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RESEARCH PAPER

Bearing capacity of the bucket spudcan foundation for offshore jack-up drilling platforms

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Abstract: To compare the bearing capacities of the traditional spudcan and the bucket spudcan, the effects of different type spudcans on the rigidity of pile legs and the entire bearing capacity were analyzed in detail. Through the loading method of Swipe and constant displacement, this paper plots the spatial failure envelopes of the vertical-horizontal load, vertical-moment load, vertical-horizontal-moment load of the bucket spudcan and traditional spudcan under the mode of composite loading, as well as the spatial failure envelopes of the vertical static load-vertical cycling limit load, vertical static-load horizontal cycling limit load based on these two spudcans under the mode of cycling loading. Theoretical study showed that the skirt system of bucket spudcan can increase the effective embedded depth, consequently improving the foundation rigidity and entire stiffness of a jack-up drilling platform. It is found that the bearing capacity of the horizontal load and moment load of the new spudcan is increased by at least 10% than that of the traditional spudcan, especially the horizontal load being up to 20% in the dynamic load condition. Under the action of limit storm loading condition including wind, wave and flow loads, the entire bearing capacity of the jackup rig in stiff clay is increased by about 46% with the bucket spudcan foundation compared to the traditional one.

Key words: bucket spudcan foundation; offshore jackup rig; bearing capacity; numerical simulation; failure envelopes

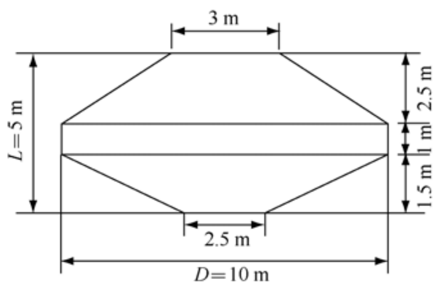
With the wide application of offshore jack-up drilling platforms, the bearing capacity of traditional spudcans under environmental loads such as offshore extreme wind, wave and current loads has been challenged. Bucket foundation is a new spudcan, developed in recent years, which enables offshore jack-up drilling platforms to bear higher moment and horizontal load. During the installation, the jack-up drilling platform is mainly under vertical loads, which will change under the action of horizontal loads and moments due to storms, waves and currents. Therefore, the basic performance of spudcans under the combined action of vertical loads, horizontal loads and moments is especially important for analysis of offshore jack-up rigs. In this paper, the ultimate bearing capacity of bucket spudcan is discussed, and the advantages of this bucket spudcan as the foundation of offshore jack-up rigs is described.

1 Comparison of ultimate bearing capacity between traditional spudcans and bucket spudcans

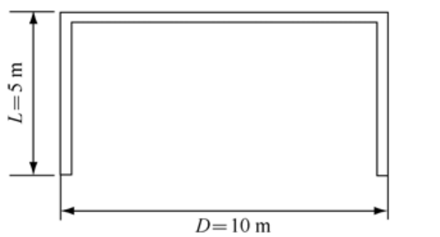
1.1 Establishment of numerical model

The geometry for traditional spudcans and bucket spudcans is shown in Fig. 1. It can be seen that the horizontal cross sections for the two types are both circular: the diameter (D) is 10 m, height (L) is 5 m and the value of D/L is 2. The soil (clay) parameters are: $c_u/(\gamma' D)$=0.15; kD/c_u=0.

The displacement load controlling method is applied to



(a) Traditional spudcan



(b) Bucket spudcan

Fig. 1 Geometry for two types of spudcan

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load the ultimate bearing capacity for spudcans. And the Swipe loading method and fixed displacement ratio loading method are used to plot envelopes of spudcan bearing capacity[1–4]. In the loading process, the ratio of the horizontal displacement increment δ_h to the vertical displacement increment δ_v (δ_h/δ_v) takes 0, 0.25, 1, 4 and ∞; the ratio of spudcan moment rotation angle δ_θ to vertical displacement increment δ_v(δ_θ/δ_v) takes 0, 0.25, 1, 4 and ∞. Considering the project actuality, the coefficient of friction (μ) between spudcan and soil is taken as 0.65. The soil-spudcan system uses a 3D ABAQUS model, where horizontal constraints are applied on soil side faces, fixed constraints are applied on soil bottom surface, and the top surface is free; in order to avoid boundary effects, soil in the finite element model is taken as 120 m in width and 100 m in depth. The constitutive model of clay is selected as a Mohr-Coulomb model.

1.2 Comparison of ultimate bearing capacity under static load

The bearing capacity of traditional spudcan and bucket spudcan is compared under vertical load, horizontal load, moment load and combination loads respectively through numerical calculation. Furthermore, the failure envelopes under combination loads for both spudcans are compared.

In order to characterize bearing capacity, the loads and displacements are normalized. The ratios of loads to ultimate loads, such as V/V_{ult}, H/H_{ult} and M/M_{ult} are used to present normalized vertical load, horizontal load and moment load on the foundation, respectively. The failure envelopes of normalized bearing capacity are formed by plotting the end points of every load paths, which can be obtained by Swipe loading method (in *H*-*V* and *V*-*M* space) and fixed displacement ratio loading method. In order to compare the bearing capacity conveniently, the horizontal load and moment bearing capacity for two types of spudcan under different vertical loads V/V_{ult} are given in Fig. 2.

In *H*-*V* space, orthogonalized failure envelopes (Fig. 2a) for bucket and traditional spudcans can be approximately expressed by the elliptic equation:

$$\left(\frac{V}{V_{ult}}\right)^a + \left(\frac{H}{H_{ult}}\right)^b = 1 \tag{1}$$

As to the coefficient of this elliptic curve, for bucket spudcans the values are $a_1=b_1=3$, which are similar to the proposed values by Senders[5]; for traditional spudcans, the values are $a_2=3$, $b_2=1.25$.

Similarly, in the *V*-*M* space, the orthogonalized failure envelopes (Fig. 2b) for bucket and traditional spudcans can also be approximately expressed by the elliptic equation:

$$\left(\frac{V}{V_{ult}}\right)^c + \left(\frac{M}{M_{ult}}\right)^d = 1 \tag{2}$$

The coefficient of this elliptic curve are taken as the values: $c_1=4$, $d_1=2$ for bucket spudcans, which are nearly equal to the proposed values by Bransby[6]; $c_2=3$, $d_2=1.25$ for traditional spudcans.

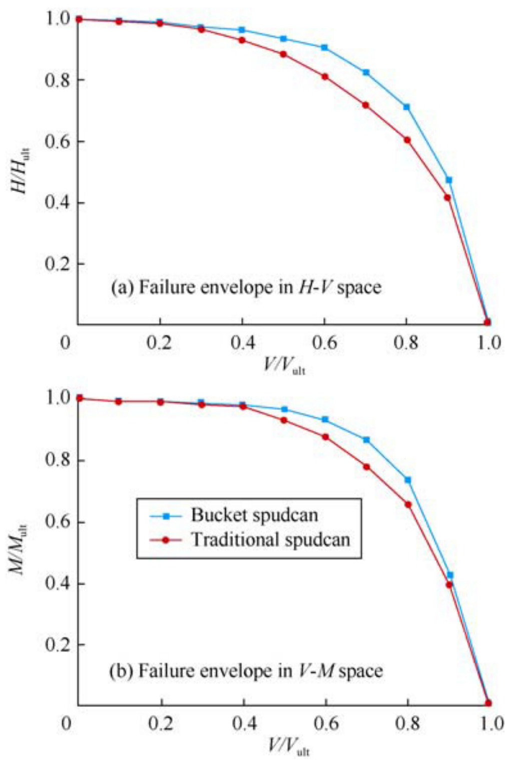

Fig. 2 Failure envelopes in different bearing loads spaces

It can be seen from the comparison results that, under the same vertical force, the bearing capacities of bucket spudcans for horizontal and moment loads are higher than those of traditional one. As shown in Fig. 2a, the difference in horizontal bearing capacity between bucket spudcans and traditional spudcans expands gradually from the vertical load point of $V/V_{ult}=0.3$. Near the vertical load point of $V/V_{ult}=0.6$, the horizontal bearing capacity of bucket spudcans is over 10% more than that of traditional spudcans. This is because the foundation failure mode becomes the Green mode[7] with the increase of vertical load V/V_{ult}, in which the skirt system of bucket spudcan plays a greater role so that the horizontal bearing capacity of bucket spudcan is much higher than that of the traditional one. However, with the vertical load V/V_{ult} close to 1, the level of bearing capacity for both spudcans is gradually close again.

As Fig. 2b shows, from the vertical load point of $V/V_{ult}=0.5$, the moment bearing capacity for bucket spudcans gradually has bigger difference with that of traditional spudcans. With the vertical load V/V_{ult} continuing to increase, the advantage of bucket spudcans is relatively significant. But when the vertical load V/V_{ult} is close to 1, the Prandtl failure mode[8] is developed, which means the advantage of new spudcan will be no longer obvious. Overall, with the change of the V/V_{ult}, the improvement for moment bearing capacity of new spudcans is not obvious compared with that of traditional spudcans.

Bransby et al.[9] gives the formula for failure envelope of bucket spudcan in *V*-*H*-*M* space:

$$\alpha_3\sqrt{\left(\frac{M^*}{M_{ult}}\right)^{\alpha_1} + \left(\frac{H}{H_{ult}}\right)^{\alpha_2}} + \left(\frac{V}{V_{ult}}\right)^2 = 1 \tag{3}$$

where,

$$M^{*}=M-Hw$$

Moreover, Taiebat et al.[10] gives the expression equation for yield surface of bucket spudcans in the undrained homogenous clay condition:

$$\left(\frac{V}{V_{\mathrm{ult}}}\right)^{2}+\left[\frac{M}{M_{\mathrm{ult}}}\left(1-\alpha_{1}\frac{HM}{H_{\mathrm{ult}}\left|M_{\mathrm{ult}}\right|}\right)\right]^{2}+\left|\left(\frac{H}{H_{\mathrm{ult}}}\right)^{3}\right|=1 \quad (4)$$

For the 3D failure envelope of traditional circular spudcan, Martin et al.[11–14] gives the empirical formula for yield surface in the overconsolidated clay condition, that is, the formula of model B is:

$$\left(\frac{M}{M_{\mathrm{ult}}}\right)^{2}+\left(\frac{H}{H_{\mathrm{ult}}}\right)^{2}-2\overline{e}\frac{M}{M_{\mathrm{ult}}}\frac{H}{H_{\mathrm{ult}}}-\overline{\beta}^{2}\left(\frac{V}{V_{\mathrm{ult}}}\right)^{2\beta_{1}}\left(1-\frac{V}{V_{\mathrm{ult}}}\right)^{2\beta_{2}}=1 \quad (5)$$

Where,

$$H_{\mathrm{ult}}=h_{0}V_{\mathrm{ult}} \qquad M_{\mathrm{ult}}=m_{0}DV_{\mathrm{ult}}$$

$$\overline{e}=e_{1}+e_{2}\frac{V}{V_{\mathrm{ult}}}\left(\frac{V}{V_{\mathrm{ult}}}-1\right) \qquad \overline{\beta}=\frac{(\beta_{1}+\beta_{2})^{(\beta_{1}+\beta_{2})}}{\beta_{1}^{\beta_{1}}\beta_{2}^{\beta_{2}}}$$

where, h_0=0.127, m_0=0.083, e_1=0.518, e_2=1.180, β_1=0.764, β_2=0.882.

In order to compare the bearing capacity of bucket spudcans and traditional spudcans in *H-M* space under different vertical loads, the bearing capacity under three conditions where vertical load V/V_{ult} is 0.4, 0.5 and 0.8 respectively is analyzed. Fig. 3 illustrates the control points and failure envelopes in *H-M* space for both types of spudcans under different vertical loads. Results from the finite element model of bucket spudcan is more similar to results of equation (3); and results from the finite element model of traditional spudcan is more similar to results of equation (5). By comparison of the results of finite element model and the calculation results from equations (3) and (5), it is found that the theoretical values are more conservative.

It can be seen from Fig. 3, the bearing capacity of bucket spudcans is generally higher than that of traditional spudcans. With the increase of V/V_{ult} value, this advantage is more obvious, which is closely related to the structural skirt features of bucket spudcans. The structural features of bucket spudcans not only improve the bearing capacity of horizontal and moment loads, but also improve the rigidity of pile legs. Consequently, the bearing capacity of the offshore jack-up drilling platform is increased. Under the low vertical loads (V/V_{ult} is 0.4, 0.5), the difference of bearing capacity between the traditional spudcan and bucket spudcan is very small. However, when V/V_{ult} is 0.8, the difference is more obvious.

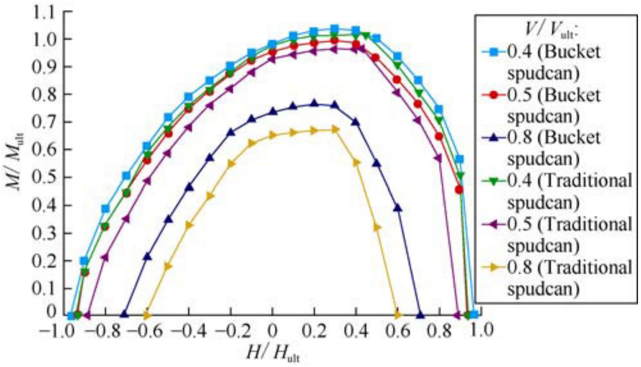

Fig. 3 Failure envelope in *H-M* space

Under conditions of vertical load V/V_{ult}=0.4, 0.5 and the horizontal load H/H_{ult}=–1.0, the soil in the contact surface between the spudcan and the foundation is damaged. Until the H/H_{ult} value is close to 1, the Hansen failure mode[15] is formed. When the vertical load V/V_{ult} is 0.8, the difference of failure mode is quite obvious; and when the H/H_{ult} value is close to 0.3, the soil damage region will be extended downwards to form Hansen failure mode.

In general, compared with traditional circular spudcans, the bucket spudcans in similar geometry have much higher rigidity and horizontal bearing capacity. Namely, bucket spudcans with skirts under vertical load have better combined bearing capacity. However, for moment bearing capacity, bucket spudcans have no significant advantage compared with traditional spudcans, which agrees with the conclusions of reference [16].

1.3 Comparison of ultimate bearing capacity under cyclic loads

In the real sea environment, offshore jack-up drilling platforms are usually subjected to coupling action of wind, wave and current, which is actually a cyclic load. In order to compare the ultimate bearing capacity of traditional spudcans and bucket spudcans under cyclic loads, the same finite element model is used to simulate the behaviors of both spudcans. The cycles of cyclic load is taken as 2000. And the average period of the general wave is about 10 s. So the 2 000 times is corresponding to about 6 h, which is equivalent to the time when the foundation suffers a typical wave loads.

In order to compare the ultimate bearing capacity of the foundation under cyclic load and static load, taking ultimate bearing capacity of the foundation under static load as the normalization parameters, the calculation results are normalized to obtain V/V_{ult}, V_c/V_{ult} and H_c/H_{ult}. Fig. 4 illustrates the simulation results of vertical and horizontal cyclic ultimate bearing capacity for traditional spudcans and bucket spudcans under different vertical loads. In general, the cyclic bearing capacity of bucket spudcan is higher than the traditional spudcan; the advantage of horizontal cyclic load is more obvious than that of vertical cyclic load.

As Fig. 4a shows, when the soil is damaged under the combined action of static load and cyclic load, the vertical static load on the foundation is different, and the corresponding vertical ultimate cyclic load is also different. As V/V_{ult} is around 0.3, the ultimate cyclic loads for both types are the maximum. That is, when the spudcan is under low static load, the foundation damage is mainly caused by the cyclic load; when the spudcan is under high static load, the foundation damage is mainly caused by the static load. The results are

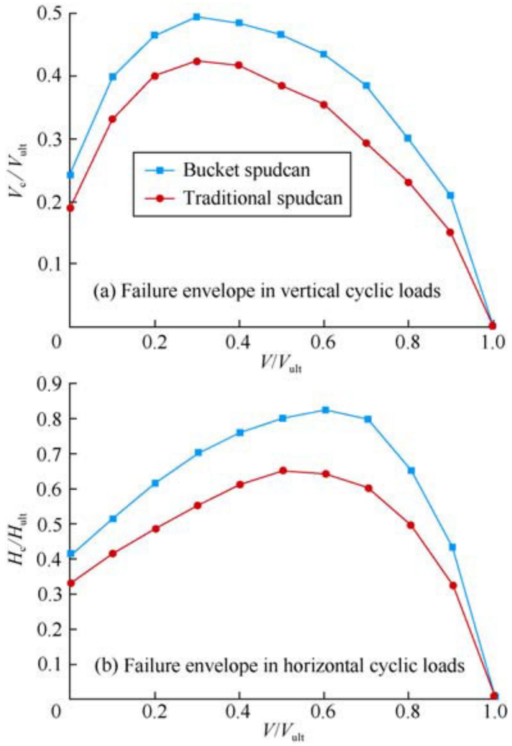

Fig. 4 Envelope of ultimate bearing capacity under vertical cyclic load and horizontal cyclic load for traditional spudcan and bucket spudcan

similar to the conclusions of references [17–19]. In addition, the calculation results also show that, in the determined cyclic loading conditions and other relevant conditions in the paper, the maximum vertical cyclic loads of bucket spudcan and traditional spudcan are 50% and 42% of the ultimate vertical static loads, respectively, and the numerical difference between them is about 14%.

As shown in Fig. 4b, when the foundation is under vertical static load, the calculated ultimate bearing capacity of traditional spudcans for horizontal cyclic load is significantly lower than the ultimate bearing capacity for horizontal static load, while for bucket spudcans, the decrease is smaller. Furthermore, under different vertical static loads, the corresponding horizontal cyclic loads on the foundation when the foundation is damaged are also different. As V/V_{ult} is 0.6 and 0.5, the ultimate bearing capacity for horizontal cyclic load for both types of spudcans is up to the maximum, respectively. And the ultimate bearing capacities of bucket spudcans and traditional spudcans for horizontal cyclic loads are 84% and 65% of their ultimate bearing capacities for horizontal static load, respectively, and the numerical difference between them is 22%. The results show that bucket spudcans have more advantages in horizontal bearing capacity than traditional spudcans, especially under cyclic load.

2 Advantages of bucket spudcans for offshore jack-up drilling platforms foundation

In this paper, the offshore jack-up drilling platform in the actual size is taken as the model. The force bearing performances of traditional spudcans and bucket spudcans in the real ocean storm conditions are analyzed comparatively. In this way, the advantages of bucket spudcans as the foundation of jack-up drilling platform are presented more obviously. The changes in rigidity of pile leg and bearing capacity of the platform are analyzed.

2.1 Numerical model

A finite element model of the platform is established based on the typical three-leg jack-up drilling platform of Bohai series (Fig. 5). The pile legs of the platform are distributed uniformly: distance (r) is 34.8 m, platform length (z) is 46.6 m, platform depth (h) is 5.5 m and length of pile legs (l) is 78.4 m. Geometries of the traditional circular spudcan and bucket spudcan are shown in Fig. 1. For the direction of environmental forces, the side of two legs is taken as the windward side.

Soil is the hard clay and the parameters are: undrained shear strength c_u=45 kPa, $c_u/(\gamma' D)$=0.64, kD/c_u=0, and cyclic shear strength of soil can be seen in references [20–22]. Ocean environmental loads are the typical values in the depth of 35 m in the Bohai area. The coupling combinations of wind, wave and current loads are calculated by software SACS. The environmental parameters are: wind speed of 32.47 m/s; wave height of 8.9 m (the average height of waves occurs 5 times per minute); current velocity of 155 cm/s at the ocean surface; current velocity of 115 cm/s at the ocean bottom; the highest water level of 4.15 m; the lowest water level of −1.06 m. The values above are the maximums appearing in average time of 50 a.

2.2 Comparison of rigidity

Offshore jack-up drilling platform rigidity (f)[23–25] is defined as the ratio of the actual moment at the leg bottom (M_r) to the moment (M_f) calculated by the theoretical assumption of complete fixed support at the leg bottom, which is expressed as:

$$f=\frac{M_r}{M_f}=\frac{K_r}{K_r+EI/L} \quad (6)$$

When the leg is fully fixed, f=1; when the leg is fully

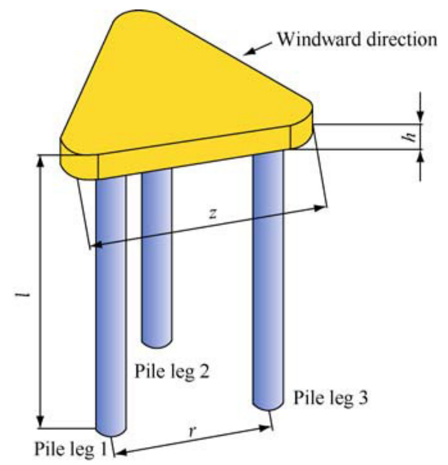

Fig. 5 Sketch for typical three-leg jack-up drilling platform

hinged, f=0; in general, 0<f<1. Studies show that restraint moment or rigidity is closely related to the platform size, soil properties, spudcan size and the loads.

Fig. 6 shows that the rigidities of three legs with the change of H/H_{ult}. When the foundation of platform is a traditional spudcan and a bucket spudcan respectively, the rigidity difference between them is relatively large, and the rigidity of the bucket spudcan is better than that of the traditional one. Generally, with the increase of horizontal load, the rigidity of legs shows decreasing trend. The leg rigidity decreases greatly from H/H_{ult}=0.4 for bucket spudcan and H/H_{ult}=0.25 for traditional spudcan. As to two types of spudcan, the rigidity for three legs of platform is both high, but the value is not the same. For the bucket spudcan, rigidity of Pile leg 1 changes from 0.95 to 0.72 with the increase of horizontal loads, while rigidity of Pile leg 2 and Pile leg 3 changes from 0.92 to 0.60. For the traditional spudcan, rigidity of Pile leg 1 changes from 0.78 to 0.56 with the increase of horizontal loads, while rigidity of Pile leg 2 and leg 3 changes from 0.75 to 0.47. The bucket spudcan has obvious superiorities, because the skirt structure can improve the rigidity of pile leg.

2.3 Comparison of bearing capacity

The platform response in storm load from environment loads is taken as the reference standard to compare the traditional spudcan and bucket spudcan. During SCAS calculation, storm load sub-coefficient is defined as n, which is increased gradually. The bearing capacities of traditional spudcan and bucket spudcan are analyzed according to n.

Fig. 7 shows the horizontal displacement (x) of the jack-up drilling platform under storm loads. When n<1, the horizontal displacement can be reduced by about 18% with the bucket spudcan compared with the traditional one. When n>1, the reduction of horizontal displacement is much more. The results indicate the bucket spudcan with the skirt structure not only improves the platform rigidity, but also improve the dynamic performance of the platform. For the overall capacity of the platform, the bucket spudcan increases n from 1.27 of traditional spudcan to 1.85, by 46%. This indicates that bucket spudcan can significantly increase the effective embedded depth of the foundation, transfer a part of loads to the deeper

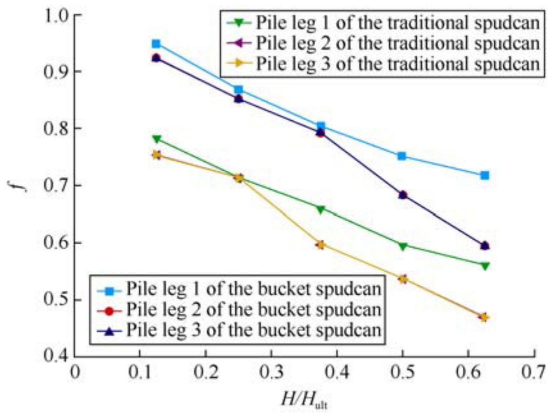

Fig. 6 Rigidity of pile legs

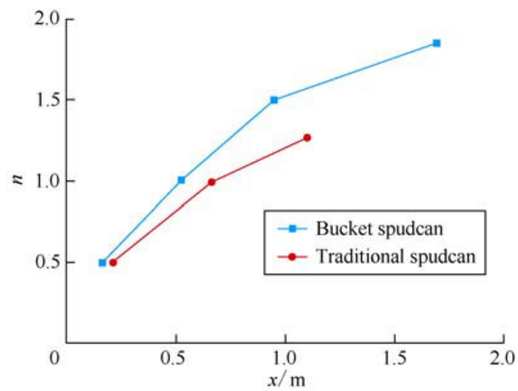

Fig. 7 Relationship between horizontal displacement and load coefficient

soil layers and improve the overall rigidity of the platform, which is consistent with the test results in reference [26].

For different load coefficients, the changes of moment at the leg bottom of traditional spudcan and bucket spudcan are analyzed. It is found that, in the same embedded depth of the foundation, the bucket spudcan foundation has more lateral area in contact with the soil, which can withstand higher loads compared with the traditional spudcan. Fig. 8 shows the moment at the leg bottom for two different spudcans with different n. It can be seen that, bucket spudcan with skirt structures enables the moment bearing capacity of platform leeward and windward legs to increase by 45%–55%, which also verifies the earlier conclusions. The test results from reference [26] also show that the bucket spudcan can provide much higher rigidity than the traditional one. According to the analysis above, during the initial stage of loading, the bucket spudcan has high rigidity and the leeward spudcan is similar to completely fixed support. With the increase of loading, the fixed support changes into rotation axis, which increases the moment bearing capacity of the whole platform.

3 Conclusions

By use of Swipe loading method and fixed displacement ratio loading method, the failure envelopes in the V-H, V-M and V-H-M spaces under the mode of composite loads as well as the failure envelopes in V-V_c and V-H_c spaces under cyclic loads for the bucket spudcan and traditional spudcan are plotted. So the ultimate bearing capacities of the two types of

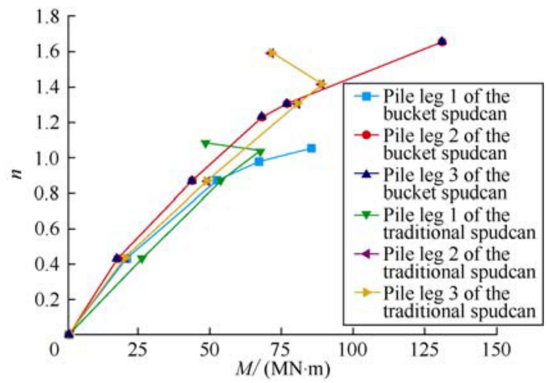

Fig. 8 Relationship between moment and load coefficient

spudcans are compared. Then the 3D finite element model of the three-leg jack-up drilling platform in the actual size is built. Under the conditions of limit storm dynamic load, the bearing capacities of bucket spudcans and traditional spudcans are compared, and the influence of different spudcan type on the leg rigidity and overall bearing capacity of the platform is analyzed in detail.

Theoretical study shows that the skirt system of bucket spudcans can increase the effective embedded depth, consequently improve the foundation fixation and the entire rigidity of the platform. It is found that the bearing capacity of the bucket spudcan for horizontal load and moment load is increased by at least 10% than that of the traditional spudcan, especially horizontal bearing capacity increasing by 20% under cyclic load. Under the action of limit storm load conditions including wind, wave and current, the entire bearing capacity of the typical jack-up rig in stiff clay is increased by about 46% with the bucket spudcan foundation compared to the traditional one.

Nomenclature

c_u—undrained shear strength of soil, kPa;
γ'—unit weight of soil, kN/m^3;
k—increasing rate of c_u with the depth of soil, kPa/m;
V—vertical static load, MN;
V_{ult}—ultimate vertical static load, MN;
H—horizontal static load, MN;
H_{ult}—ultimate horizontal static load, MN;
h_0—load transferring coefficient between horizontal load and vertical load;
M—moment, MN·m;
M_{ult}—ultimate moment, MN·m;
m_0—moment adjustment factor;
D—diameter of spudcan, m;
M^*—moment at reference point, MN·m;
w—height from foundation to reference point of loads, m;
α_1, α_2, α_3—correlation coefficients;
β_1, β_2—vertical load adjustment factors;
e_1, e_2—vertical load effect coefficients;
a, b, c, d—coefficients of elliptic curve equation;
V_c—ultimate vertical cyclic load, MN;
H_c—ultimate horizontal cyclic load, MN;
K_r—rotation rigidity of foundation, MN·m/rad;
EI—bending rigidity of pile leg, MN·m^2.

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