of jack-up platforms.**

## Keywords

**Jack-up; egg shell formation; pile shoe penetration; penetration prediction; failure mechanism.**

## 1. Introduction

With successive breakthroughs in China's offshore oil and gas industry, offshore hydrocarbon development has become a key driver of national energy growth, and the exploration and exploitation of new marine oil and gas resources has become an inevitable trend. As offshore oilfield exploration is gradually shifting from shallow waters to deeper waters, increasingly complex seabed geological conditions—such as multilayered stratigraphy, heterogeneous soil distribution, and weakly consolidated sediments—combined with harsher marine environmental conditions, are bringing greater challenges to the operational safety of drilling platforms. Jack-up drilling platforms, which are suitable for a wide range of seabed soil conditions and moderate water depths, have strong operational capabilities, are relatively easy to construct, and are highly mobile. For these reasons, jack-ups are widely used in offshore petroleum development and account for approximately 40% of the global offshore drilling fleet. However, during operations, jack-up platforms are often exposed to unexpected spudcan punch-through incidents, which may lead to structural damage, significant economic losses, and serious safety hazards. According to statistics from MSL, punch-through accidents account for as much as 53% of all jack-up platform accidents. Although comprehensive site-specific geotechnical investigations and assessments are generally conducted prior to platform installation, many punch-through incidents still occur each year. The frequent occurrence of punch-through accidents is closely related to complex seabed stratigraphy. In certain regions, the upper seabed sediments are primarily composed of silt, underlain by interbedded layers of silty clay, sand, and clay. Under hard-over-soft stratigraphic conditions, during the preload phase, spudcan foundations may penetrate the upper stiff soil layer and subsequently experience rapid settlement in the underlying soft soils. This sudden penetration often exceeds the self-leveling capacity of the platform, thereby triggering punch-through failure. Globally, regions with high punch-through risk and a significant number of operating jack-up platforms are concentrated in North America, the Middle East, and Asia. In recent years, with Southeast Asian countries intensifying offshore oil and gas development, the number of jack-up platforms operating in these waters has continued to increase. Statistics show that more than 80% of punch-through accidents recorded between 2000 and 2008 occurred in Asia, highlighting the urgent need for effective prediction and preventive measures to mitigate punch-through risks during jack-up platform operations.

## 2. Study on the Mechanisms of Spudcan Punch-Through

### 2.1. Mechanisms of Spudcan Foundation Punch-Through Failure

In a stratigraphy consisting of a sand layer overlying clay, the penetration resistance of the spudcan foundation during installation is significantly influenced by the underlying soft clay, as illustrated in Fig. 2-1. From the schematic relationship between the spudcan penetration process and the bearing capacity of the foundation soil, it can be observed that, in the initial stage, the bearing capacity of the seabed soil exhibits a gradual increase with increasing penetration depth. However, at a certain depth within the sand layer, the soil bearing capacity reaches a peak value and subsequently experiences a sharp reduction due to the formation of plastic shear zones. This reduction can be attributed to the preload applied on the spudcan during the penetration process. Since this preload cannot be immediately released, it exceeds the ultimate bearing capacity of the soil, thereby triggering a shear failure in the subsoil. This process reveals the intrinsic mechanism governing the variation of soil bearing capacity during spudcan punch-through failure in sand-over-clay stratigraphy.

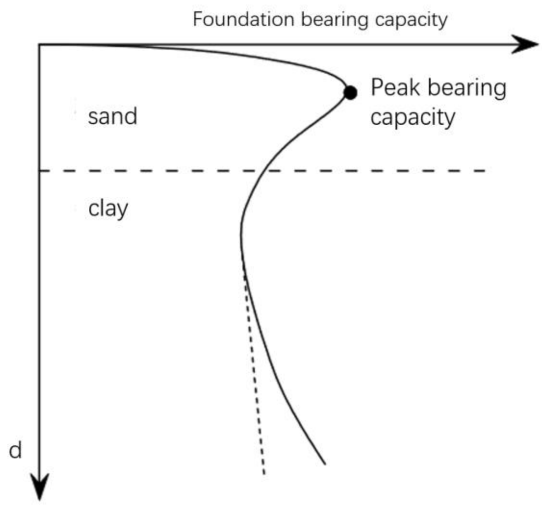


Fig. 1 Schematic diagram of puncture damage

### 2.2. Study on the Bearing Capacity of “Eggshell” Stratigraphy

The "Eggshell" Formation, specifically referring to a stratigraphic structure characterized by a thin, hard upper soil layer and a thicker, softer lower soil layer. When a self-elevating platform's pile leg is driven into such a formation, there is a high likelihood of penetration risks, namely the sudden and rapid subsidence of individual pile legs. This phenomenon not only affects the stability of single pile legs but may also cause uneven settlement of the entire platform, potentially leading to structural failure or functional impairment, thereby posing a direct threat to the overall safety of the platform. Therefore, for self-elevating platforms installed on the

"Eggshell" formation, it is essential to identify these stratigraphic features and evaluate their potential impact on platform stability.Research on the bearing capacity of "Eggshell" strata should consider the interactions between different soil layers and the influence of a rigid-over-soft profile on overall load-bearing performance. When encountering soil profiles with hard-over-soft layers, due to differences in soil strength and deformation characteristics, pile shoes may suddenly undergo penetration, posing a potential safety hazard. This situation involves four typical types of stratigraphic combinations:

Hard Over Soft Clay Layer

When the upper layer is a hard clay and the lower layer is a soft clay, the significant difference in strength and deformation behavior between the layers can lead to the transfer of substantial horizontal loads to the pile shoe, while the soft clay may experience significant deformations. For bearing capacity analysis of such soft-over-hard clay strata, methods such as the Brown and Meyerhof approach[1] and projected area method are widely used. During pile driving operations, failure tends to occur through shearing around the pile shoe in the seabed clay, with the ultimate bearing capacity peaking and then sharply declining as penetration progresses. The occurrence of penetration failure depends on specific soil parameters. Research by Lin et al.[2] indicates that the ultimate bearing capacity is primarily controlled by the strength of the lower soft clay layer and increases with its strength. As the ratio of upper to lower soil layer strengths decreases, the peak bearing capacity increases, and the critical displacement at which penetration failure might occur (i.e., the potential penetrative depth) is elevated, thereby reducing the penetration risk.

Sand Over Clay Layer

When the upper layer is sandy soil and the lower layer is clay, the sand may exhibit higher stiffness, while the clay may display relatively lower strength. This combination can result in substantial vertical loads during pile installation and may induce sudden penetration due to the lubricating property of the sand layer. Therefore, the study of layered foundation bearing capacity and its relation to penetration failure mechanisms is crucial. Commonly, methods such as Hanna & Meyerhof[3], and the projected area method are used in engineering practice for calculating the bearing capacity of sand-over-clay strata; subsequent developments include Lee-2013[4], Hu-2014[5], and Zheng-2022[6] approaches.

Soft–Hard–Soft Clay Layered Profile

When the stratigraphy shows soft–hard–soft clay layers, the middle hard layer generally provides higher bearing stiffness, while the adjacent soft layers are weaker. Under vertical load, this configuration can result in uneven load transfer: the upper soft clay may undergo large deformations initially, while the underlying soft layer may cause additional settlements at depth, leading to overall bearing performance deterioration. The presence of the hard layer can offer localized support, but the weak surrounding soft layers can induce localized failure or sliding. In designing structures on such complex strata, it is important to analyze how the thickness and burial depth of the hard layer influence capacity and settlement patterns. Engineering codes often employ top-down calculation methods, with modifications such as Zheng-2015[7] providing more refined analysis of bearing capacity and failure mechanisms for such composite strata.

Clay–Sand–Clay Layered Profile

When the stratigraphy consists of an upper clay layer, a middle sand layer, and a lower clay layer, the sand layer often exhibits high stiffness and permeability, while the adjacent clay layers are relatively less strong. Under vertical loading, the load transfer at the pile tip can be altered by the intervening sand layer: the upper clay may compress initially, while the sand temporarily bears the majority of the load; however, if the lower clay has insufficient strength, it may experience cumulative settlements or localized failure. This layered foundation exhibits

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distinct interlayer interactions, with the sand layer potentially enhancing the load-bearing capacity, yet the soft clay at the bottom controlling overall deformation. Special attention is required to the thickness and placement of the intermediate sand layer to evaluate its impact on capacity and failure modes. In practice, standard top-down calculations are used, along with improved methods such as Ullah-2017[8], although presently no highly accurate method exists for calculating the penetrative peak resistance for such three-layer systems.

## 3. Domestic and International Research Status

### 3.1. Current Research Status of Bearing Capacity Calculation

There are numerous theoretical calculation methods for assessing the bearing capacity of drilling vessel foundations. The formulation of these methods relies on empirical formulas and theoretical frameworks from soil mechanics, material mechanics, and foundation engineering, with the core objective of accurately predicting the spudcan penetration resistance, penetration depth, and potential failure modes using mathematical models. Currently, the widely adopted international prediction methods include the semi-theoretical semi-empirical calculation formulas proposed in the SNAME specification [9] and the ISO specification [10]. The formulas provided in the domestic standard "Specification for Marine Well Site Investigation SY/T 6707-2008" [11] are based on the same principles as the SNAME specification.

For the foundation bearing capacity of spudcans in single-layer clay, the calculation formula proposed by Skempton [12] is widely used in various specifications, including the marine well site investigation code and the SNAME specification [9]. In the case of double-layer soils, Yamaguchi [13] proposed a projected area method to calculate the foundation bearing capacity by projecting the upper load onto the lower soil layer. However, this method does not specify the value of the dilatancy angle or account for the contribution of shear resistance in sandy layers. Subsequently, based on experimental results of the bearing capacity of circular foundations in stiff-over-soft clay, Brown and Meyerhof proposed the renowned Brown & Meyerhof formula [1], which considers the influence of the undrained shear strength of both the upper and lower clay layers on the foundation bearing capacity. This formula has been widely applied in offshore engineering. Hanna and Meyerhof [14] further proposed a punching shear method to evaluate foundation bearing capacity, which assumes the presence of vertical sand columns and considers the shear resistance in the sand layer. For foundations with more than two soil layers, Yuan Fanfan et al. [15] extended the theory of layered foundation ultimate bearing capacity by Hanna and Meyerhof [14], improving the double-layer foundation formula to adapt to multi-layer foundation calculations. Through large-scale load tests, they compared and validated the improved Meyerhof-Hanna formula [14], the Hansen weighted average method, and the diffusion angle method. The results showed that the improved formula has high agreement with measured values and is suitable for multi-layer foundations; the weighted average method exhibits significant calculation errors when there are large differences in soil layer strength; and the diffusion angle method yields results close to measured values but tends to be conservative.

Hossain and Randolph proposed a new method for predicting penetration profiles in single-layer clay. However, since the clay was modeled as an ideal plastic material without considering softening effects, the profile forms were not accurately simulated, leading to an overestimation of the penetration resistance curve. Later, Hossain and Randolph considered the influence of strain-softening parameters of heterogeneous single-layer clay on traditional spudcan penetration resistance. They supplemented previous centrifuge experiments with finite element numerical simulation analyses to explore the effects of parameters such as layer thickness, strength ratio, and foundation roughness on penetration resistance.

Lee et al. [17] proposed a new stress failure model and derived a formula for calculating peak penetration resistance, which was validated using centrifuge experimental data for dense sand overlying clay.

Hu et al. [18] described a method for characterizing the full load-penetration resistance distribution during the penetration of spudcans of mobile jack-up platforms through sand interlayers within clay layers, based on large deformation finite element analysis and geotechnical centrifuge experiments. The improved Mohr-Coulomb and Tresca models were used to describe the behavior of sand and clay, considering the effects of strain softening on soil response. Zheng et al. [19] considered the influence of variations in soil plug thickness on penetration resistance and improved existing methods by introducing equivalent shear strength to account for the contribution of the third soil layer to the first layer.

Under the premise of considering the softening strain caused by clay remolding, Zheng et al. [19] proposed a semi-empirical design method based on centrifuge experimental data and numerical simulation results. They also made certain adjustments to the ISO method, considering the influence of soil plugs on bearing capacity in soft soil when determining peak penetration resistance.

Zheng Jingbin et al. [20] summarized existing penetration resistance prediction methods and their advantages and disadvantages, indicating that the method recommended by the ISO specification is overly conservative and neglects the soil plug effect. They proposed new methods for predicting penetration resistance in "sand-clay" double-layer soils, three-layer cohesive soils, and "clay-sand-clay" formations, and compared the accuracy of these methods. The results showed that the proposed improved methods, based on a more accurate characterization of actual failure modes and consideration of the soil plug effect, significantly enhance the prediction accuracy of spudcan punch-through risks in complex formations.

Wu Bing et al. [21] assumed that the bearing capacity of a foundation on "stiff-soft-stiff" clay is the sum of the lateral friction generated by punching shear failure in the "stiff-soft" clay and the bearing capacity provided by extrusion failure in the "soft-stiff" clay, based on a "bottom-up" prediction model. Through finite element simulation analysis, they validated the rationality of the failure model assumed by the "bottom-up" method. Based on the results of variable-parameter finite element analysis, they modified the extrusion failure bearing capacity formula and proposed a prediction method for the vertical bearing capacity of circular foundations on "stiff-soft-stiff" three-layer clay.

Zheng et al. [22] found that the peak resistance predicted by the Hu-2014 model was higher than the centrifuge experimental results of Craig & Chua [23] and Hossain et al. [24]. Based on centrifuge experiments and large deformation finite element (LDFE) results, they suggested that the calculation of the distribution factor (DF) should comprehensively consider the undrained shear strength at the sand-clay interface (s_um), the undrained shear strength gradient of the underlying clay layer (k), the thickness of the overlying sand layer (H_s), the spudcan diameter (D), and the relative density of the overlying sand layer (I_D). On the basis of the Hu-2014 model, they introduced the undrained shear strength at the sand-clay interface (s_um) and the undrained shear strength gradient of the underlying clay layer (k) to modify the distribution factor (DF), establishing the Zheng-2022 model.

## 3.2. Centrifuge Testing

## 3.3. Numerical Simulation

As a critical form of deep foundation, spudcan foundations are extensively utilized in offshore engineering and high-rise structures. Significant progress has been made in numerical simulation analyses of spudcan foundations, with finite element (FE) simulation technology emerging as a primary tool for investigating their mechanical behavior. Utilizing discretization

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techniques within computational software, FE simulations effectively capture soil-structure interaction during spudcan penetration. This approach accommodates complex geological conditions and structural configurations, including multi-layered soils, varying soil properties, and specific spudcan geometries and material attributes. Through finite element modeling, researchers conduct detailed parametric studies to accurately predict key indicators such as stress distribution, deformation behavior, and penetration depth during spudcan penetration. Research foci include bearing capacity and deformation characteristics of spudcans in multi-layered soils, soil response during penetration, and spudcan-soil interaction. Methodologically, techniques such as large deformation finite element (LDFE) analysis and the arbitrary Lagrangian-Eulerian (ALE) method are widely adopted. These methods simulate nonlinear soil deformation and flow behavior during spudcan penetration, enhancing prediction accuracy and reliability.

In 2011, Hu Zhihui et al. [25] addressed punch-through accidents during the preloading of jack-up platforms on stiff-over-soft soil foundations, where rapid settlement into the soft layer occurs after penetrating the stiff crust. Statistical analyses indicated that such incidents account for approximately 55% of platform accidents, severely impacting operational safety. Punch-through is closely associated with stratigraphic complexity and platform performance, with its severity influenced by factors such as relative thickness of the stiff layer, strength ratio between stiff and soft soils, and preload magnitude. Through case studies in the western South China Sea, they proposed an active penetration strategy for layered foundations to mitigate punch-through risks, validating the effectiveness of preventive measures.

Hu et al. [26] developed a comprehensive analytical method integrating large deformation finite element (LDFE) analysis and centrifuge testing to characterize the load-penetration resistance curve during spudcan penetration in sand-over-clay formations. The Coupled Eulerian-Lagrangian (CEL) approach was employed to address large deformation problems during spudcan penetration through sand into clay, incorporating strain softening effects on soil response via modified Mohr-Coulomb and Tresca models. Results demonstrated excellent agreement between CEL simulations and centrifuge test data, with applicability extending to medium-dense to dense sands and spudcans with cone angles ranging from 0° to 21°. Additionally, a bearing capacity expression for spudcan penetration in clay was established.

Zheng et al. [27] introduced a novel design method for spudcan penetration in stiff-soft clay strata using CEL-based LDFE analysis, accounting for strain softening and rate dependence of shear strength. Finite element results were validated against centrifuge model test data, and design formulas were constructed based on combined measured and computational data. This method incorporates the effect of bottom soil plugging and additional resistance, providing estimates of punch-through depth, bearing capacity at the punch-through point, interface capacity between stiff and soft layers, and bearing capacity in the bottom layer. Comparisons revealed that the punch-through method recommended in the ISO specification yields conservative estimates of punch-through capacity, and guidance for improving the method was provided.

Wu Bing et al.[21] validated the rationality of the failure mechanism assumed in the "bottom-up" method—a recommended approach for three-layer soil calculations—through finite element simulations. They found that existing formulas neglect the influence of overlying soil layers on extrusion failure mode, leading to significant underestimation of bearing capacity due to extrusion failure in "soft-stiff" clay. Based on variable-parameter finite element analysis, the extrusion failure bearing capacity formula was modified, and a predictive method for vertical bearing capacity of circular foundations on "stiff-soft-stiff" three-layer clay was proposed.

### 3.4. Machine Learning

In recent years, the application of machine learning (ML) in geotechnical engineering has evolved from empirical fitting to data-mechanism integration. Internationally, supervised learning based on large-scale field and laboratory databases is widely used for inverse analysis of geotechnical parameters (e.g., cohesion, internal friction angle, compression index), prediction of bearing capacity and settlement, slope stability and liquefaction assessment, optimization of tunneling parameters, and evaluation of seismic ground motion-site effects. Subsequent advancements include physics-informed learning constrained by finite element/discrete element methods, Bayesian updating and probabilistic graphical models for uncertainty quantification, and meta-learning/multi-fidelity modeling to replace computationally intensive numerical analyses with rapid surrogate models. Spatiotemporal sequence modeling integrating InSAR, IoT monitoring, and multi-source remote sensing has also emerged as a paradigm for disaster early warning and health monitoring. Domestically, machine learning has been rapidly adopted in interpretation of cone penetration test (CPT) data, prediction of pile ultimate bearing capacity and excavation deformation, consolidation of soft foundations, control of subway/tunneling construction, and assessment of offshore wind pile foundations and port structures. To address challenges of small sample sizes and regional variability, transfer learning, active learning, and semi-supervised methods are employed to alleviate data scarcity and labeling costs, while interpretability techniques (e.g., feature importance, SHAP) enhance engineering acceptability. Overall trends indicate: ① a shift from "black-box regression" to interpretable "physics-statistics hybrid" models; ② transition from single-task prediction to closed-loop decision-making in full-process digital twins (investigation-design-construction-operation); ③ expansion from point predictions to interval and risk-based reliability design; and ④ multi-modal data integration (surveying, monitoring, remote sensing, textual reports) as a new growth area. Current bottlenecks include sample heterogeneity and quality control, reproducibility and sharing of data and code, limited cross-regional generalization, and insufficient quantification of model uncertainty. For engineering applications, key pathways to transition from "academically usable" to "engineering-trustworthy" involve establishing standardized data protocols and industry benchmarks, embedding mechanistic priors, and enhancing integration with codified design methods.

## 4. Existing Prediction Methods

### 4.1. Existing Calculation Formulas

#### 4.1.1. Load Expansion Method

The load expansion method [10] ignores the direct contribution of the sand layer to the bearing capacity, assuming that the load on the overlying sand layer is transmitted to the top surface of the underlying clay layer at an expansion angle $\alpha$($\alpha$=arctan $(1/n_s)$), forming an equivalent circular foundation (diameter $D' = D + 2h/n_s$), and only considering the bearing capacity of the equivalent foundation on the underlying clay layer

$$q_{\text{peak}} = \left(1 + \frac{2H_s}{n_s D}\right)^2 (s_u N_c s_c d_c + p_0{}' - H_s \gamma_s') \tag{2-1}$$

In equation (2-1): $H_s$is the thickness of the overlying sand layer, m； $n_s$s is the dimensionless load expansion factor, with values ranging from 3~5; D is the maximum cross-sectional diameter of the pile boot, m； $s_u$ is the undrained shear strength of clay, kPa； $N_c$ is the bearing capacity coefficient of clay, dimensionless; $s_c$ is the shape correction coefficient, dimensionless; $d_c$ is the depth correction coefficient, dimensionless; The effective overlying pressure at the position of the lowest point of the maximum cross-section of the pile shoe is represented by $p_0{}'$, kPa; $\gamma_s'$ 'is the effective unit bulk density of sandy soil, kN/m3.

#### 4.1.2. Punching and cutting method

The punching shear method assumes that the load on the overlying sand layer is transmitted to the top surface of the underlying clay layer at an expansion angle α (α=0), forming an equivalent circular foundation (diameter $D' = D$). In addition to the bearing capacity of the equivalent foundation on the top surface of the underlying clay layer, the frictional resistance along the shear failure surface of the overlying sand layer is also considered. The calculation formula for the bearing capacity of the pile shoe sand clay layer is given, that is

$$q = (s_u N_c s_c d_c + p_0{}') + 2\frac{H_s}{D}(\gamma_s' H_s + 2p_0{}')K_s \tan\varphi' - H_s \gamma_s' \quad (2\text{-}2)$$

In equation (2-2): Ks is the impulse shear coefficient, dimensionless; $\varphi'$ 'is the effective internal friction angle of sandy soil, in degrees. Error in SNAME specification and "Marine Well Site Investigation Specification", $K_s \cdot \tan\varphi' \approx 3 \cdot s_u/\gamma_s' D$.

### 4.2. Other Prediction Methods

The Lee-2013 method [4] assumes that the load on the overlying sand layer is transferred to the top surface of the underlying clay layer at an extension angle α (α = ψ). By integrating the shear resistance along the shear failure area of the overlying sand layer and considering the vertical bearing capacity of the underlying clay layer and the effective weight of the sand plug at the spudcan base, the peak resistance of the spudcan in sand-clay strata is given as:

$$q_{\text{peak}} = (N_{c0} s_{um} + p_0)\left(1 + \frac{2H_s}{D}\tan\psi\right)^{E^*} + \frac{\gamma_s' D}{2\tan\psi(E^* + 1)}\left[1 - \left(1 - \frac{2H_s}{D}E^*\tan\psi\right)\left(1 + \frac{2H_s}{D}\tan\psi\right)^{E^*}\right] \quad (2\text{-}3)$$

$$E^* = 2\left[1 + D_F\left(\frac{\sin\varphi' cos\psi}{tan\psi(1 - \sin\varphi' sin\psi)} - 1\right)\right] \quad (2\text{-}4)$$

In equations (2-3) and (2-4): $N_{co}$ represents the bearing capacity coefficient of clay at the bottom of the circular foundation, which is dimensionless; $s_{um}$ denotes the undrained shear strength of clay at the interface between sand and clay strata, kPa; $p_0$ signifies the overlying effective pressure, also in kPa; $\psi$ indicates the dilatancy angle of the overlying sand layer, in degrees（°）;$E^*$ is a fitting coefficient related to the friction angle and dilatancy angle of sand, which is dimensionless; $D_F = \sigma_n{}'/\bar{\sigma}_z{}''$ represents a dimensionless distribution factor that links the normal effective stress $\sigma_n{}'$ and the vertical average effective stress $\bar{\sigma}_z{}'$on the shear failure surface in the overlying sand layer.

## 5. Summary

Self elevating drilling platforms play an important role in the development of offshore oil and gas resources, but their pile shoes are prone to puncture accidents in complex formations, especially in "eggshell" formations, which seriously threaten the safety and operational efficiency of the platform. This article systematically reviews the failure mechanism, existing prediction methods, and research progress of pile boot puncture, and looks forward to future research directions.

1. Puncture mainly occurs in layered foundations with hard upper and soft lower layers, such as combinations of hard clay soft clay, sand clay, etc. During the penetration process of pile boots, the bearing capacity first reaches its peak and then sharply decreases due to soil shear failure, resulting in rapid settlement (puncture). The four typical stratigraphic combinations have different failure characteristics, and their bearing capacity mechanisms need to be studied separately.

2. The calculation of bearing capacity has evolved from early methods such as Skempton and Yamaguchi to methods such as Brown&Meyerhof and Hanna&Meyerhof that consider the interaction between multiple layers of soil. In recent years, Lee, Hu, Zheng, and others have proposed more accurate models, such as the Zheng-2022 model, which significantly improves prediction accuracy. Centrifuge experiments and numerical simulations validate theoretical models through physical experiments and numerical methods (such as CEL large deformation finite element analysis), revealing soil response and failure mechanisms, and providing a basis for engineering design. Machine learning applications are gradually shifting from empirical fitting to data mechanism fusion, demonstrating potential in parameter inversion, risk prediction, construction control, and other areas. However, challenges such as sample quality and generalization ability still need to be addressed.

3. The existing prediction methods mainly include load expansion method and impulse shear method, as well as improved models such as Lee-2013, Hu-2014, Zheng-2022 developed in the future. These methods are continuously optimized in terms of considering soil blockage effects, strain softening, interlayer interactions, etc., but there are still certain conservatism or limitations in their applicability.

4. Future research should continue to deepen the understanding of the interaction mechanism between pile-soil in complex strata, promote interdisciplinary collaboration (such as the integration of machine learning and physical models), and establish a more intelligent and reliable puncture prediction and prevention system. At the same time, it is necessary to strengthen on-site data collection and standardization to enhance the engineering applicability and credibility of the model.

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