

Review of Horizontal Bearing Behavior of Monopod and Tripod Suction Bucket Foundations for Offshore Wind Turbines

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Abstract: As a foundation solution for offshore wind turbines, suction bucket foundations offer significant advantages in resisting high-intensity horizontal loads induced by wind and waves. This paper systematically reviews the research progress on the horizontal bearing behavior of monopod and tripod suction bucket foundations. It summarizes the methods for determining the ultimate horizontal bearing capacity, the variation pattern of the rotational center position, the failure modes, and influencing factors for monopod foundations. The applications and limitations of analytical methods, including the limit equilibrium method, limit analysis method, and subgrade reaction methods are critically discussed. Subsequently, the current research status on the pile group effect of tripod suction bucket foundations, the variation patterns of bearing capacity with spacing and load direction, as well as layout optimization, has been reviewed. Conclusively, the paper identifies existing research gaps, such as the influence of drainage conditions in silty clay, the lack of robust theoretical calculation models for the bearing capacity of tripod foundations, and insufficient research on the bearing mechanisms of non-standard tripod configurations. Recommendations for future research directions are provided.

Keywords: Suction bucket foundation; Horizontal bearing capacity; Monopod foundation; Tripod foundation.

1. Introduction

The offshore wind power industry in China is undergoing rapid development [1]. The foundation is critical for ensuring the stable operation of offshore wind turbine generators and constitutes a substantial portion of the total project investment. Suction bucket foundations have garnered significant attention in offshore wind engineering due to their advantages, including relatively straightforward installation, suitability for greater water depths, and potential for reusability. As the capacity of individual wind turbines continues to increase, the horizontal loads imposed on the foundations become more severe, making research into the bearing behavior of suction bucket foundations particularly important [2]. Currently, the analytical methods for predicting the horizontal response of monopod suction bucket foundations remain imperfect. While tripod suction bucket foundations can enhance overall stiffness and bearing capacity, their group effects and performance under complex loading conditions require further in-depth investigation [3]. This paper focuses on the bearing characteristics of bucket foundations for wind turbines under horizontal loading [4]. Through a synthesis of model test data and numerical analyses, it aims to provide theoretical support and methodological guidance for the design and application of suction bucket foundations in silty clay seabeds [5]. Therefore, this review systematically summarizes and evaluates the existing research on the horizontal bearing behavior of both monopod and tripod suction bucket foundations, highlighting current challenges and future directions.

2. Horizontal Bearing Behavior of Monopod Suction Bucket Foundations

In recent years, suction bucket foundations have seen increasingly widespread application as a novel foundation type for offshore wind turbines. A defining characteristic of offshore wind turbines is that their foundations are subjected to high-intensity horizontal loads, such as those from wind and wave actions. To accurately understand the engineering behavior of suction bucket foundations, researchers worldwide have conducted extensive field tests, model tests, theoretical analyses, and finite element analyses since their inception. This body of work has provided valuable empirical data and insights for subsequent research.

2.1 Model Construction

Control of the tilt at the top of a suction bucket foundation is of paramount importance for ensuring the normal operation of offshore wind turbines, as the performance of the turbine itself imposes a limit on the maximum permissible rotation angle of the tower. According to the Chinese offshore wind power code GB/T 50571—2010, the daily variation rate of the top tilt during foundation installation should be less than 0.3%, and the absolute tilt must not exceed 5%. Regarding the determination of the ultimate bearing capacity for suction bucket foundations,

some scholars have assumed a maximum rotation angle of 0.02 rad when calculating the horizontal ultimate capacity [6,7]. As shown in Figure 1, the load-rotation curve for a suction bucket foundation under horizontal loading typically exhibits a strain-hardening response. Consequently, foundation failure generally occurs at a relatively large rotation angle. Graham et al. [8] proposed that the load corresponding to the intersection point of two tangents (yield point *a*) should be considered the ultimate bearing capacity. Alternatively, Jara [9] and Zhu et al. [10] suggested that the load corresponding to a specified allowable rotation angle or the inflection point on the load-deflection curve (yield point *b*) can be taken as the ultimate bearing capacity for design purposes.

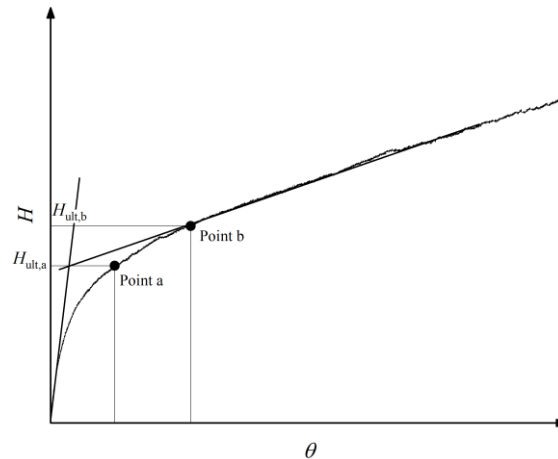


Figure 1. Schematic diagram of yield point location

Horizontal loads, including those generated by wind and wave actions, are generally exerted at a certain elevation above the centroid of a suction bucket foundation. This introduces an additional moment load on the foundation, with the magnitude of this moment increasing with the height of the load application point [11]. Consequently, the ultimate horizontal bearing capacity decreases as the load eccentricity (or height) increases, although the degree of this influence diminishes with further increases in eccentricity [12]. Through finite element analysis of a monopod suction bucket foundation with a diameter of 12m and a skirt length of 12m, Deb et al. [13] found that in dense sand, the foundation's horizontal capacity decreased significantly as the load application height increased from 0m to 100m. Accompanying this increase in load height was an increase in the displacement of the foundation's top plate, attributable to the greater horizontal force applied at the mudline level [14]. Li et al. [15] investigated the horizontal capacity of skirted bucket suction foundations using 1-g small-scale model tests. Their results indicated that under ultimate loading conditions, the deviation between the position of the center of rotation and the central axis of the skirted bucket increased with increasing load eccentricity. Centrifuge tests conducted by Allersma et al. [16] on bucket suction foundations under horizontal loading revealed several key findings: the soil density exhibited a linear relationship with horizontal bearing capacity; the bearing capacity in clay was approximately three times greater than that in sand; and the bearing capacity increased as the angle between the load direction and the horizontal plane decreased. Furthermore, the maximum bearing capacity was achieved when the load was applied at a height corresponding to 0.4 to 0.6 times the bucket's skirt length.

2.2 Rotational Failure Mechanism and Soil Response

As illustrated in Figure 2, the location of the center of rotation under horizontal loading is a critical factor influencing the failure mechanism of suction bucket foundations [17], and its position can be determined based on the schematic diagram. Liu et al. [18], through three-dimensional finite element analysis, found that the center of rotation shifts as the aspect ratio (L/D) of the suction bucket increases; when $L/D > 0.5$, the center of rotation is located on the central axis at a depth of approximately $0.7L$ below the mudline. Wang et al. [17] investigated the variation of the rotation center location with the soil strength heterogeneity ratio under undrained conditions. They observed that the ratio of the rotation center depth to the foundation diameter increases with the increase of the heterogeneity ratio kD/s_{u0} (where s_{u0} is the undrained shear strength at the mudline, and k is the gradient of undrained shear strength with depth z). Similarly, Wang et al. [19] and Zhu et al. [20], using small-scale model tests and centrifuge tests respectively, also found that the rotation center for suction bucket foundations in silt and sand is located at approximately 80% of the skirt height. Based on test results and the instantaneous variation path of the rotation center from a finite element model of a caisson-type suction foundation, Jia et al. [21] discovered that as the horizontal load increases, the instantaneous center of rotation moves from the upper central region towards the bottom in the loading direction. Under the ultimate horizontal load, the rotation center was located about $0.8H$ below the lid surface near the subdivision plate along the load direction. Through a series of finite

element simulations, Yun et al. [22] found that under horizontal loading, the rotation center in clay is not always at 0.5 times the foundation height but varies with the aspect ratio of the suction bucket. Conversely, Zhu et al. [23] argued that considering the influence of soil shear action on the horizontal bearing capacity, the rotation center should be assumed to be below the foundation base. This viewpoint contradicts the conclusions of Zhu [24], who stated that when the bucket aspect ratio is within a certain range, the rotation center should be located at a point between the mudline and the base.

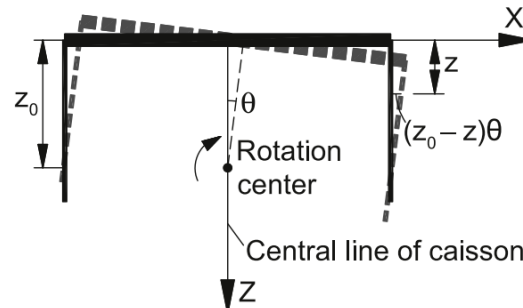


Figure 2. Validation of water levels[17]

Liu et al. [25], Yang et al. [12], and Wang et al. [19] analyzed the ultimate horizontal bearing capacity through 1-g small-scale model tests, finite element simulations, and centrifuge tests respectively. Dimensional analysis revealed no clear correlation between the dimensionless ultimate horizontal capacity and the foundation aspect ratio (L/D) in the centrifuge tests. In contrast, results from the 1-g model tests and finite element analyses showed a gradual increase in the dimensionless horizontal capacity with increasing L/D . The differing foundation diameters used in these studies may account for the inconsistent relationship observed in the centrifuge tests, as the dimensionless capacity tends to decrease with increasing foundation diameter. This indicates that further analysis is required to fully understand the behavior of the dimensionless horizontal capacity. Employing the Mohr-Coulomb yield criterion to model sandy soil foundations, Jin et al. [26] observed distinct failure mechanisms. Compared to suction foundations in cohesive soil, those in saturated sand can form an active failure wedge in the soil behind the foundation, potentially leading to partial collapse of the foundation soil. For foundations with a relatively small aspect ratio, failure typically involves overturning about a point near the base, accompanied by overall horizontal sliding. As the aspect ratio increases, the failure mode shifts to a forward rotational failure.

Using small-scale model and centrifuge tests in clay, Liu et al. [27] identified the formation of tensile cracks between the soil and the foundation's rear face. This soil-structure separation was found to have a more pronounced effect when the aspect ratio and the coefficient of shear strength heterogeneity were higher. The studies also noted that the occurrence of these tensile cracks has a lesser impact on the vertical bearing capacity factor than on the horizontal one. Consequently, in finite element simulations, the interface cannot be simplistically modeled as rough and bonded; the potential for soil-structure separation and its effect on horizontal capacity must be considered. 1-g model tests on soft carried out by Coffman et al. [28], normally consolidated clays demonstrated that the undrained soil strength is insufficient to support a vertical face at the separation gap, causing the soil to collapse immediately upon gap formation, with the rear soil mass subsequently moving horizontally with the foundation. linked the formation of rear-side tensile cracks to the location of the center of rotation. Their research suggested that when a crack forms, the rotation center is located at a depth of approximately 0.73 times the foundation height. If crack formation is not considered, the rotation center is estimated to be at a depth of about $0.67L$.



Figure 3. Separation phenomenon of soil behind the foundation[27]

Experimental studies by Lee et al. [29] indicate that the failure mode of suction bucket foundations varies with changes in the foundation's aspect ratio. Employing a nonlinear three-dimensional finite element analysis method, Kourkoulis et al. [30] investigated the bearing behavior of suction bucket foundations under monotonic horizontal

loading, accounting for the soil-structure interface adhesion factor. Their analysis delineated the failure mechanism for a foundation with an aspect ratio of 0.5, as illustrated in Figure 4. When the soil is uniform and perfect contact is maintained between the foundation and the soil (Figure 4(a)), the soil plug inside the bucket moves with the foundation and can thus be considered quasi-rigid. The resulting failure mechanism resembles the hemispherical failure mechanism identified by Bransby et al. [31]. In clay with undrained shear strength increasing with depth (Figure 4(b)), the lower available strength at shallower depths leads to a more developed shear failure zone compared to uniform soil. This soil property causes partial movement of the internal soil plug. In accordance with findings from Mana et al. [32], Yun et al. [33], Bransby et al. [31], and Mana et al. [34], a hemispherical failure mechanism develops within the suction bucket foundation, which subsequently limits the downward settlement of the foundation. Under conditions of low adhesion at the soil-structure interface in non-uniform soil (Figure 4(c)), the reduced frictional resistance may lead to foundation sliding or separation from the soil. This can even induce upheaval of the foundation soil in the direction opposite to the loading.

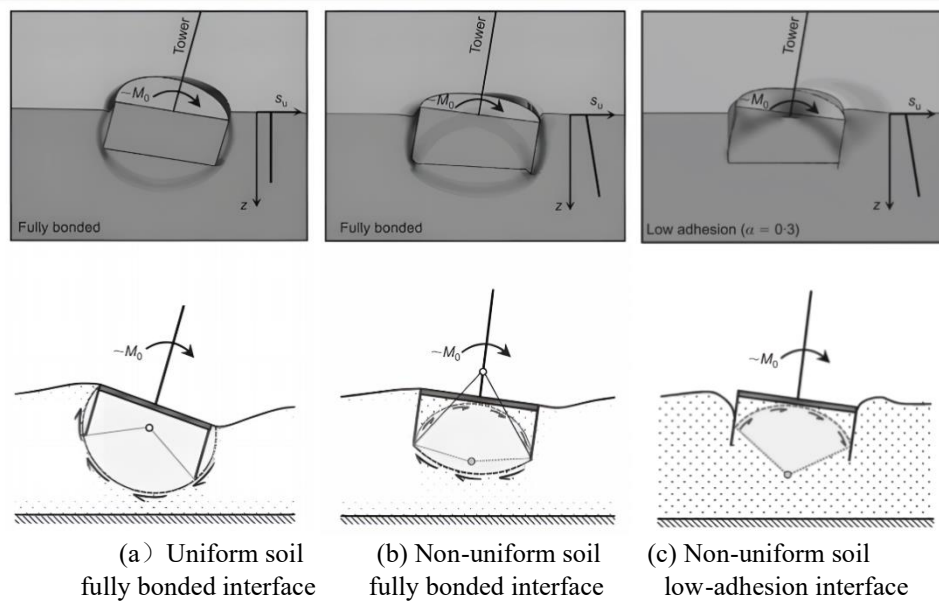


Figure 4. Failure mechanism of suction foundation at a height-to-diameter ratio of 0.5[30]

Murff et al. [35] pioneered the application of an upper-bound plastic limit method to assess the horizontal bearing capacity of suction bucket foundations. The assumed failure mechanism, illustrated in Figure 5, comprises a failure wedge at the mudline, a plane strain flow-around region, and a scoop-shaped failure surface at the foundation tip. Building upon the failure wedge concept proposed by Murff et al. [35], Randolph et al. [36] developed the calculation program AGSPANC, which effectively computes the bearing capacity of suction bucket foundations under combined vertical and horizontal loading. Furthermore, Randolph et al. [36] proposed a modified model for cases where the load is applied above the mudline, leading to a forward-tilting failure mode. This model incorporates active and passive failure wedges, along with a scoop-shaped failure at their base. The validity of this method has been corroborated through comparisons with numerical simulations and centrifuge test results.

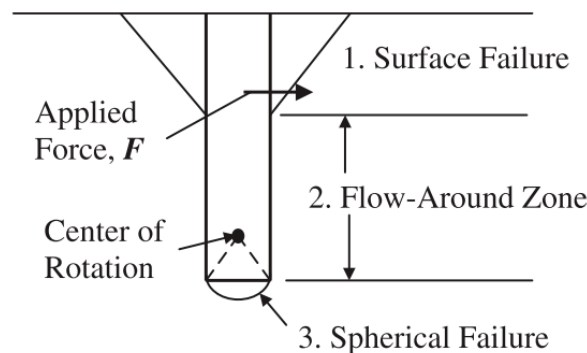


Figure 5. Failure mechanism proposed by Murff et al.[35]

2.3 Theoretical Analysis Methods

Among the theoretical analytical approaches used in the study of suction bucket foundation bearing capacity, the most commonly employed are the limit equilibrium method and the limit analysis method [37]. The limit equilibrium method is a traditional approach for approximately solving geotechnical stability problems. Its advantages, including model simplicity, convenient formulation, and ease of understanding, have led to its widespread application in practice. In the large-scale 1-g model tests conducted by Deng et al. [38], soil pressure cells were used to measure the interaction forces between the bucket skirt and the soil. The study found that under overturning loads, the increase in soil pressure on the skirt in the passive zone followed a binomial distribution with depth and exhibited a linear relationship with the subgrade horizontal reaction coefficient. In the research by Shi et al. [39], where horizontal load was applied at the bucket top, the distribution of soil pressure around the suction bucket foundation under horizontal loading was found to be similar to that of a rigid foundation. Under this loading condition, the primary mode of movement for the bucket suction foundation was rotation, with the soil resistance in the passive zone showing a parabolic distribution. Sukumaran et al. [40] utilized the ideal elastoplastic von Mises criterion to simulate soil yielding. They analyzed the relationship between the ultimate bearing capacity of bucket suction foundations in soft clay under undrained conditions and the point of horizontal load application, while also investigating the distribution of lateral earth pressure on the exterior of the foundation. As shown in Figure 6, Achmus et al. [41] employed the finite element method to determine the horizontal stress distribution acting between the skirt and the soil on the plane of symmetry at failure. Their findings indicated that as the load application height increased, the foundation's pivot point moved upward, a phenomenon bearing similarities to the response observed in piles.

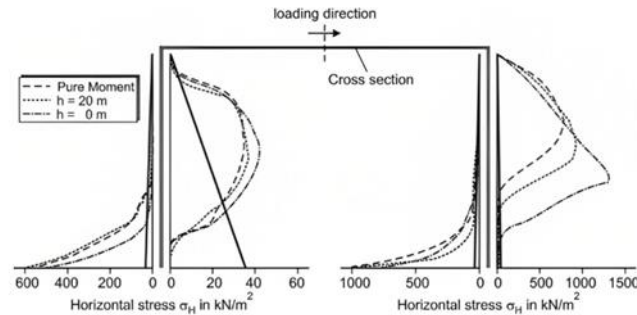


Figure 6. Soil stress distribution along the skirt in the ultimate state [41]

Liu et al. [42] postulated that under horizontal loading, a suction bucket foundation rotates about a pivot point at the bottom of its front side, with soil resistance acting solely on this front face. Based on a plane strain problem assumption, they derived a simplified formula for calculating the horizontal bearing capacity of bucket foundations. However, the assumed location of this rotation center warrants further examination. Zhang et al. [43], while neglecting the influence of frictional resistance on horizontal capacity, proposed that soil resistance is distributed on the upper-middle part of the front side and the lower part of the rear side of the bucket. By establishing equilibrium equations for a three-dimensional problem, they derived an expression for the horizontal bearing capacity and determined the location of the rotation center. Building upon previous experimental and theoretical research, Sun et al. [44] abstracted and simplified the three-dimensional stress state of a monopod suction bucket foundation under horizontal load in saturated soft clay (as shown in Figure 7). Applying the limit equilibrium method, they derived a calculation formula suitable for estimating the ultimate horizontal bearing capacity in engineering practice. The reliability of the formula was verified through comparison with experimental results.

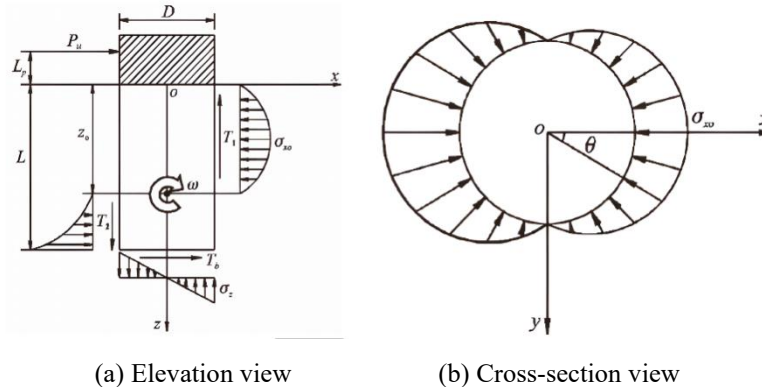


Figure 7. Schematic model of suction foundation under horizontal ultimate loading conditions [44]

Yang et al. [12], based on the findings of Liu et al. [45] and Zhu et al. [20] regarding the distribution of earth pressure along the skirt wall of suction bucket foundations in silt under horizontal loading, proposed a simplified method for distributing soil stresses along the internal and external walls of the foundation (as illustrated in Figure 8). Their method posits that the maximum passive earth pressure on the external wall, above a depth of z_1 , should be calculated using Coulomb's theory. Conversely, the maximum passive earth pressure on the internal wall should be calculated using Rankine's theory. They noted that this distinction is necessary because the wedge analysis method inherent in Coulomb's theory is constrained by the presence of the foundation skirt and is therefore not suitable for evaluating the soil within the bucket.

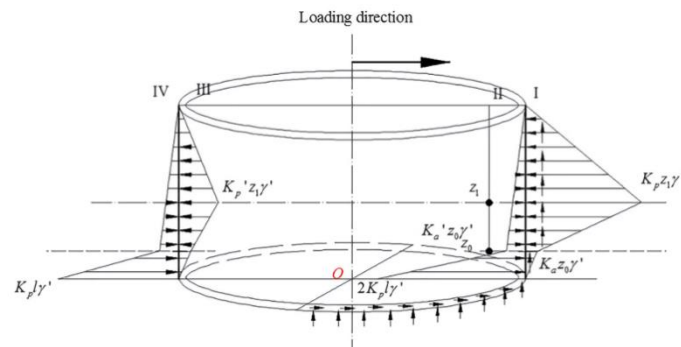


Figure 8. Simplified distribution of earth pressure on suction foundation [12]

Hung et al. [46] employed three-dimensional finite element analysis to investigate formulas for the bearing capacity of suction bucket foundations in normally consolidated, uniform clay under undrained conditions. Their work also aimed at predicting the failure envelope of the foundations under combined loading conditions for the assessment of ultimate bearing capacity. Ding et al. [47] proposed a novel composite suction bucket foundation with a relatively low aspect ratio for offshore wind farms. Through experimental investigation, they determined the deformation mode of the surrounding clay, the soil-foundation interaction, and the ultimate bearing capacity. Their results indicated that under the ultimate horizontal load, the instantaneous center of rotation was located approximately $0.8L$ from the ground surface around the caisson wall in the direction of loading. Furthermore, based on the identified rotation center location, they established analytical expressions for earth pressure distribution and ultimate bearing capacity. The accuracy of both the experimental results and the analytical expressions was validated through finite element numerical simulations. As shown in Figure 9, the distribution of foundation earth pressure and the location of the rotation center can be obtained.

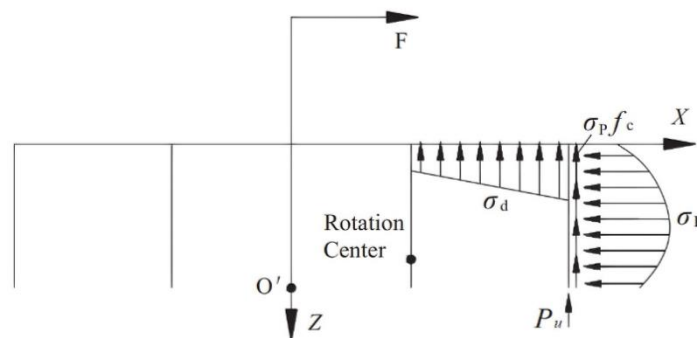


Figure 9. Simplified principal soil pressure distribution on the composite suction foundation [47]

Based on centrifuge model tests conducted by Ma et al. [48], the location of the suction bucket foundation's center of rotation can be approximated at a depth of 0.5 times the foundation height and a horizontal distance of 0.21 times the diameter from the foundation's central axis. This simplification facilitates the representation of the soil resistance distribution around the foundation (as shown in Figure 10) and led to the proposal of an expression for the ultimate horizontal bearing capacity of the caisson-type suction bucket foundation.

Zhang et al. [49] investigated the bearing behavior of suction foundations under horizontal loads in undrained saturated soft clay by means of a three-dimensional finite element method. Their results indicated that when the loading point is close to the mid-height of the suction foundation, the rotational center shifts toward the top of the foundation, leading to the maximum passive failure zone and the ultimate horizontal bearing capacity. On this basis, they proposed an equation for calculating the ultimate horizontal bearing capacity of suction foundations (as shown in Figure 11). However, this method neglects the fact that the soil resistance acting on the skirt wall of the

foundation around the rotational center does not reach the yield strength, which inevitably introduces certain errors into the calculation results.

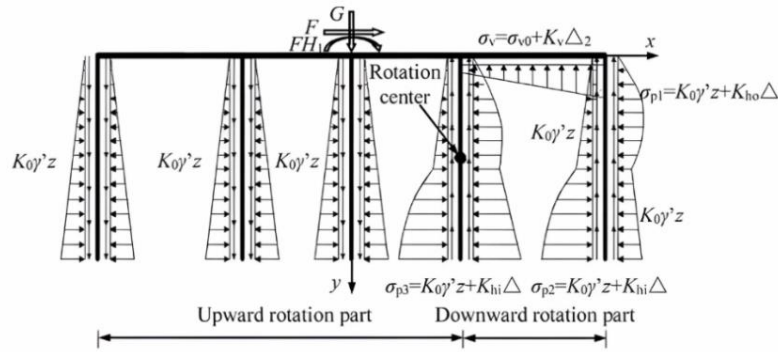


Figure 10 Soil stress distribution around the chamber-type suction foundation [48]

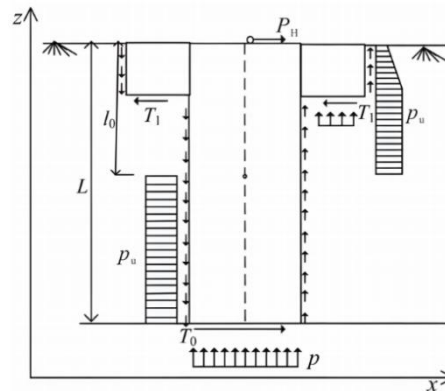


Figure 11 Force diagram of the skirted suction foundation under horizontal loading[49]

Currently, methods for predicting the lateral load-displacement response of piles include the elastic continuum method [50], the finite element method [51-54], and the subgrade reaction (or Winkler spring) method [50,55-57]. The elastic continuum method is only suitable for analyzing pile foundations under very low lateral loads as it does not account for soil yielding. The finite element method can be used for the nonlinear analysis of laterally loaded piles, but it requires complex soil constitutive models whose parameters are often difficult, if not impossible, to obtain in design practice [50]. The subgrade reaction method is the most widely used approach due to its mathematical convenience and ease of incorporating soil nonlinearity and non-homogeneity. In this method, the surrounding soil is replaced by a series of independent springs attached along the pile. To account for soil nonlinearity, these springs can be represented by so-called *p-y* curves, which define the relationship between the soil resistance per unit pile length (*p*) and the pile deflection (*y*). Using the subgrade reaction method, the response of a pile under lateral loading can be determined by solving the following differential equation:

$$E_p I_p \frac{d^4 y}{dz^4} + K_h y = 0 \tag{1}$$

where $E_p I_p$ is the bending stiffness of the pile, and *y* is the horizontal displacement of the pile at depth *z*. K_h is the horizontal subgrade reaction modulus (or spring stiffness), defined as

$$k_h = \frac{P}{y} \tag{2}$$

However, the subgrade reaction method has clear limitations, primarily its neglect of the continuity of the soil medium. Moreover, in practical analysis, the selection of appropriate *p-y* curves required for the analysis is often challenging due to a lack of instrumented pile load test data.

Given that *p-y* curves were originally derived for small-diameter and slender piles, their direct application in the design of increasingly larger modern wind turbines may be problematic. As the capacity of individual wind turbine units increases—and foundations scale up accordingly to reduce costs—their slenderness ratios become significantly smaller than those of the pile models proposed by Matlock [58] and Cox et al. [59]. In some cases, piles with a sufficiently low length-to-diameter ratio supporting the structure can be considered rigid [50]. For a rigid pile under lateral load, pile bending can be neglected, and the displacement at the mudline is primarily caused by rotation about a center located at a certain depth below the mudline. In this scenario, the pile can be analyzed by simply considering force and moment equilibrium, without the need to solve the differential equation. Poulos

et al. [60], Zhang et al. [56], and Liu et al. [55] respectively developed analytical methods for predicting the nonlinear load-displacement response of laterally loaded rigid piles in cohesionless/cohesive soils, as illustrated in Figure 12. The validity of these methods was verified through analysis of laboratory model piles, centrifuge model piles, and field pile tests.

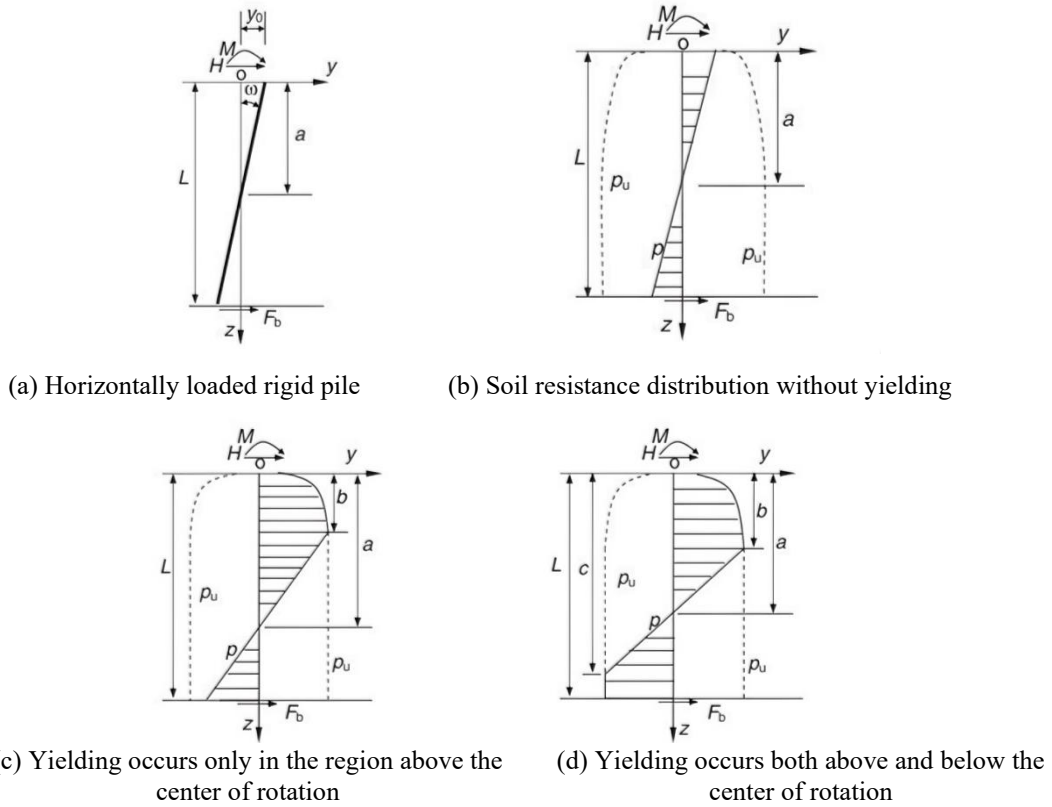


Figure 12. Soil resistance distribution [50]

As illustrated in Figure 13, slender piles exhibit a flexible response under horizontal loading, while large-diameter piles or suction bucket foundations demonstrate a rigid response [61]. When employing p - y curves to streamline the design of suction bucket foundations, the curves proposed in the DNV (Det Norske Veritas) standards [62] lack sufficient accuracy. Østergaard et al. [63] conducted finite element analyses to investigate horizontally loaded suction bucket foundations in drained sandy soil and developed p - y curve formulations to accurately simulate and characterize the variation in soil pressure. However, the model parameters assumed by Østergaard et al. [64] were insufficient for precisely predicting soil pressure. To address this, Vethanayagam et al. [61] proposed a p - y curve formulation for suction bucket foundations in clay that incorporates parameters such as effective vertical stress, soil stiffness, foundation diameter, and the angle of internal friction or undrained shear strength. Nevertheless, the p - y curves obtained through empirical fitting of data based on a small-strain hardening model have not yet been compared with results from finite element analyses to predict the ultimate bearing capacity of bucket suction foundations.

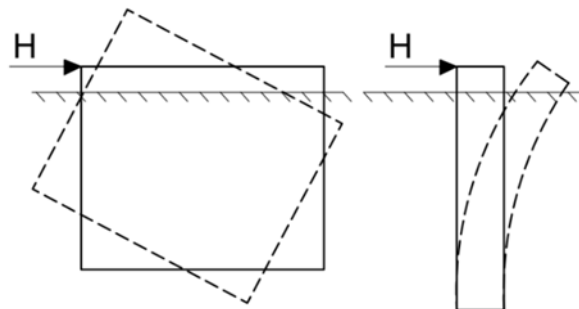


Figure 13 Response of non-slender and slender piles to horizontal loading [61]

Nielsen et al. [64] reported field measurements of the accumulated rotation of a met-mast supported by a suction bucket foundation (15m in diameter, 7.5m in skirt length) installed at the Dogger Bank offshore wind farm. The foundation was installed in a soil profile consisting primarily of sand overlying clay. The results indicated that the accumulated rotation of the suction bucket foundation stabilized at approximately 0.06° within one to two months after installation and operation. Furthermore, this accumulated rotation recovered after the foundation was subjected to storm loading. Subsequent wave loads did not induce permanent deformation. Nielsen et al. [64] attributed the disappearance of permanent accumulated deformation under extreme storm loading to the generation of negative pore water pressure around the suction bucket foundation, which enhances its instantaneous bearing capacity and thereby counteracts the effects of subsequent wave loads. Currently, many existing and potential offshore wind farm sites in China are characterized by soil strata consisting largely of silt or silty clay. However, most research on the bearing behavior of suction bucket foundations has focused on sand and clay, often neglecting the capacity enhancement provided by negative pore water pressure. Therefore, investigating the influence of the drainage conditions in the surrounding soil on the bearing performance of suction bucket foundations under horizontal loading is of paramount importance.

3. Research Status on Tripod Suction bucket Foundations

Research on the bearing performance response of tripod suction bucket foundations under horizontal loading remains relatively scarce, especially when compared to that of single-bucket foundations [65].

3.1 Pile Group Effect and Bearing Capacity Characteristics

Martin et al. [66] applied plasticity theory to analyze the pile group effect of two-dimensional parallel strip foundations under vertical loading, in which the group effect is primarily influenced by the pile spacing, with the heterogeneity of clay being essentially negligible except for closely spaced piles. According to the study by Hung et al. [47], as the aspect ratio L/D of a single-suction bucket foundation increases, its behavior under horizontal loading transitions from pure horizontal sliding to rotational movement. Concurrently, the aspect ratio affects the pile group effect of tripod suction bucket foundations. Gourvenec et al. [67] conducted two-dimensional finite element analyses to investigate the bearing behavior of double-skirted foundations in homogeneous clay under undrained conditions; the vertical, horizontal, and moment bearing capacities were analyzed based on the spacing between the foundation skirts. Gourvenec et al. [68] extended the work by performing two-dimensional finite element analyses on the pile group effect of double-skirted foundations with an aspect ratio of $L/D = 0.5$ in homogeneous clay. The study found that the group effect on vertical bearing capacity is negligible; the horizontal bearing capacity increases significantly with the increasing spacing of the tripod suction bucket foundation and tends to approach a constant value. Due to the interaction among the individual buckets of a tripod suction bucket foundation, its bearing capacity differs considerably from that of a single-suction bucket foundation. Kim et al. [69] compared the bearing capacities of single-bucket and tripod suction bucket foundations in clay using three-dimensional finite element analysis, revealing that the bearing capacity factors increase with the aspect ratio L/D and the spacing-to-diameter ratio S/D , reaching a maximum at $S/D \geq 2$. To evaluate the horizontal bearing capacity of tripod suction bucket foundations in undrained clay, Hung et al. [70] carried out a series of three-dimensional finite element analyses, examining the effects of foundation spacing, embedment depth, and clay heterogeneity on the horizontal bearing capacity.

Tran et al. [71] investigated the moment bearing capacity of tripod suction bucket foundations in sand based on extensive finite element analyses, finding a linear increasing trend with the rise of the spacing-to-diameter ratio. Finally, they proposed equations accounting for the effects of foundation spacing, foundation height, foundation diameter, vertical load, and the unit weight of the foundation soil on the bearing capacity. By analyzing the bearing behavior of single-bucket and tripod suction bucket foundations using the Hardening Soil constitutive model in the finite element software PLAXIS 3D, Bagheri et al. [72] presented curves depicting the relationship between horizontal load-displacement and normalized overturning moment for both foundation types. They found that the foundation geometry and loading height significantly influence the ultimate horizontal bearing capacity, with the capacity of the tripod suction bucket foundation being markedly higher than that of the single-bucket foundation.

3.2 Effect of Arrangement Orientation and Loading Angle

There is a distinct dominant wind direction for offshore wind power projects in the South China Sea of China; under normal power generation conditions, they are expected to be subjected to wind loads from the northeast direction during most of their operation. The Guangdong Electric Power Design Institute has also pointed out the close relationship between the dominant wind direction and the layout of tripod suction bucket foundations for wind power generation [73], as shown in Figure 14.

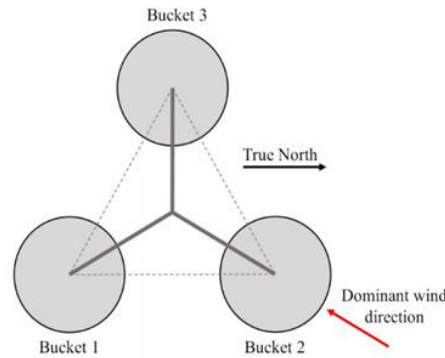


Figure 14. Relationship between wind turbine foundation layout and the prevailing wind direction [73]

Jasna et al. [74] conducted three-dimensional numerical simulation analysis using ABAQUS 6.16 to determine and compare the horizontal bearing capacities of single-bucket and tripod suction bucket foundations under drained monotonic horizontal loading conditions. The research results indicate that the ultimate horizontal bearing capacity of the tripod suction bucket foundation increases with the increase in foundation diameter and loading conditions. To investigate the bearing capacity response of tripod suction bucket foundations in undrained foundation soils under vertical load, moment, and combined load, Stergiou et al. [75] performed three-dimensional finite element analysis and presented the failure load envelope. Faizi et al [76] proposed a new type of tripod suction bucket foundation for offshore wind turbines—the hybrid tripod suction bucket foundation (as shown in Figure 15), which has greater overturning resistance compared with the traditional tripod suction bucket foundation. Based on ABAQUS finite element analysis and centrifuge tests, Faizi et al. [76] found that the bearing capacity of the tripod suction bucket foundation largely depends on the foundation spacing and load application direction. Generally speaking, the larger the spacing of the suction foundations, the greater their anti-overturning capacity.

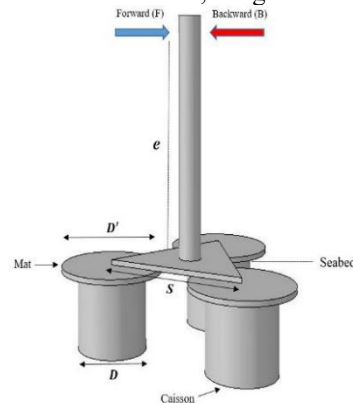


Figure 15. Schematic diagram of a hybrid triple suction bucket foundation [76]

Due to the influence of the prevailing offshore wind direction on the working surface of wind turbine blades, the horizontal loads and moments borne by the wind turbine foundation within the plane vary with different loading angles, making the ultimate bearing capacity analysis more complex. Based on the finite element simulation analysis by Liu Shujie [77], a displacement-controlled method was adopted to investigate the bearing capacity characteristics of a tripod suction bucket foundation in homogeneous soil under individual load components. For different directions of horizontal load, the most unfavorable and favorable orientations for the ultimate horizontal bearing capacity of the tripod suction bucket foundation were identified. Furthermore, the effects of soil shear strength and effective unit weight on the ultimate bearing capacity of the multi-suction bucket foundation under monotonic loading conditions were discussed. Liu et al. [78] established a three-dimensional finite element numerical model of an offshore wind turbine tripod bucket foundation using the software ABAQUS, studying the ultimate bearing capacity characteristics of the multi-suction bucket foundation under horizontal loading. The results showed that as the bucket spacing increases, the ultimate bearing capacity of the tripod suction bucket foundation improves. Meanwhile, with increasing bucket spacing, the influence of the horizontal load direction on the ultimate bearing capacity gradually diminishes, although the most favorable and unfavorable load directions remain unchanged. Based on a physical simulation model, Ren et al. [79] investigated the local scour around the tripod suction bucket foundation at the Yangjiang Shapa Offshore Wind Farm. The results indicated that the flow around the bucket walls and the top rib plate of the foundation are the main factors affecting the scour of the tripod suction bucket foundation. Therefore, deep dredging of the seabed before foundation installation is beneficial to structural stability, and greater dredging depth has a more significant impact on structural stability.

4. Conclusion

Suction bucket foundations serve as a crucial foundation solution for offshore wind turbines, with their horizontal bearing behavior being central to engineering design and safety evaluation. This review synthesizes the current research status on the horizontal performance of both monopod and tripod suction bucket foundations.

For monopod foundations, existing research has clarified fundamental behavioral patterns, including the variation of the rotational center, the transition in failure modes from sliding to overturning with increasing aspect ratio, and the significant influence of load eccentricity and soil type on capacity. Although analytical models based on limit equilibrium, limit analysis, and adapted p-y curve methods have been developed, their application remains limited — particularly for large-diameter foundations in intermediate soils such as silty clay, where partial drainage and excess pore pressure effects are not sufficiently addressed.

Tripod foundations exhibit greater overall stiffness and higher bearing capacity compared to monopod configurations. Their performance is governed largely by group effects, which are sensitive to bucket spacing, load direction relative to the foundation layout, and the aspect ratio of individual buckets. While increasing spacing generally enhances capacity, the underlying interaction mechanisms and the collaborative response under complex multi-directional loading lack comprehensive theoretical and quantitative characterization.

Several research gaps remain prominent. Primarily, the influence of partial drainage and pore pressure evolution in soils such as silty clay is not adequately captured in current design approaches. Subsequently, robust and generalized theoretical models for predicting the combined loading capacity of tripod foundations — particularly under asymmetric loading — are still lacking. Thirdly, studies on innovative tripod configurations and their behavior under realistic cyclic multi-directional loading remain limited.

Future research should prioritize the development of advanced numerical models that can realistically simulate coupled soil–fluid–structure interaction and drainage effects. There is a clear need for a unified design framework for tripod foundations, validated through systematic physical modeling and field monitoring. Furthermore, optimization of foundation geometry and layout tailored to site-specific soil and metocean conditions is essential to improve the reliability and cost-effectiveness of suction bucket foundations. Progress in these areas will provide important technical support for the advancement of offshore wind energy, particularly in challenging marine environments such as China's coastal and far-sea regions.

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6. References

- [1] Ou C, Chen X, Hu K, Cao Y, et al. Factors influencing the digital intelligence transformation of offshore wind power enterprise. *Ocean & Coastal Management*. 2024; 259: 107463.
- [2] Gao D, Pan X, Liang B, et al. A Review and Design Principle of Fixed-Bottom Foundation Scour Protection Schemes for Offshore Wind Energy. *Journal of Marine Science and Engineering*. 2024; 12(4):15-27.
- [3] Kou H, Zhang X, Wang Y, et al. Predicting the monotonic horizontal behavior of tripod bucket foundations in clay. *Applied Ocean Research*. 2024; 142: 103849.
- [4] Liu R, Yuan X, Liu Z, et al. Horizontal loading characteristics and load-bearing capacity calculation method for bucket foundations in clay. *Ocean Engineering*. 2025; 340: 122260.
- [5] Luo L, Li Z, Zhou Z, et al. Assessing suction bucket jacket foundation installations in the South China Sea: Insights from field installation experiences. *Marine Structures*. 2024; 96: 103630.
- [6] Kuo Y S, Achmus M, Abdel-Rahman K. Estimation of lateral deformation of monopile foundations by use of cyclic triaxial tests. *Chinese Journal of Geotechnical Engineering*. 2009; 31(11): 1729-1734.
- [7] Li DY, Ma SL, Zhang YK, et al. Lateral Bearing Capacity of Modified Suction Caissons Determined by Using the Limit Equilibrium Method. *China Ocean Engineering*. 2018; 32(4): 461-466.
- [8] Graham J, Pinkney RB, Lew KV, et al. Curve-fitting and laboratory data. *Canadian Geotechnical Journal*. 1982; 19(2): 201-205.
- [9] Villalobos Jara F, Jara FV. Model testing of foundations for offshore wind turbines. 2006.
- [10] Zhu B, Byrne BW, Houlsby GT. Cyclic moment loading of suction caissons in sand. *Frontiers in Offshore Geotechnics II*. 2011.
- [11] Li DY, Chen CJ, Zhang YK, et al. Review of horizontal loading on suction caisson of offshore wind turbines. *Ocean Engineering*. 2020; 38(04): 137-147.
- [12] Yang X, Zeng X, Wang X. Lateral-Moment Loading Capacity and Bearing Behavior of Suction Bucket Foundations for Offshore Wind Turbines in Sand. *International Journal of Geomechanics*. 2018; 18(11): 04018152.

- [13] Deb TK, Singh B. Response and capacity of monopod caisson foundation under eccentric lateral loads. *Marine Georesources & Geotechnology*. 2018; 36(4): 452-464.
- [14] Kumar ND, Rao SN. Lateral Load: Deflection Response of an Embedded Caisson in Marine Clay. *Marine Georesources & Geotechnology*. 2012; 30(1): 1-31.
- [15] Li D, Zhang Y, Feng L, et al. Capacity of modified suction caissons in marine sand under static horizontal loading. *Ocean Engineering*. 2015; 102: 1-16.
- [16] Allersma H, Kierstein A, Maes D. Centrifuge Modelling On Suction Piles Under Cyclic And Long Term Vertical Loading. 2025.
- [17] Wang J, Liu R, Yang X, et al. An optimised failure envelope approach of bucket foundation in undrained clay. *Ships and Offshore Structures*. 2021; 16(2): 42-55.
- [18] Liu M, Lian J, Yang M. Experimental and numerical studies on lateral bearing capacity of bucket foundation in saturated sand. *Ocean Engineering*. 2017; 144: 14-20.
- [19] Wang X, Yang X, Zeng X. Centrifuge modeling of lateral bearing behavior of offshore wind turbine with suction bucket foundation in sand. *Ocean Engineering*. 2017; 139: 140-151.
- [20] Zhu B, Kong D, Chen R, et al. Installation and lateral loading tests of suction caissons in silt. *Canadian Geotechnical Journal*. 2011; 48(7): 1070-1084.
- [21] Jia N, Zhang P, Liu Y, et al. Bearing capacity of composite bucket foundations for offshore wind turbines in silty sand. *Ocean Engineering*. 2018; 151: 1-11.
- [22] Yun G, Bransby M F. The horizontal-moment capacity of embedded foundations in undrained soil. *Canadian Geotechnical Journal*. 2007; 44(4): 409-424.
- [23] Zhu ZX, Wen NL. Research on the Horizontal Bearing Capacity of Bucket Foundations under the Soil Shearing Effect. *Port Engineering Technology*. 2005; 30 (04): 43-45.
- [24] Ran CH. Computation of earth pressure on large diameter cylinder under service ultimate state. *Chinese Journal of Geotechnical Engineering*. 2002; 24 (3): 313-318.
- [25] Liu M, Lian J, Yang M. Experimental and numerical studies on lateral bearing capacity of bucket foundation in saturated sand. *Ocean Engineering*. 2017; 144: 14-20.
- [26] Jin JC, Zhang YT, Yang YH, et al. Research on horizontal ultimate bearing capacity of suction bucket foundation in saturated sand ground. *Journal of Geomechanics*. 2013; 124: 225-231.
- [27] Liu Y, Li SH, Sun GD, et al. Experimental and numerical simulation study on the bearing capacity model of suction pile foundation. *China Offshore Oil & Gas*. 2022; 34(02):194-202.
- [28] Coffman, Richard A, et al. Measured horizontal capacity of suction caissons. *Offshore Technology Conference*. OTC. 2004.
- [29] Hung LC, Lee SH, Vicent S, et al. An experimental investigation of the cyclic response of bucket foundations in soft clay under one-way cyclic horizontal loads. *Applied Ocean Research*. 2018; 71: 59-68.
- [30] Ksourkouli RS, Lekakakis PC, Gelagoti FM, et al. Suction caisson foundations for offshore wind turbines subjected to wave and earthquake loading: effect of soil–foundation interface. *Géotechnique*. 2014; 64(3): 171-185.
- [31] Bransby MF, Yun GJ. The undrained capacity of skirted strip foundations under combined loading. *Géotechnique*. 2009; 59(2): 115-125.
- [32] Mana DSK, Randolph SG & MF. A numerical study of the vertical bearing capacity of skirted foundations. In *Offshore Geotechnics II*. 2010.
- [33] Yun G, Bransby MF. The Undrained Vertical Bearing Capacity of Skirted Foundations. *Soils and Foundations*. 2007; 47(3): 493-505.
- [34] Mana DSK, Gourvenec S, Martin CM. Critical Skirt Spacing for Shallow Foundations under General Loading. *Journal of Geotechnical and Geoenvironmental Engineering*. 2013; 139(9): 1554-1566.
- [35] Murff JD, Hamilton JM. P - Ultimate for Undrained Analysis of Laterally Loaded Piles. *Journal of Geotechnical Engineering*. 1993; 119(1): 91-107.
- [36] Randolph MF, House AR. Analysis of Suction Caisson Capacity in Clay. *Offshore Technology Conference*. 2002.
- [37] Niu XN, Liao X, Li Y. A Review on the Bearing Capacity Studies of the Suction Bucket Foundation for Offshore Wind Turbines. *Journal of Ocean Technology*. 2020; 427.
- [38] Deng W, Carter J. Predictions of the Vertical Pullout Capacity of Suction Caissons in Fine-grained Soils. University of Sydney, Department of Civil Engineering. Centre for Geotechnical Research. 1999.
- [39] Shi XC, Xu RQ, Sai XN, et al. Experimental study on horizontal bearing capacity of single bucket foundation. *Chinese Journal of Geotechnical Engineering*. 1999; 21(6): 723-726.
- [40] Sukumaran B, McCarron WO, Jeanjean P, et al. Efficient finite element techniques for limit analysis of suction caissons under lateral loads. *Computers and Geotechnics*. 1999; 24(2): 89-107.
- [41] Achmus M, Akdag CT, Thieken K. Load-bearing behavior of suction bucket foundations in sand. *Applied Ocean Research*. 2013; 43: 157-165.

- [42] Liu ZW, Wang JH, Qin ZR, et al. Research on the horizontal bearing capacity of bucket foundations . Chinese Journal of Geotechnical Engineering. 2000; 22(6): 691-695.
- [43] Zhang W, Zhou XR, Yu JX. The Ultimate Horizontal Bearing Force Research of Bucket Foundation in Shallow Water. China Offshore Platform. 2004.
- [44] Sun XY, Rong JM, Tang XW. Study of horizontal bearing capacity of bucket foundation on saturated soft clay ground. Rock and Soil Mechanics. 2010; 31(02): 667-672.
- [45] Liu M, Yang M, Wang H. Bearing behavior of wide-shallow bucket foundation for offshore wind turbines in drained silty sand. Ocean Engineering. 2014; 82: 169-179.
- [46] Hung LC, Kim SR. Evaluation of vertical and horizontal bearing capacities of bucket foundations in clay. Ocean Engineering. 2012; 52: 75-82.
- [47] Ding H, Liu Y, Zhang P, et al. Model tests on the bearing capacity of wide-shallow composite bucket foundations for offshore wind turbines in clay. Ocean Engineering. 2015; 103: 114-122.
- [48] Ma P, Liu R, Lian J, et al. An investigation into the lateral loading response of shallow bucket foundations for offshore wind turbines through centrifuge modeling in sand. Applied Ocean Research. 2019; 87: 192-203.
- [49] Zhang Wei, Ma Zhenjie. Numerical analysis of horizontal bearing performance of suction piles in soft clay foundations. Journal of Waterway and Harbor. 2022; 43(3): 377-382, 389.
- [50] Zhang L, Ernst H, Einstein H. Nonlinear Analysis of Laterally Loaded Rock-Socketed Shafts. Journal of Geotechnical and Geoenvironmental Engineering. 2000; 126(11): 955-968.
- [51] Wakai A, Gose S, Ugai K. 3-D Elasto-Plastic Finite Element Analyses of Pile Foundations Subjected to Lateral Loading. Soils and Foundations. 1999; 39(1): 97-111
- [52] Huchegowda BK, Teja M, Kalyan Kumar G. Evaluation of Lateral Capacity of Pile Foundation Using Finite Element Method in Layered Soil. Advances in Geotechnical and Transportation Engineering. 2020;47: 79-84.
- [53] Adeel MB, Aaqib M, Pervaiz U, et al. Numerical response of pile foundations in granular soils subjected to lateral load. Geomechanics & engineering. 2022; 28(1): 11-23.
- [54] Wang J, Sun G, Chen G, et al. Finite element analyses of improved lateral performance of monopile when combined with bucket foundation for offshore wind turbines. Applied Ocean Research. 2021; 111: 102647.
- [55] Liu P, Jiang C, Lin M, et al. Nonlinear analysis of laterally loaded rigid piles at the crest of clay slopes. Computers and Geotechnics. 2020; 126: 103715.
- [56] Zhang L. Nonlinear analysis of laterally loaded rigid piles in cohesionless soil. Computers and Geotechnics. 2009; 36(5): 718-724.
- [57] Kumar S, Lalvani L, Omar M. Nonlinear Response of Single Piles in Sand Subjected to Lateral Loads using khmax Approach. Geotechnical & Geological Engineering. 2006; 24(1): 163-181.
- [58] Matlock H. Correlation for Design of Laterally Loaded Piles in Soft Clay. Offshore Technology Conference. 1970.
- [59] Cox WR, Reese LC, Grubbs BR. Field Testing of Laterally Loaded Piles In Sand. 2025.
- [60] Poulos HG, Davis EH. Pile foundation analysis and design. 1980.
- [61] Vethanayagam, Vinojan, Lars Bo Ibsen. Determination of py Curves for Bucket Foundations in Silt and Sand Using Finite Element Modelling. 2017.
- [62] Veritas D N. Design of Offshore Wind Turbine Structure. Offshore Standard DNV-OS-J101. 2004.
- [63] Østergaard, M.U, Knudsen, BS, Ibsen, L.B. P-y curves for bucket foundations in sand using finite element modeling. In Frontiers in Offshore Geotechnics III. 2015.
- [64] Nielsen SD, Ibsen LB, Nielsen SA. Performance of a Mono Bucket Foundation - A Case Study at Dogger Bank. International Journal of Offshore and Polar Engineering. 2017; 27(03): 326-332.
- [65] Wang LZ, Wang H, Zhu B, et al. Comparison of monotonic and cyclic lateral response between monopod and tripod bucket foundations in medium dense sand. Ocean Engineering. 2018; 155: 88-105.
- [66] Martin C, Hazell E. Bearing capacity of parallel strip footings on non-homogeneous clay. Frontiers in Offshore Geotechnics. 2005.
- [67] Gourvenec S, Steinepreis M. Undrained Limit States of Shallow Foundations Acting in Consort. International Journal of Geomechanics. 2007; 7(3): 194-205.
- [68] Gourvenec S, Jensen K. Effect of Embedment and Spacing of Cojoined Skirted Foundation Systems on Undrained Limit States under General Loading. International Journal of Geomechanics. 2009; 9(6): 267-279.
- [69] Kim SR, Hung LC, Oh M. Group effect on bearing capacities of tripod bucket foundations in undrained clay. Ocean Engineering. 2014; 79: 1-9.
- [70] Hung LC, Kim SR. Evaluation of combined horizontal-moment bearing capacities of tripod bucket foundations in undrained clay. Ocean Engineering. 2014; 85: 100-109.
- [71] Tran Q A, Solowski W, Karstunen M, et al. Modelling of Fall-cone Tests with Strain-rate Effects. Procedia Engineering. 2017; 175: 293-301.

- [72] Bagheri P, Son S, Lee D, et al. Numerical modeling of monopod and tripod bucket foundation. 2019.
- [73] Liu B, Zhang Y, Ma Z, et al. Design considerations of suction caisson foundations for offshore wind turbines in Southern China. *Applied Ocean Research*. 2020; 104: 102358.
- [74] Jasna PH, John BM, Nair RP. Comparative Study of Monopod and Tripod Suction Caisson Foundation for an Offshore Wind. Springer International Publishin. 2022; 98: 355-363.
- [75] Stergiou T, Terzis D, Georgiadis K. Undrained bearing capacity of tripod skirted foundations under eccentric loading. *Geotechnik*. 2015;38(1):17-27.
- [76] Faizi K, Faramarzi A, Dirar S, et al. Investigating the monotonic behaviour of hybrid tripod suction bucket foundations for offshore wind towers in sand. *Applied Ocean Research*. 2019; 89: 176-187.
- [77] Liu SJ. Study on bearing capacity characteristics of suction multi-bucket composite foundations for offshore wind turbines. Dalian University of Technology. 2009.
- [78] Liu SJ, Wang ZT, Rong MT. Numerical analysis of bearing capacity behavior of multi-bucket suctional foundation for offshore wind turbine under monotonic loading. *Ocean Engineering*, 2010;76: 31-35.
- [79] Ren Y, Liu B, Liu X J, et al. Study on Local Scour of Suction Bucket Foundations at Offshore Wind Farms in Shapa of Yangjiang. *People's Pearl River*. 2022;178: 107-113.