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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.

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 75,300 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 85 m in length, 1.7 m in diameter and about 0.03 m in thickness. In the latter wind farm, mono-piles are chosen, with about 50 m in length and 5 m 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 3 MW 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 30 m diameter and 7 m 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, atten-

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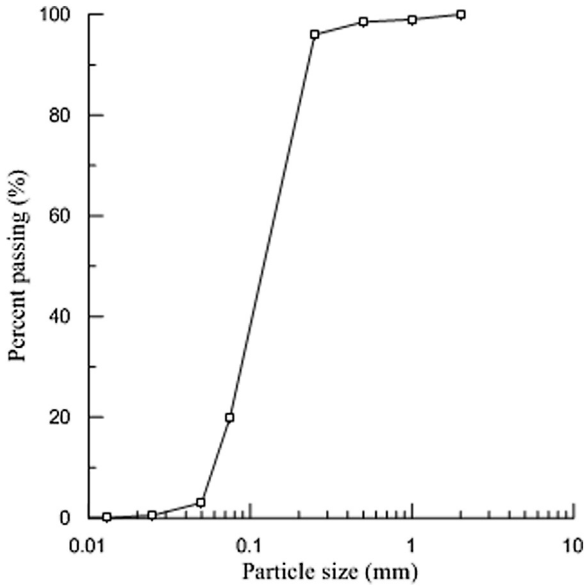

Fig. 1. Grading curve for the sand bed.

tion 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 0.075–0.25 mm, and 20% silt with the grain size in a range of 0.005–0.075 mm. The sand was evenly rained into the testing platform (4m × 4m × 2.5m), 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 0.5 m/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 2.0 m in depth overlaid by 0.15 m 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 35.7 mm and the penetrating rate is 0.2 cm/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 1900 kg/m^3, 30°, 0.26, 0.65 and 0.63, respectively.

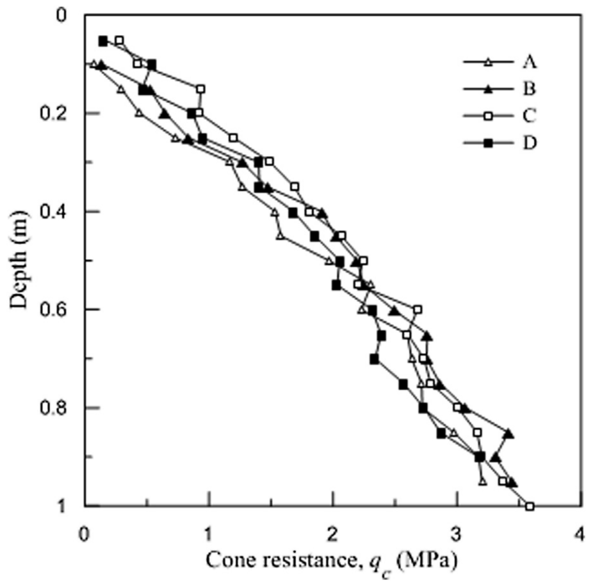

Fig. 2. CPT results of the test sand: Cone resistance, q_c (MPa).

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

The used caisson has an internal diameter (D) of 1.5 m and a skirt height (L) of 0.5 m. Thickness of the skirt is 0.01 m. 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 0.02 m 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 0.0095 m 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