Large-scale experimental investigation of the installation of suction caissons in silt sand

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Abstract:

Offshore wind power is a rapidly growing area of electricity in China. In the present paper, interaction mechanisms between the caisson for wind turbines and saturated silt sand are investigated with laboratory tests based on two different installation methods, jacking installation and suction installation. For the jacking installation process, the results indicate that the soil pressures inner and outer the skirt of the caisson vary with a similar feature and the magnitudes of the two are nearly balanced. The tip resistance plays a key role in the total jacking installation resistance. This paper examines the predictive performance of q_c method and API approach for jacking installation resistance. It is demonstrated that the q_c method provides better predictions. The resistance coefficients are recommended. For the case of suction installation, however, the changes of soil pressures inner and outer the skirt are contrasting. Specifically, the inner pressure and tip resistance fall dramatically, but the outer pressure increases when suction is applied. Seepage effect is found to be an important mechanism for the installation of suction caisson. The reduction ratios of the inner friction and tip resistance follow a power-function with the normalized suction. Based on the test results, a prediction method for the required suction has been developed and evaluated.

Key words: soil pressure, tip resistance, installation resistance, seepage effect, required suction, resistance reduction

1. Introduction

As a clean and renewable power, wind power is regarded as a promising choice to decrease the use of diesel fuel as well as to solve global energy shortages. In China, wind power has been developed with an accelerating rate in the past ten years. The installed wind-capacity of China had achieved 75300 MW by the end of 2012, which accounted for about 27% of the total wind-capacity in the world. Most of the generated power in China is from the inland areas except 390 MW from the offshore area, where has been recognized as an important area to develop wind power. At present, there are two offshore wind farms in operation in China and more offshore wind farms are in plan. One is Shanghai Donghai Bridge Offshore Wind Farm and the other is Jiangsu Rudong Offshore Wind Farm. The foundations adopted in the former farm are pile groups with concrete caps [1]. Each foundation consists of eight steel pipe elevated piles, with 85m in length, 1.7m in diameter and about 0.03m in thickness. In the latter wind farm, mono-piles are chosen, with about 50m in length and 5m in diameter. For the foundation of the wind turbines, two types of foundation are most widely used in the two farms. One is mono-piles and the other is jackets. However, one major disadvantage of them is high expense, which restrains their commercial scale in offshore wind power industry in China.

To decrease the installation cost of the foundation for wind turbines, a type of foundations for offshore platforms, called suction caissons, has recently been developed and used because of its advantages of economic feasibility and environment-friendly work principles [2-6]. Since the first suction caisson was installed for a 3MW wind turbine in 2002 Denmark, more and more efforts have been made on suction caissons for wind turbines [7-10]. For example, a large composite bucket foundation CBF-3-150 (with a 30m diameter and 7m skirt length) developed by Tianjin University for 3.0 MW wind turbine was installed in 2010 Jiangsu, China. Nevertheless, one challenge for suction caissons is how to penetrate into the seabed deep enough to keep the required bearing capacity and stability, especially in sand, where the penetration resistance is quite large [11-12]. To solve this problem, a suction technology is usually employed within the skirt compartment to produce an increased driving force in addition to the self-weight of the caisson. Additionally, the suction will also generate hydraulic gradients in sand, which may reduce the installation resistance. However, attention must be paid when the suction is used, because a high hydraulic gradient will cause piping in the sand within the compartment, which may lead to installation failure [13-14].

To investigate the installation of suction caissons, a number of studies have been completed [15-18]. Most of the

previous studies stressed the algorithms to calculate the penetration resistance and required suction. Nevertheless, available experiences on the installation are still very limited due mainly to the lack of enough special field and laboratory observations. Furthermore, the soil-skirt interaction and seepage effect during installation have not been investigated thoroughly yet. Consequently, in spite of their promising prospect of engineering application, the suction caissons for wind turbines developed rather slowly so far [1]. As the soils in the sites for many present and potential offshore wind farms in China are silt sand, the research on the installation of suction caissons in this soil is reasonable.

The main objectives of the present study are to investigate (1) the interaction between the sand and skirt during both jacking installation and suction installation conditions; (2) the mechanism of resistance reduction due to seepage; (3) the seepage effect and calculation methods for the required suction. The arrangement of this paper is as follows. In section 2, the materials, the equipment and the approach used for the experiment are presented. The test and predicted results of the jacking installation tests are presented in section 3. The results of the suction installation tests, comparisons with the previous studies and discussions are in section 4. The conclusions of the paper are given in section 5.

2. Materials, equipment, and procedures

2.1. Materials and equipment

The silt sand used in the experiment is similar to that of a proposed wind farm site off the east coast of Tianjin City. A grading curve of the sand is shown in Fig. 1. It can be seen that the sand is mainly composed of 76% fine sand with the grain size in a range of 0.075-0.25mm, and 20% silt with the grain size in a range of 0.005-0.075mm. The sand was evenly rained into the testing platform ($4\text{m} \times 4\text{m} \times 2.5\text{m}$), and each layer was prepared elaborately with a thickness of 0.1m. After filling, the sand was saturated by elevating the water with a water supply and drainage system with a velocity of 0.5m/day. The velocity is slow, to avoid uneven seepage or piping in the sand. And then the sand bed was fully vibrated with a vibrating rod to release the gas in it and left for static settlement for two months. The final form of the sand bed is about 2.0m in depth overlaid by 0.15m fresh water to keep the sand saturated during the tests. Four cone penetration tests (CPT) were randomly conducted in the sand bed and the cone resistance q_c records are shown in Fig. 2. The diameter of the cone used is 35.7mm and the penetrating rate is 0.2cm/s. Some other soil parameters of the sand bed, such as the saturated density, effective internal friction angle, saturated moisture content, void ratio and relative

density were tested as well in the soil mechanics laboratory, and the values are 1900kg/m^3 , 30° , 0.26, 0.65 and 0.63, respectively.

The used caisson has an internal diameter (D) of 1.5m and a skirt height (L) of 0.5m. Thickness of the skirt is 0.01m. The caisson is made of steel except the top lid which is made of transparent plexiglass. The tip of the caisson is a circular flat base. The detailed dimensions of the caisson are listed in Table 1. Six soil pressure sensors with a diameter of 0.02m are embedded in the skirt wall of the caisson used for measuring the soil pressures acting on the skirt during installation. As shown in Fig. 3, three of them are toward inside and the remaining three are toward outside, and the sensors with the same subscripts are in the same heights from the skirt tip. The distances from the skirt tip to the soil pressure sensors are 0.06, 0.18, and 0.30 m, respectively. Moreover, three micro soil pressure sensors with a diameter of 0.0095m are embedded in the skirt tip equidistantly, to measure the tip resistance acting on the annulus. The micro soil pressure sensors are installed towards the underlying sand, and named T-1, T-2, and T-3 respectively. The instrumentation can provide a direct recognition on the tip resistance.

There are three valves on the top lid of the caisson, which are used for pumping, gas exit in the self-weight penetration stage, and suction transducer, respectively (see Fig. 4a). In the jacking installation tests, a hydraulic cylinder provides the reaction forces. The hydraulic cylinder is fixed on the steel reaction beam attached to the side walls of the platform (see Fig. 4b). The stable suction in the installation process is accomplished with an adjustable suction system, which consists of a vacuum pump, a vacuum regulating reservoir and several global valves. The vacuum regulating reservoir is set in the middle of the vacuum pump and the caisson through reinforced plastic pipes to provide a stable suction acting on the caisson, as shown in Fig. 4(c).

2.2. Procedures

Five tests were completed in this study: Ja-Inst-1, Ja-Inst-2, Su-Inst-3, Su-Inst-4 and Su-Inst-5, which could be classified into two kinds (see Table 2). The first two (Ja-Inst-1, Ja-Inst-2) are the jacking installation tests; Su-Inst-3, Su-Inst-4 and Su-Inst-5 are the suction installation tests. A summary of the test conditions and the corresponding hydraulic rates in the jacking installation tests is listed in Table 2. The purpose of the jacking installation tests is threefold. Firstly, it provides the unreduced penetration resistance under no pore water flow, which is relevant to the self-weight penetration. Secondly, the results of the resistance-displacement relation are compared with those of the

suction installation tests to study the reduction effect, which is the base of the suction installation resistance calculation [12]. Thirdly, the jacking test results can offer a reference for the case of caisson installation in sand with clay layers, where the pore water flow can be prevented [11]. The purpose of Ja-Inst-2 is to study the effect of the penetration rates on the resistance.

Either kind of the tests is further composed of two different stages (the intermediate stage between the two for preparation is not included). For the jacking installation, in the first stage the caisson sinks into the sand bed till reaching the stable condition under self-weight. The valve for gas exit keeps open so the water and gas inside is released. The hydraulic jack is then added from the hydraulic cylinder and reaction beam. For the suction installation, the first stage is similar as the jacking installation; in the second stage, the gas exit valve is turned off and the adjustable suction system is then turned on to pump the gas and water out of the caisson. In Su-Inst-3, the suction was applied in five steps and the pressure is stable in each step with the values of 2.0kPa, 3.7kPa, 5.0kPa, 6.0kPa and 7.0kPa, respectively.

As for Su-Inst-4 and Su-Inst-5, the aim is to investigate the effect of the loading process on the installation. Four steps of stable suction were applied in Su-Inst-4 with the values of 2.4kPa, 3.6kPa, 5.2kPa and 6.7kPa respectively. Three steps of stable suction were applied with the values of 3.0kPa, 4.8kPa and 6.5kPa respectively in Su-Inst-5. During each step, the suction was continued till the penetration of the caisson stopped sinking completely. The displacement of the caisson was tested with a pull rod displacement sensor and the tilt angle of the caisson was monitored with an inclinometer fixed on the caisson lid. The hydraulic force acting on the caisson was measured with a compression load cell mounted under the hydraulic cylinder. In the suction installation tests, an additional suction transducer was fixed on the top lid to record the suction within the skirt compartment of the caisson.

3. Results of the jacking installation tests

3.1. Installation displacements and soil pressures

The measured displacements of Ja-Inst-1 and Ja-Inst-2 tests are superimposed in Fig. 5. As we can see, the caisson penetrated about 11.4 cm into the sand bed under self-weight (482kg) in Ja-Inst-1. The penetrating rate was simplified into uniform in the stage. Then the caisson was uniformly pushed down extra 38.2cm with a rate of 0.1 cm/s by the hydraulic cylinder in the second stage. The total penetration displacement was about 49.6cm at last. With a different

penetration rate, 0.2cm/s, the results in Ja-Inst-2 test are used to examine the sensitivity of the penetration resistances to penetration rate. The final displacement of Ja-Inst-2 test was 48.3cm. In addition, the tilt angles in the above two tests were very small, varying in a range of 0.14-0.22°. The measured results show that the soil pressures and the penetration resistances are not sensitive to the rates within the range of 0.1-0.2cm/s. Detailed analyses on the soil pressures are as follows and the contents about the penetration resistances are presented in section 3.2.

As shown in Fig. 3, the soil pressure sensors towards inside are denoted as I-1, I-2 and I-3, and the outside are O-1, O-2 and O-3. Fig. 6(a) and Fig. 6(b) show the curves of the soil pressures acting on the inside and outside of the skirt in Ja-Inst-1 test, respectively. As we can see, both the inner and outer soil pressures grow rapidly with the displacement. The inner soil pressures are almost equivalent to the outer. There is not a harder compaction in the inner sand under the current case ($z/D < 0.34$). The slope of the curves of the soil pressures varies in the range of 26.5~29.2kPa/m. As for the in situ condition, the lateral soil pressure can be calculated as

$$p=K_0\gamma'h+\gamma_w h_w=(K_0\gamma'+\gamma_w)h+\gamma_w(h_w-h) \quad (1)$$

where γ' is the submerged weight of the sand; h is the depth of the soil pressure sensor below the sand surface; $\gamma'h$ is the in-situ vertical effective soil pressure; K_0 is the lateral pressure coefficient, $K_0 \approx 1 - \sin\phi' = 0.5$ [19]; γ_w is the unit weight of water; h_w is the depth of the soil pressure sensor below the surface of the water, $h_w = h + 0.15$ m. So the slope of the in situ lateral soil pressure to depth is $(K_0\gamma' + \gamma_w) = 14.2$ kPa/m, much smaller than the range of 28~31kPa/m of the test. This indicates that the sand around the skirt was strongly compacted during installation and the stress level of the sand was increased considerably due to soil-skirt interaction. Andersen et al. [11] recommended the lateral soil pressure coefficient K within the range of 0.8-1.85 for predicting the pressures on the skirt during installation through back-calculations of the test data of laboratory and field installation tests. When K is chosen as 1.85, the predicted slope is 26.12kPa/m and close with the test results.

Fig. 7 shows the curves of the tip resistances measured by the sensors T-1, T-2 and T-3 in Ja-Inst-1 test. As we can see, the unit tip resistance grew nearly linearly with the displacement, and it is much bigger than the inner and outer soil pressures on the skirt. Fig. 7 also shows the comparisons between the measured tip resistance and the predicted results with two different approaches, one is the API approach and the other is the q_c method. API [20] calculates the tip resistance with the following equation

$$q_{tip} = p_0 N_q \quad (2)$$

where p_0 is effective overburden pressure at the skirt tip; N_q is dimensionless bearing capacity factor. The relative density and measured cone resistance both indicate that the sand is medium dense. As for this sand type, API [20] suggests N_q value of 40. As for the q_c method, the tip resistance is predicted as

$$q_{tip} = k_p q_c(z) \quad (3)$$

where $q_c(z)$ is the cone resistance at the depth z under the sand surface; k_p is the empirical coefficients, relating q_c to the tip resistance. The cone resistance q_c here is taken as the average value of the four CPT test results (see Fig. 2). In the UWA-05 method for driven piles, a k_p value of 0.6 was suggested for the tip of open-ended piles, which may be appropriate for driven piles at deep depths (and thus high stress levels) [21]. As for the suction caisson in this research, the penetrating depth is much shallower and lower k_p values are usually appropriate. In principle, this value should be adjusted according to the sand density, with higher values appropriate in looser sand, and even lower values possible for extremely dense sand. Senders and Randolph [12] suggested k_p value of 0.2 for very dense sand. The silt sand is medium dense and a k_p value of 0.35 is used for the prediction calculations. This k_p value is very similar to the value of 0.3 given in DnV [22]. The prediction of the unit tip resistance with the q_c method gives a very good agreement with the measurement, however, the prediction with API approach is much lower than the measurement (see Fig. 7).

3.2. Predicted and test results of the unreduced installation resistance

The penetration rate is constant in Stage II (see Fig. 5), so the installation resistance satisfies

$$G' + F = R = R_f + R_{tip} \quad (4)$$

where G' is the weight of the caisson, adjusted for buoyancy as increasing amounts of the caisson become submerged as the penetration proceeded; F is the hydraulic force measured by the load cell placed between the hydraulic cylinder and the caisson; R is the total installation resistance; R_f is the skirt friction; R_{tip} is the tip resistance. According to weighing in advance and the measured F curves, the curve of the installation resistance R against the displacement is drawn, as shown in Fig. 8. The slope of the curves illustrates that the growth rate of the resistance increases gradually before the relative displacement (z/D) reached 0.23 or so, and tended towards stability afterwards. The measured installation resistances are not sensitive to the penetration rates within 0.1-0.2cm/s.

The tip resistance is calculated based on the average values of the measured unit tip resistance and the tip area πD_t . Then the skirt friction is determined as the net of the total resistance subtracting the tip resistance (see Fig. 9). The q_c method is used here to make a prediction for the skirt friction, as

$$R_f = \pi D_t \int_0^z k_f q_c(l) dz + \pi D_o \int_0^z k_f q_c(l) dz \quad (5)$$

where k_f is the empirical coefficients, relating q_c to the skirt friction. An empirical value of $k_f=0.0018$ is able to give a good prediction of the skirt friction. The k_f value of 0.0018 is higher than the most probable value of 0.001 recommended by DNV [22] and also slightly higher than the empirical values of 0.001 and 0.0015 used by Andersen et al. [11]. Additionally, in the UWA-05 method, Lehane et al. [21] recommended k_f values for the lower two diameters of an open-ended pile, derived from installation data. The k_f value was linked to the ratio of internal to external diameter (D_i/D_o), as

$$k_f = C \left[1 - \left(\frac{D_i}{D_o} \right)^2 \right]^{0.3} \cdot \tan \delta \quad (6)$$

where the coefficient C was suggested as 0.021; δ is the interface friction angle. According to the measured soil pressures acting on the skirt and the skirt friction, δ is calculated using dynamic friction theory ($f = p \times \tan \delta$), and the value of $\tan \delta$ is about 0.419. For the present caisson with a D_i/D_o ratio of 0.987, the k_f value is 0.003, which is much higher for the present work. The k_f value of 0.0018 here agrees well with the value used in Senders and Randolph [12]. Fig 8 shows the predicted total jacking installation resistance with $k_f=0.0018$ and $k_p=0.35$. It can be seen that the predicted results agree well with the experimental data.

4. Results of the suction installation tests

4.1. Displacements and soil pressures

Fig. 10 shows the applied suction (i.e. the absolute value of the negative pressure) beneath the top lid and the displacements of the caisson in the suction installation tests. In Su-Inst-3, the caisson sank into the sand bed 9.4 cm under self-weight and then penetrated 8.5cm, 9.9cm, 6.9cm, 7.1cm and 5.8cm with the action of the corresponding step of stable suction (see Fig. 10a). In Su-Inst-4, the caisson firstly penetrated into the sand bed 11.6cm in Stage I and then penetrated 7.6cm, 7.8cm, 9.1cm and 8.4cm with the action of the corresponding step of suction in Stage II (see Fig. 10b). As for Su-Inst-5, the displacements were 10.3cm in Stage I, and 10.7cm, 11.9cm, 10.7cm respectively in Stage II.

It can be seen that when stable suction was applied, the displacement firstly grew linearly, and then the growth flattened out. Additionally, the tilt angles varied in the range of 0.2°-0.4° in the three suction installation tests. The tilt angles were much smaller, benefitting from the application of stable suctions, than those of our previous suction installation tests without suction adjustments, in which the tilt angles usually exceeded 2°.

Fig. 11 shows the curves of the measured unit tip resistances against time in Su-Inst-3 test. It can be seen that the unit tip resistance proposes noticeable changes with the application of the suction. When a stable suction was applied, the suction caisson began to sink into the sand and the tip resistance slowly increased. The tip resistance tended towards stability after the penetration halted, while the suction still remained stable. At this point, the sum of the tip resistance and the skirt friction equals the sum of the suction load ($\pi D_t^2 S/4$, S is the applied suction) and the buoyant weight of the caisson. However, when the stable suction disappeared, the tip resistance dropped dramatically, because the suction load disappeared. Compared with the counterpart in jacking installation tests, the tip resistance in Su-Inst-3 is much smaller, due to seepage effect.

Fig. 12 shows the curves of the measured inner and outer soil pressures in Su-Inst-3 test. It can be seen that the soil pressures are very different from those of the jacking installation tests. The outer soil pressures increased when stable suction was applied. The inner soil pressures, however, decreased dramatically after stable suction was applied. Negative values occurred at the points where the penetration depth was small (see Fig. 12), due to the negative pressure within the caisson. The inner pressures were much lower than the outer when suction was applied. When the suction disappeared, the inner soil pressures grew suddenly and the outer pressures, however, barely changed. The values of the inner and outer pressures were nearly the same when suction disappeared. Compared with the counterparts in Ja-Inst-1, the inner soil pressures declined considerably when suction was applied, but the outer soil pressures were barely affected by the suction.

4.2. Seepage effect on the installation resistance

When the penetration halted at the end of each loading step, namely the equilibrium points, the total resistance R were calculated as the sum of G' and suction load $\pi D_t^2 S/4$. Based on the measured data, the tip resistance and the inner and outer skirt frictions were also calculated at the equilibrium points. Fig. 13 shows the ratios the resistance of Su-Inst-3 test to the counterparts of Ja-Inst-1 test. The ratios of the total resistance are 73.4%, 54.9%, 51.4%, 43.9%

and 38.4%, respectively. It can be seen that seepage effect is very apparent in the silt sand. The ratios of the inner friction at the five equilibrium points are 49.9%, 30.8%, 33.7%, 26.3% and 13.7%, respectively. The ratios of the tip resistance are 73.4%, 53.6%, 49.6%, 41.3% and 34.8%, respectively. The ratios of the outer friction are much bigger, with the values of 105.7%, 106.5%, 102.3%, 105.3% and 101.4%, respectively. These ratios indicate that the suction is able to greatly reduce the inner friction and tip resistance, but the outer friction is barely influenced.

4.3. Comparisons and discussions

4.3.1. Critical suction S_{crit}

As mentioned before, suction is able to reduce the penetration resistance and beneficial to the installation in sand. However, when suction is applied, caution is needed to prevent piping. The critical state which may cause piping in the suction installation has been investigated using numerical methods by several researchers [12-14]. For example, Feld [14] proposed the critical suction S_{crit} using the finite element program SEEP, as

$$\frac{S_{crit}}{\gamma' D} = 1.32 \left(\frac{z}{D} \right)^{0.75} \quad (7)$$

Senders and Randolph [12] recommended the critical suction as

$$\frac{S_{crit}}{\gamma' D} = \left\{ \pi - \arctan \left[5 \left(z / D \right)^{0.85} \right] \right\} \left(2 - \frac{2}{\pi} \right) \frac{z}{D} \quad (8)$$

Moreover, the required suction S_{req} for the installation in sand was approximately derived by Senders and Randolph [12], as

$$S_{req} = \min \left(\frac{R_{fO} + R_{fI} + R_{tip} - G'}{R_{fI} + R_{tip} + 0.25 \pi D_I^2 S_{crit}}, 1 \right) S_{crit} \quad (9)$$

According to the previous study, S_{req} expressed in Eq. (9) should not exceed S_{crit} , in order to keep seepage stability of the inner sand. Otherwise, piping may occur. Fig. 14 shows the comparisons between the applied suctions in the tests and the calculated critical suction with Eq. (8). It can be seen that in the Su-Inst-3 test, the applied suctions are lower than the calculated critical suction. But in the Su-Inst-4 and Su-Inst-5 tests, there are some periods in which the aforementioned requirement is not fulfilled (see Fig. 14). Contrasting to the previous conclusions, no piping in the caisson was observed in the two tests. No sand boil was observed, the surface of the sand remained calm and the

overlying water remained clear. The reason is due to the assumed critical state $i_{crit} = \gamma'/\gamma_w$ (where i_{crit} is the critical hydraulic gradient), based on which Eqs. (7) and (8) were established. In the critical state, the decreasing trend of the sand permeability with the increasing depth, which has proved to be able to increase the critical suction [23-24], was not taken into account. Additionally, the upward seepage flow made the inner sand looser and more permeable, which is also able to reduce the internal hydraulic gradient and raises the critical suction [13, 25]. This implies that a potential exists for the suction to exceed the calculated S_{crit} and the suction higher than the predicted with Eqs. (7) and (8) could be applied during suction installation.

4.3.2. Resistance reduction ratio α and required suction S_{req}

The resistance reduction ratio α is defined as

$$\alpha = (R_j - R_s) / R_j \quad (10)$$

where R_j is the jacking penetration resistance; R_s is the suction penetration resistance.

The resistance reduction ratios at the equilibrium points were calculated based on the test results of the two installation conditions. The reduction ratios of the inner friction and tip resistance were plotted in Figs. 15a and 15b respectively, against the ratios of the applied suction to S_{crit} calculated with Eq. (8). As shown in Fig. 15, power functions fit the reduction ratios well by using the least square method. As for the inner friction, the reduction ratio α_f is expressed as

$$\alpha_f = 0.865 \times (S/S_{crit})^{1.03} \quad (11)$$

And the fitting formula for the tip resistance is as follow

$$\alpha_{tip} = 0.707 \times (S/S_{crit})^{1.86} \quad (12)$$

The S_{crit} value in Eqs. (11) and (12) is calculated with Eq. (8), which does not account for a loosening effect and is therefore not the real critical value.

As for the outer friction, the values in the two test conditions are very close, with the reductions ratios within the range of -0.02~0.07. So the seepage effect on the outer friction can be ignored here, as

$$\alpha_o = 0 \quad (13)$$

The reduction ratio of the outer friction agrees well with that of Senders and Randolph [12]. However, the reduction ratios of the inner friction and tip resistance are different, as shown in Fig. 16. In the method of Senders and Randolph

[12], the inner friction and tip resistance were both assumed to reduce linearly with S/S_{crit} : remaining unchanged when $S=0$ and turning to zero when $S=S_{crit}$. The present reduction ratios of the inner friction and tip resistance are smaller and the ratio of the tip resistance shows strong nonlinearity.

Then based on Eqs. (11), (12) and (13), a new expression for S_{req} is established, as

$$S_{req} = \left[(1 - \alpha_{tip}) R_{tip} + (1 - \alpha_I) R_{fI} + (1 - \alpha_O) R_{fO} - G' \right] / (0.25\pi D_t^2) \quad (14)$$

In order to verify the new method, the required suctions in the suction tests were predicted with Eqs. (9) and (14) respectively. As shown in Fig. 17, the predicted results with Eq. (9) are lower than the measured, but the predicted results with Eq. (14) are in reasonable agreement with the observations. The predicted results with Eq. (14) are more exact and reliable for the installation of suction caissons in silt sand.

5. Conclusions

Suction caisson foundations have very good prospects in wind power projects along the offshore of eastern China. In the present study, several laboratory tests were carried out to investigate the installation of suction caissons in saturated silt sand. The thickness of the sand bed is 2.0m. The caisson used in the tests is made of steel with 1.5m in the diameter and 0.5m in the skirt length. Six pressure sensors are embedded in the skirt to record the soil pressures acting on the skirt wall. And three micro soil pressure sensors are embedded in the skirt tip to measure the tip resistance acting on the annulus. An adjustable suction system was designed to make stable vacuum in the caisson. Two comparative kinds of tests were completed based on with and without suction, namely jacking installation and suction installation.

For the jacking installation, the test results indicate that the inner and outer soil pressures acting on the skirt are close. The predictive performances of q_c method and API approach are examined for jacking installation resistance. It shows that the jacking installation resistance can be better predicted with the cone resistance q_c measured in the CPT tests, with the coefficients $k_f=0.0018$ and $k_p=0.35$. This paper examines It is demonstrated that the q_c method provides better predictions. The tip resistance plays a main role in the jacking installation resistance. For the suction installation, the inner soil pressures and tip resistance drop when suction is applied. However, the outer soil pressures increase. Moreover, the measured data show that the inner skirt friction and tip resistance were reduced greatly due to seepage effect while the outer skirt friction nearly remained unchanged, compared with the counterparts in the jacking

installation tests. Then using the measurements, the reduction ratios of the resistance were calculated. Power functions can be used to describe both the reduction ratios of the inner friction and tip resistance against S/S_{crit} . Based on the test results, a new prediction method for the required suction S_{req} was established for the installation of suction caissons in slit sand, which proved more exact and reliable.

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Table 1 Details of the caisson dimensions

Diameter D (m)	Skirt length L (m)	L/D ratio	skirt thickness (m)	Self-weight (kg)
1.5	0.5	0.33	0.01	482

Table 2 Outline of the laboratory tests carried out

Caisson diameter (m)	Case	Code	Penetration rate (cm/s)	Procedures	Note
1.5	1	Ja-Inst-1	0.1	Phase I self-weight penetration, Phase II jacked penetration	Jacked by the hydraulic cylinder
	1	Ja-Inst-2	0.2		
	2	Su-Inst-3	—	Phase I self-weight penetration, Phase II suction penetration	Pumping using the regulation reservoir
	2	Su-Inst-4	—		
	2	Su-Inst-5	—		

Figure 1

Figure 2

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