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Bearing behavior and accumulated rotation of modified suction caisson (MSC) in saturated sand under cyclic loading

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Abstract: Modified suction caisson is a new type of suction foundation for offshore wind power engineering. Model tests were carried out to investigate the variation of cumulative rotation angle and its influencing factors of the regular suction caisson (RSC) and modified suction caisson (MSC) under horizontal cyclic loading. The cyclic loading mode includes one-way cyclic loading and variable-amplitude cyclic loading. The experimental results showed that the cumulative rotation angle of the RSC and MSC under horizontal cyclic loading mainly occurs within the first 200 loading cycles. The cumulative rotation angle was found to increase with the increase of cyclic loading amplitude and the number of loading cycles. However, the increasing rate of cumulative rotation angle decreases with the increase of loading cycle number. The relationship between the cumulative rotation angle and the number of loading cycles can be well fitted by a power function. By using Leblanc method and Miner's rule, the cumulative rotation angle of the suction caisson foundation under long-term variable-amplitude cyclic loading was transformed into that under constant amplitude cyclic loading and then can be estimated. It was found that when the loading amplitude increases step by step, the predicted cumulative rotation angle of the RSC and MSC obtained by using the Leblanc method and Miner's law is slightly higher than the measured model test results, indicating that the sequence and amplitude of cyclic loading have a certain influence on the cumulative rotation angle of the suction caisson foundation. In addition, the influence of cyclic loading on the ultimate bearing capacity of suction caisson foundation was studied and it was found that the ultimate bearing capacities of the RSC and MSC after cyclic loading are higher than those before cyclic loading. The research results can provide a basis for the design of the suction caisson foundation of offshore wind power.

Keywords: modified suction caisson (MSC); cyclic loading; loading amplitude; cyclic loading sequence; cumulative rotation angle

1 Introduction

The foundation of the offshore wind turbine is subjected to long-term horizontal cyclic loading during the operation period, which results in the accumulation of pore water pressure in the soil and the reduction of soil strength[1]. This fact will eventually lead to cumulative rotation angle of the foundation, permanent deformation of the structure[2], and resonance phenomena[3]. If the tilt angle of the foundation exceeds the allowable value (generally $2^{\circ}-5^{\circ}$), the offshore wind turbine will stop working[4]. Therefore, it is necessary to clarify the cyclic bearing capacity and cumulative deformation characteristics of the foundation of offshore wind turbine to ensure the safe operation of the offshore wind turbines.

The suction caisson foundation has the advantages of cost-saving, construction convenience, and being reusable, and can be applied widely in the field of ocean engineering[5]. In recent years, suction caisson foundation has been applied to offshore wind power engineering. In order to improve the horizontal bearing capacity of the suction caisson foundation, Li et al.[6–7] proposed a type of modified suction caisson foundation (see Fig. 1). For this type of suction caisson foundation, the horizontal bearing capacity and bending moment bearing capacity are improved by increasing the contact area with soil based on the setting of the skirted structure on the top of the suction caisson foundation, and the ability of the suction caisson foundation to resist resonance is also enhanced.

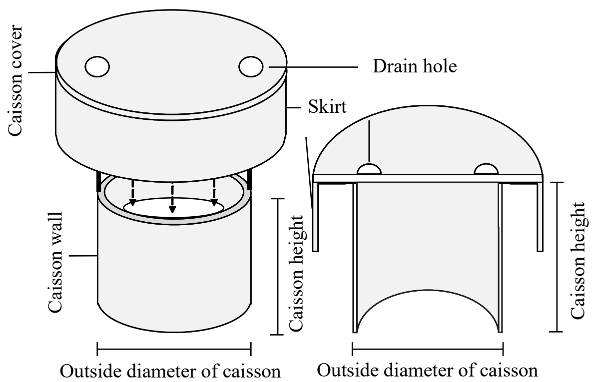

Fig. 1 Modified suction caisson foundation

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Nowadays, many researchers have carried out a series of studies on the horizontal cyclic loading characteristics of regular suction caisson foundation[8−11]. Zhu et al.[3] conducted the cyclic loading tests on the suction caisson foundation in loose dry sand. They found that the cumulative rotation angle of the suction caisson foundation increased with the increase of the number of cyclic loading and the amplitude of cyclic loading, while the number of cycles had no obvious effect on the stiffness during the unloading process. Cox et al.[12] presented that in the case of full drainage, the stiffness of the suction caisson foundation increased logarithmically with the increase of the number of cyclic loading. Nielsen et al.[13] found the drainage conditions had a significant influence on the test results while they conducted the cyclic loading tests on the suction caisson foundation in saturated dense sand under different loading frequencies. In addition, the response of the foundation was highly dependent on the loading frequency. The higher the loading frequency, the higher the excess pore water pressure would be generated in the soil, resulting in the larger cumulative rotation angle of the foundation.

The amplitude and frequency of cyclic loading acting on the foundation of the offshore wind turbine are often affected by water depth and wave height, so it is necessary to study the equivalence of cyclic loading under variable and constant loading amplitude, which can be used to truly reflect the actual loading condition of the foundation. At present, the rainflow-counting is mainly used to study the effect of irregular cyclic loading on the foundation of offshore wind turbine. That is, the cyclic loading with variable amplitude is decomposed into a series of cyclic loading with constant amplitude for analysis[14]. However, the bearing characteristics of the suction caisson foundation under different loading sequences of cyclic loading with variable amplitude need to be further studied.

Many studies on the pile foundation have been carried out. Lin et al.[15] used the strain superposition method based on damage relationship[16] to calculate the cumulative horizontal displacement of the pile under cyclic loading with variable amplitude, but the number of cyclic loading was only 50, which could not reflect the long-term cyclic bearing characteristics of the foundation. Peralta[17] conducted the variable amplitude cyclic loading tests with 45 000 cycles, and found that this method of Lin et al.[15] would underestimate the cumulative displacement of pile foundation. Through model tests, Byrne et al.[18] found that the cumulative rotation angle of the pile was independent of the sequence of cyclic loading with different amplitudes, and the cumulative rotation angle of the pile under cyclic loading of variable amplitude can be analyzed by linear superposition using Miner's rule[19]. In addition, Abadie et al.[20] found that the response of the pile under cyclic loading with multi amplitude was significantly nonlinear, especially when large plastic deformation occurred. However, Wang et al.[21] calculated the permanent cumulative rotation angle of the pile during a 39-hour storm according to Miner's rule, and found that the cumulative rotation angle of the pile mainly depended on soil strength, loading characteristics, and preloading history. They considered that the effect of nonlinear irregular cyclic loading on the permanent cumulative rotation of the piles was limited.

In this work, a self-developed loading system for the foundation of the offshore wind turbine was used to study the variation of cumulative rotation angle of regular and modified suction caisson foundations in saturated sand under horizontal cyclic loading. The loading methods include one-way cyclic loading, cyclic loading with amplitude increasing step by step and cyclic loading with amplitude decreasing step by step.

2 Model test

2.1 Testing apparatus

Figure 2 shows the self-designed loading system for the model test, in which the horizontal load is applied by the electro-hydraulic servo actuator, and the loading height and direction can be adjusted. LVDT displacement sensor and force sensor are installed inside the actuator to measure the displacement of the loading point and the load on the foundation during the loading process. The goniometer is fixed on the foundation roof to measure the rotation angle of the foundation during the test. Figure 3 is the schematic diagram of test device. The diameter of the cylindrical model box is 1.0 m, and the height is 0.5 m. The dimension of this model box can eliminate the effect of boundary conditions. The drainage system is set at the bottom of the model box, and a 6 cm thick gravel cushion is used as the drainage layer to ensure that the water level in the model box drops evenly in the process of drainage so that the sand foundation can be consolidated uniformly. A geotextile layer is laid on the cushion as the filter layer to prevent the sand particles from being taken away by the water flow during the drainage of the model box. Figure 4 shows the regular and modified suction caisson foundation models made of stainless steel. The Dimensions and self-weights of these two suction caisson foundation models are listed in Table 1.

2.2 Suction penetration device

Figure 5 is the schematic diagram of the suction penetration device for the suction caisson foundation. Suction caisson foundation penetrates into the soil to a certain depth under its own weight firstly; then air and water in the foundation are extracted by peristaltic pump. A pressure

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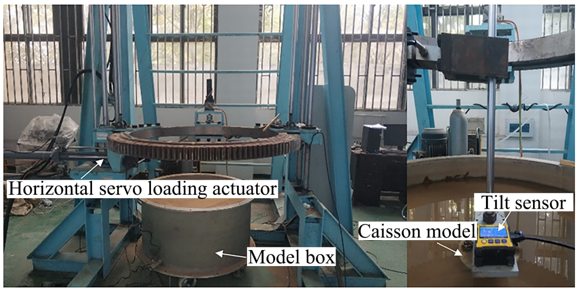


Fig. 2 Loading system of model test

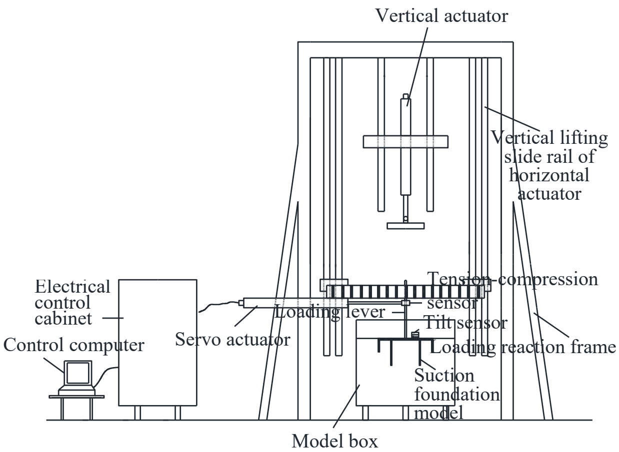


Fig. 3 Schematic diagram of test setup

Fig. 4 MSC model and RSC model

Table 1 Dimensions and self-weight of caisson models

Foundation model	Self-weight /N	Diameter /mm	Height /mm	Width /mm	Height /mm	Thickness of bearing platform /mm
Regular suction caisson foundation	23.5	160	150	—	—	10
Modified suction caisson foundation	40.2	160	150	30	50	10

difference (suction) is formed between the inside and outside of the foundation and the foundation penetrates into the seabed further under the action of suction.

2.3 Sand for test

The sand used in the test is Fujian fine sea sand, and its physical parameters are shown in Table 2. The relative density of the test sand foundation is 65%.

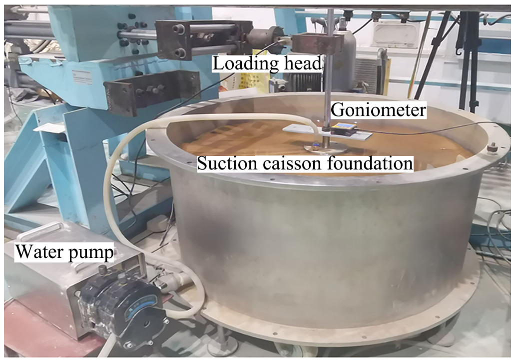


Fig. 5 Suction penetration device

Table 2 Parameters of test sand

Coefficient of uniformity	Coefficient of curvature	Saturated unit weight /(kN • m^{-3})	Specific density	Maximum void ratio	Minimum Void ratio	Relative density
2.2	1.13	20.2	2.63	0.95	0.61	65

2.4 Testing process

Firstly, the horizontal monotonic loading tests were carried out to obtain the horizontal ultimate bearing capacities of regular and modified suction caisson foundations. The loading height in the test was 2.5 times the diameter of the foundation. The displacement-controlled loading method was adopted in horizontal monotonic loading tests. The offshore environment was dominated by local drainage[22]. Therefore, the loading rate of 0.3 mm/s was used to simulate the partial drainage state in all tests. Table 3 gives the horizontal ultimate bearing capacity of regular and modified suction caisson foundations, H_{MAX}.

The sinusoidal loading was adopted to carry out the cyclic loading. The corresponding amplitude was determined by the method proposed by LeBlanc et al.[23], as shown below:

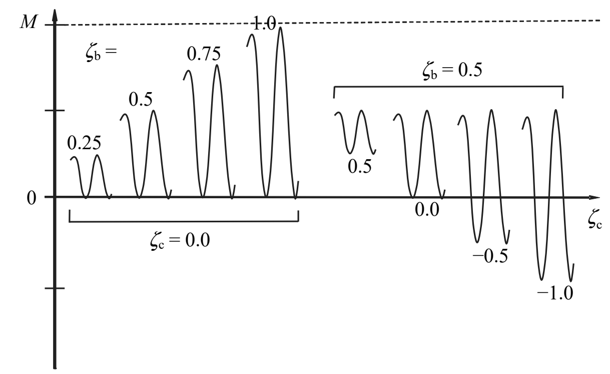
$$\zeta_b = \frac{M_{max}}{M_R}, \quad \zeta_c = \frac{M_{min}}{M_{max}} \tag{1}$$

where M_R is the ultimate bearing moment of the suction caisson foundation under horizontal monotonic loading; M_{min} and M_{max} are respectively the minimum and maximum bending moments acting on the suction caisson lid during cyclic loading; ζ_c represents the direction of cyclic loading. When $\zeta_c = 1$, the loading method is monotonic loading; when $\zeta_c = 0$, the loading method is one-way cyclic loading; and when $\zeta_c = -1$, the loading method is symmetric bidirectional cyclic loading. It can be seen from Eq. (1) that ζ_b and ζ_c are dimensionless parameters. Figure 6(a) shows the forms of cyclic loading under different conditions of ζ_b and ζ_c, where M is the cyclic bending moment load on the suction caisson foundation. Figure 6(b) shows the schematic diagram of some parameters, including the lateral displacement y at the height h equal to 2.5 times the diameter of the foundation

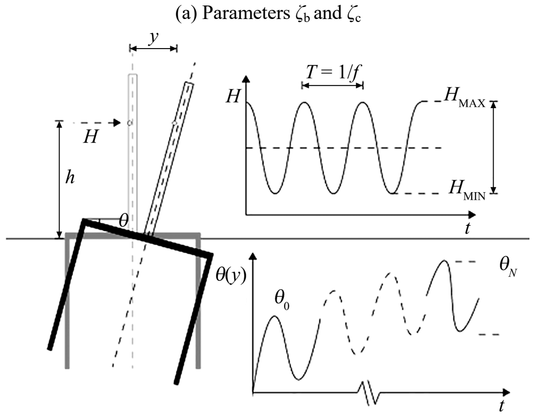
Table 3 Loading form of model test (monotonic loading and cyclic loading)

Stage	No.	Loading method	Foundation type	Loading description
1—Monotonic loading test (displacement-controlled)	I-H	Loading rate 0.3 mm/s	Regular	H_{MAX} = 32.5 N
	IO-H	Loading rate 0.3 mm/s	Modified	H_{MAX} = 37.0 N
2—One-way cyclic loading test (load-controlled)	I-CH1	Loading times 1 000	Regular	ζ_b = 0.49
	I-CH2	Loading times 1 000	Regular	ζ_b = 0.56
	I-CH3	Loading times 1 000	Regular	ζ_b = 0.62
	I-CH4	Loading times 1 000	Regular	ζ_b = 0.74
	I-CH5	Loading times 1 000	Regular	ζ_b = 0.81
	IO-CH1	Loading times 1 000	Modified	ζ_b = 0.47
	IO-CH2	Loading times 1 000	Modified	ζ_b = 0.62
	IO-CH3	Loading times 1 000	Modified	ζ_b = 0.70
	IO-CH4	Loading times 1 000	Modified	ζ_b = 0.86
3—Cyclic sequential loading test (force loading)	I-MCH1	Loading times 1 000—500—250	Regular	ζ_b = 0.52 → 0.66 → 0.80
	I-MCH2	Loading times 500—1 000—250	Regular	ζ_b = 0.65 → 0.52 → 0.80
	I-MCH3	Loading times 250—1 000—500	Regular	ζ_b = 0.79 → 0.52 → 0.65
	IO-MCH1	Loading times 1 000—500—250	Modified	ζ_b = 0.62 → 0.70 → 0.85
	IO-MCH1	Loading times 500—1 000—250	Modified	ζ_b = 0.70 → 0.61 → 0.85
	IO-MCH1	Loading times 250—1 000—500	Modified	ζ_b = 0.84 → 0.62 → 0.72

Note: ζ_b is the magnitude of cyclic loading.



(a) Parameters ζ_b and ζ_c



(b) Definition of parameters such as cumulative rotation angle

Fig. 6 Definition of cyclic loading parameters

under cyclic loading, the rotation angle θ of the foundation body under cyclic loading, and the applied cyclic load H, where H_{MAX} and H_{MIN} are the maximum and minimum cyclic loads, respectively. The cycle period T is the reciprocal of frequency f. Moreover, θ_0 is the cumulative rotation angle of the foundation at the end of the first cyclic loading, θ_N is the cumulative rotation angle of the foundation at the end of the last cyclic loading, and t is the action time of cyclic loading. The conditions of cyclic loading tests are shown in Table 3. The frequency of cyclic load was 0.2 Hz[24–25]. The test results of Foglia[26] showed that the cumulative rotation angle of the suction caisson foundation under cyclic loading was mainly concentrated in the first 300 cycles, and the increment of cumulative rotation angle was small after 1 000 cycles. Therefore, the number of cyclic loading in the test was selected as 1 000 cycles.

3 Results and discussions

3.1 Horizontal ultimate bearing capacity

In this study, the foundation is assumed to be a rigid body without considering the deformation of the foundation itself. In order to make the model test results better applied to practical engineering, The model test data are all were normalized to eliminate the scale effect.

Figure 7 shows the load–displacement curves of regular and modified suction caisson foundations under horizontal monotonic loading. In the initial stage of loading, the horizontal load on the foundation increases rapidly with the increase of lateral displacement. Then the foundation enters the plastic deformation stage, the increasing rate of horizontal load gradually decreases, and finally tends to a constant value. At this time the horizontal is taken as the ultimate bearing capacity of the foundation[27]. $F/(2R^3\gamma')$ is used to conduct normalization treatment on the ultimate bearing capacity, where F is the horizontal load on the foundation, R is the radius of the foundation, and γ' is the effective weight of soil. The normalized ultimate bearing capacity of the modified suction caisson foundation is 3.54 and that of the regular suction caisson

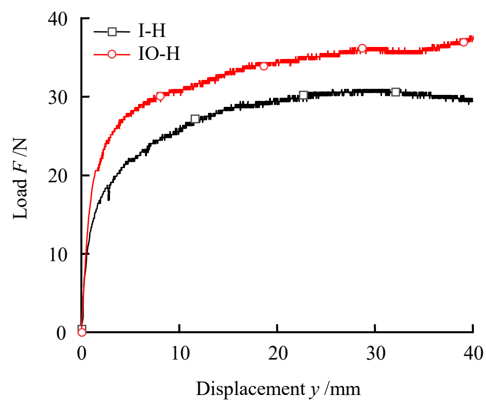


Fig. 7 Curves of horizontal load with displacnemnet

foundation is 2.97. The horizontal ultimate bearing capacity of the modified suction caisson foundation is 19.3% higher than that of the regular suction caisson foundation.

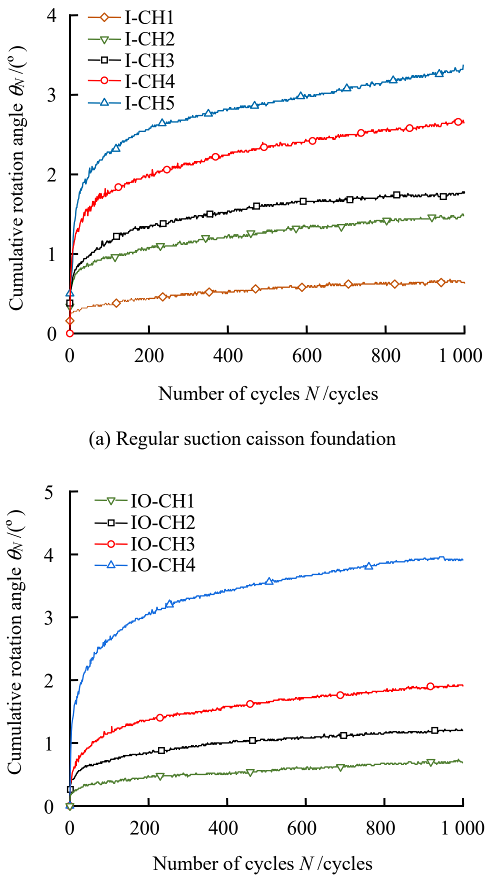
The reason why the bearing characteristics of the modified suction caisson foundation are better than that of the regular suction caisson foundation is that the modified structure enlarges the top area and side area of the foundation, which then increases the frictional resistance and soil resistance between the foundation and soil, and significantly improves the bearing capacity of the foundation. On the other hand, the stiffness of the skirted suction caisson foundation is significantly higher than that of the regular suction caisson foundation, which effectively reduces the lateral displacement and cumulative deformation of the foundation.

In addition, some numerical simulation studies showed that in the ultimate state, the earth pressure acting on the modified suction caisson foundation was much greater than that acting on the regular suction caisson foundation at the same depth, indicating that the horizontal ultimate bearing capacity of the foundation can be effectively improved by adding the skirted structure[28].

3.2 Variation of cumulative rotation angle

Figure 8 presents the variation of the cumulative rotation angle of regular and modified suction caisson foundations under different amplitudes of cyclic load. The cumulative deformation induced by cyclic loading grows significantly in the first 200 cycles. In addition, the influence of 1 000 cycles of low-amplitude cyclic loading is very small, while the influence of a few cycles of high-amplitude cyclic loading could exceed that of thousands of cycles of low-amplitude cyclic loading.

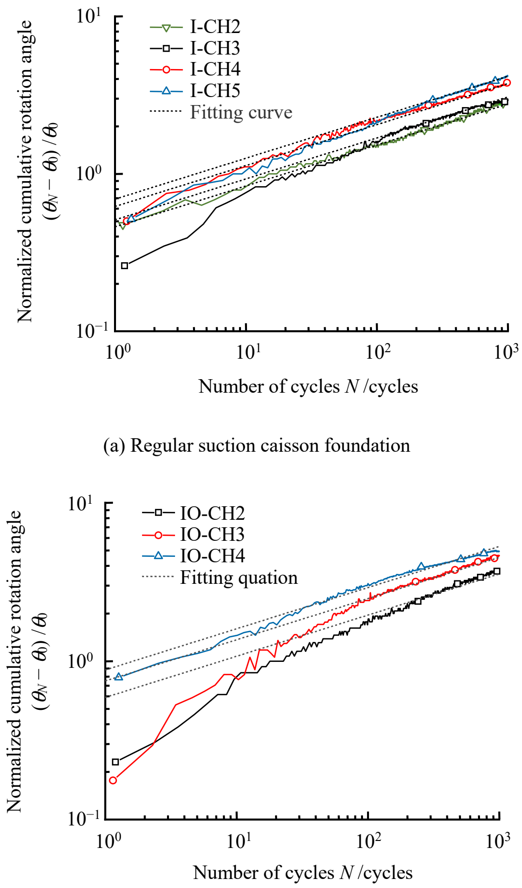
In the test, the pressure sensor was installed on the top of the foundation to measure the change of pore water pressure inside the foundation during loading. The results showed that the pore water pressure inside the foundation was small under the frequency and amplitude of the cyclic load used in this work. Therefore, the influence of the cumulative dissipation of pore water pressure on the bearing characteristics of the foundation under cyclic loading can be ignored.



(a) Regular suction caisson foundation

(b) Modified suction caisson foundation

Fig. 8 Curves of cumulative rotation angle with cycle number of the RSC and MSC under one-way cyclic loading



(a) Regular suction caisson foundation

(b) Modified suction caisson foundation

Fig. 9 Curves of normalized cumulative rotation angle with cycle number of the RSC and MSC under one-way cyclic loading

The cumulative rotation angle was normalized, and meanwhile, the number of cycles was expressed in a logarithmic form. The relationships between the normalized cumulative rotation angle and the number of cycles are shown in Fig. 9. In each horizontal cyclic loading with a given amplitude, the cumulative rotation angle of the foundation rises with the increase of the number of cycles, but the increasing rate declines gradually. This is mainly because the sand beside the foundation gradually became dense, and the stiffness of soil gradually increases as well under cyclic loading. In this work, the cumulative rotation angles of the regular and modified suction caisson foundations in sand under long-term cyclic loading of different amplitudes were predicted by using the model proposed by LeBlanc et al.[23]:

$$\theta_N = \theta_0 + \Delta\theta(N), \frac{\Delta\theta(N)}{\theta_s} = T_b(\zeta_b)T_c(\zeta_c)N^a \quad (2)$$

where a is a constant; θ_s is the cumulative rotation angle of the foundation in the monotonic loading tests. In the Eq. (2), θ_s is equal to θ_0; $\Delta\theta(N)/\theta_0$ is the normalized cumulative rotation angle of the foundation subjected to N cycles of cyclic loading, and $\Delta\theta(N)=\theta_N-\theta_0$; and T_b and T_c are the normalized functions, where T_b is considered to be only related to the cyclic load amplitude ratio ζ_b. The formula of the regular suction caisson foundation T_b is obtained by fitting as

$$T_b = 0.84\cdot\zeta_b^{1.1} \quad (3)$$

T_b for the modified suction caisson foundation is

$$T_b = 1.164\cdot\zeta_b^{1.35} \quad (4)$$

For one-way cyclic loading, T_c is always equal to 1. It can be seen that T_b would increase with the increase of ζ_b during one-way cyclic loading.

Figure 10 illustrates the variation of the parameters of T_b. D_r represents the relative density of sand. The formulas proposed by Vicent et al.[25] and Foglia et al.[29] were also compared with the formula proposed in this study, as shown in Fig. 10. Vicent et al.[25] used the saturated sand with a relative density D_r = 29%, and Foglia et al.[29] studied the saturated sand with a relative density D_r = 89%. The relative density of saturated sand used in this test was 65%. Through comparative analysis, it showed that T_b was significantly affected by the relative density of sand, and its value increased gradually with the increase of the relative density of sand. In addition,

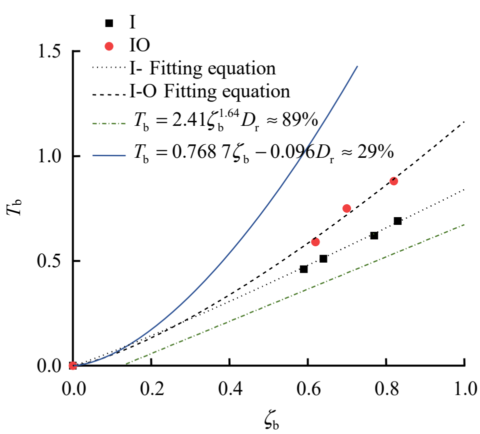


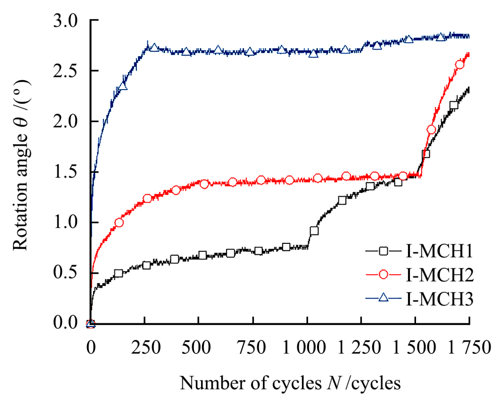
Fig. 10 Variation of the parameters of T_b

Abadie et al.[30] found that T_b also depended on the change of soil particle size. The reason why the T_b of the modified suction caisson foundation was higher than that of the regular suction caisson foundation is that the initial rotation angle of regular suction caisson foundation is too large caused by the adoption of suction penetration.

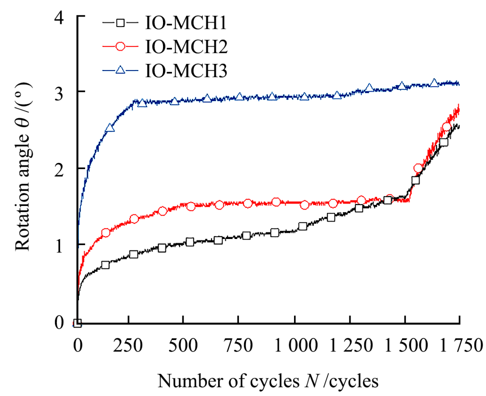
3.3 Effect of the sequence of cyclic loading

The amplitude and frequency of the cyclic load on the suction caisson foundation of offshore wind turbines often change during operation. The existing studies usually simplified the irregular marine environmental load as the continuous cyclic load with constant amplitude. Model tests were carried out to investigate the variable-amplitude effect on the cyclic bearing behavior of the MSC and RSC. Each test includes three kinds of cyclic loading forms: (1) 1 000 cycles of loading with low loading amplitude; (2) 500 cycles of loading with medium loading amplitude and (3) 250 cycles of loading with high loading amplitude. Table 4 gives the loading sequences of each test.

Figure 11 shows the variation of rotation angle of regular and modified suction caisson foundations under different amplitudes of cyclic load. As the load amplitude increases, the cumulative angle of the foundation increases significantly. Compared with the results of one-way cyclic loading tests, when the suction caisson is first subject to 1 000 cycles of loading with low loading amplitude,



(a) Regular suction caisson foundation



(b) Modified suction caisson foundation

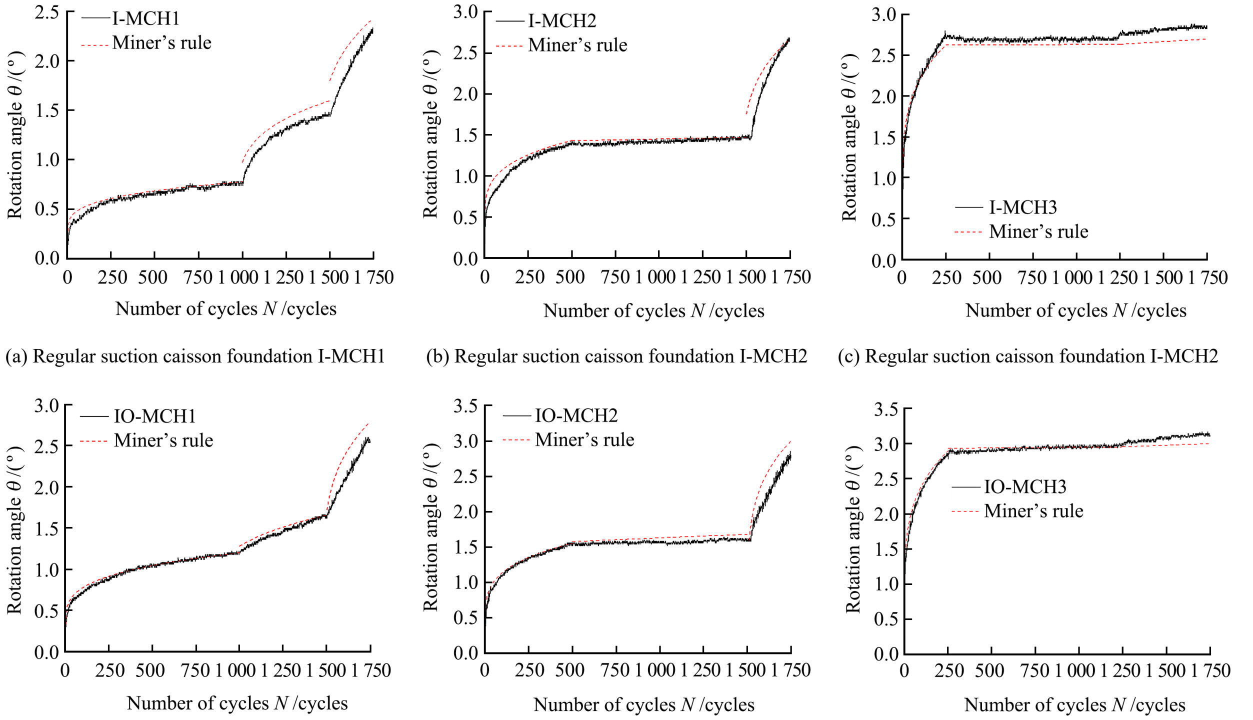
Fig. 11 Effect of cyclic loading sequence on rotation angle of suction caisson foundation

the final accumulated rotation is lower than that for the suction caisson which is first subject to 500 cycles of loading with medium loading amplitude or 250 cycles of loading with high loading amplitude. However, after experiencing 250 cycles of high amplitude cyclic loads first, the cumulative turning angle generated by low amplitude cyclic loads can be neglected, which indicates that the bearing capacity of the foundation has been improved after cycles.

In addition, Fig. 11 also shows that the sequence of cyclic loading has a certain influence on the cumulative rotation angle of suction caisson foundations. The cumulative rotation angle of the suction caisson foundations that is first subjected to a larger cyclic load would be greater than that of the suction caisson foundations that are first subjected to a smaller cyclic load. In all the tests, the order of rotation angle is I-MCH3>I-MCH2>I-MCH3, and IO-MCH3>IO-MCH2>IO-MCH1, which indicates that the cumulative rotation angle when the cyclic load is arranged in ascending order is lower than that when the cyclic load is arranged in descending order. This is because when the amplitude of the initial load is small, the sand beside the foundation would be denser under loading.

3.4 Application of Miner's rule

Fig. 12 gives the accumulated rotations with the loading cycle number of the MSC and RSC under variable-amplitude cyclic loading and the predicted accumulated rotations by using the Miner's rule. In this work, the regular and modified suction caisson foundations were linearly superposed by using the method proposed by LeBlanc et al.[23] and the Miner's rule[19].



(a) Regular suction caisson foundation I-MCH1 (b) Regular suction caisson foundation I-MCH2 (c) Regular suction caisson foundation I-MCH2

(d) Modified suction caisson foundation IO-MCH1 (e) Modified suction caisson foundation IO-MCH2 (f) Modified suction caisson foundation IO-MCH3

Fig. 12 Comparison of the rotation angle curves of the suction caisson foundation under the variable-amplitude cyclic loading with the results calculated by Miner's rule

The illustration of Miner's rule is given in Fig. 13. The cumulative rotation angle θ_a generated by the N_a cyclic loading with an amplitude of A can be equivalent obtained by the cumulative rotation angle generated by the cyclic load with an amplitude of B after N_b^0 equivalent cycles. The cumulative rotation angle arising from the cyclic load that increased step by step thus can be calculated while maintaining the cumulative rotation angle in the previous load history. The cumulative rotation angle of the foundation generated by the cyclic load with amplitude A can be calculated using Eq. (5):

$$\Delta\theta_a / \theta_s = (T_b T_c)_a \times N_a^a \quad (5)$$

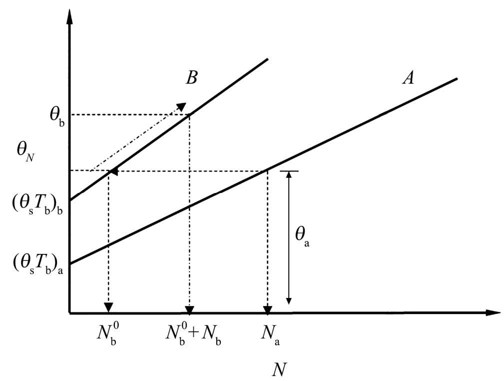


Fig. 13 Illustration of Miner's rule

where $\Delta\theta_a / \theta_s$ is the normalized cumulative rotation angle of the foundation after N_a cycles of the cyclic loading with A amplitude. The number of cycles required to make $\Delta\theta_a / \theta_s$ equivalent to that under the cyclic loading with B amplitude is

$$N_b^0 = \left(\frac{\Delta\theta_a}{(\theta_s T_b T_c)_b} \right)^{1/a} \tag{6}$$

Then, after the end of the cyclic loading with amplitude A, the cumulative rotation angle $\Delta\theta_b$, induced by N_b cycles of the cyclic loading with amplitude B is calculated by Eq. (2):

$$\Delta\theta_b = (\theta_s T_b T_c)_b \times \left(N_b^0 + N_b\right)^a \tag{7}$$

Finally, the total cumulative rotation angle of the foundation is obtained as

$$\theta_b = \Delta\theta_b + \max\left[\theta_{0,a}, \theta_{0,b}\right] \tag{8}$$

In the above Eq. (7), θ_s is taken as θ_0 in the cyclic loading tests with constant amplitude. The superposition phenomenon under cyclic loading with variable amplitude indicates that the growth of cumulative rotation angle of suction caisson foundation highly depends on the initial rotation angle accumulated in the previous load history.

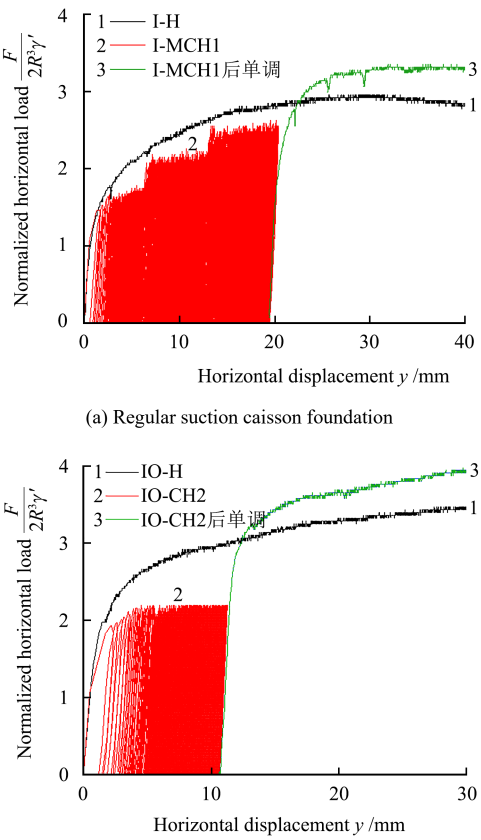
From Fig. 12, it can be noted that the predictions of the cumulative rotation angle of the foundation by Miner's rule are slightly higher than the test results, mainly because the disturbance effect caused by cyclic load on sand is ignored by Miner's rule. In addition, the final cumulative rotation angle generated by the progressively descending cyclic loading is mainly controlled by the cyclic load with high amplitude, and the effect of 250 cycles of high amplitude cyclic loads tends to require thousands of cycles of low-amplitude cyclic loads to be equivalent. Therefore, the cyclic load with high amplitude has a more important influence on the cumulative rotation angle of the foundation of the offshore wind turbine under cyclic loading.

3.5 Monotonic bearing capacity

The monotonic loading tests on the suction foundation caisson after cyclic loading were carried out to study the effect of cyclic loading on the bearing capacity of the foundation. As shown in Fig. 14, after cyclic loading, the horizontal monotonic bearing capacities of the regular and modified suction caisson foundations were higher than those without cyclic loading, which was consistent with the previous results of pile foundation presented by Abadie et al[31]. The main reason is that the sand around the foundation becomes dense under cyclic load. This is mainly because the sand around the foundation becomes dense under cyclic loading.

4 Conclusions

(1) Under cyclic loading, the cumulative rotation angle of the foundation mainly occurs in the first 200 cycles. The cumulative rotation angle rises with the increase of the amplitude of cyclic loading and the number of cyclic loading (cycles), but the growth rate decreases with the increase of the number of cyclic loading. The long-term cumulative rotation angles of regular and modified suction caisson foundations under cyclic loading with different amplitudes can be predicted by the power function.



(a) Regular suction caisson foundation

(b) Modified suction caisson foundation

Fig. 14 Monotone bearing capacity of suction caisson foundation after cyclic loading

(2) Based on LeBlanc method and Miner's rule, the situation that the cumulative rotation angle of foundation under long-term variable-amplitude cyclic loading was converted into the one under equal amplitude cyclic loading was analyzed and the cumulative rotation angle of foundation is predicted. The results showed that the sequence of cyclic loading had a certain effect on the predicted cumulative rotation angle of the foundation. When the amplitude of cyclic load increased step by step, the predicted cumulative rotation angle of the foundation was slightly higher than the measured value.

(3) After cyclic loading, the horizontal monotonic ultimate bearing capacity of regular and modified suction caisson foundations was improved to some extent compared with that before cyclic loading. The main reason is that the sand beside the foundation became dense under cyclic loading.

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