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Laboratory tests on soil–skirt interaction and penetration resistance of suction caissons during installation in sand

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ABSTRACT

As a new form of offshore foundation, suction caissons have been applied to several offshore wind power projects. In the present study, a series of tests were carried out based on laboratory scales with an aim to investigate the interaction mechanisms between the caisson and saturated sand in both jacking installation and suction installation processes. For the jacking installation, the results indicate that the inner soil pressure acting on the skirt of the caisson is equivalent to the outer when the relative sensor depth (h/D, where h and D are the sensor depth and the diameter of the caisson, respectively) is less than about 0.3. The inner soil pressure, however, exceeds the outer when $h/D > 0.3$. For the suction installation, the results show that the inner soil pressure is dramatically reduced once stable suction is applied. In contrast, the outer soil pressure increases at first and then falls down to a stable level rapidly when stable suction is applied. Based on the test results, the previous formulae of the penetration resistance and required suction of caissons have been revised and evaluated.

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1. Introduction

Wind energy, as a clean and renewable power, is considered as a promising substitute for fossil fuel and has been widely developed in many countries. Compared with the onshore wind energy, the offshore wind energy has many advantages, for example, longer time availability of wind resource, greater wind speeds and lower occupancy of land resources. Additionally, offshore wind farms in China are usually close to the civil and industrious utilities with high electric consumption and thus the problems occurred in the long distance transmission of the electricity can be avoided (Bishop and Miller, 2007; Hong and Moller, 2011). However, one problem confronting us is the installation of wind turbines since the existence of sea water, which causes the installation situation more complicated compared with that of the onshore. A proper and feasible installation method could have higher levels of electricity production, lower costs of installation and maintenance, and smaller impacts on the environment and existing human activities (Lian et al., 2011).

As a new form of offshore foundation, suction caissons are commonly used in recent years in ocean engineering because of the advantages of economic feasibility and environment-friendly work principles (Bye et al., 1995; Tjelta, 1995; Erbrich and Tjelta, 1999; Andersen et al., 2005; Jostad and Andersen, 2006; Ibsen, 2008; Li et al., 2012). Since the first suction caisson for a 3 MW wind turbine which was installed in 2002 in Denmark, suction caissons have been more and more used to install wind turbines (Houlsby et al., 2005a). Nevertheless, one challenge for suction caissons is how to penetrate deep enough to keep the required bearing capacity and stability (Andersen et al., 2008; Senders and Randolph, 2009). To do so, a suction technology is usually employed within the skirt compartment in addition to the self-weight of the caisson. In general, for clay soil, a small suction is adequate (Ding et al., 2003; Houlsby et al., 2005b; Zhu et al., 2011; Zhang et al., 2013). However, for sand, the penetration resistance is quite large and the suction is affected by multiple factors (Andersen et al., 2008; Senders and Randolph, 2009).

In sand, on one hand, the suction produces an increased downward force, which is required for penetration. On the other hand, the suction reduces the internal resistance because of upward hydraulic gradients (Brown and Nacci, 1971; Hogervorst, 1980; Sahota and Wilson, 1982). However, a high hydraulic gradient will cause piping in sand, which may lead to installation failure. Therefore, care must be taken when the suction is used (Erbrich and Tjelta, 1999; Feld, 2001). To investigate the installation of suction caissons in sand, a number of studies have been completed (Houlsby and Byrne, 2005; Andersen et al., 2008; Tran and Randolph, 2008; Senders and Randolph, 2009; Ibsen and Thilsted, 2011). Most of the previous studies placed emphasis on the calculation methods for the penetration resistance and required suction, but few investigations focused on the mechanisms between the caissons and the sand during penetration mainly

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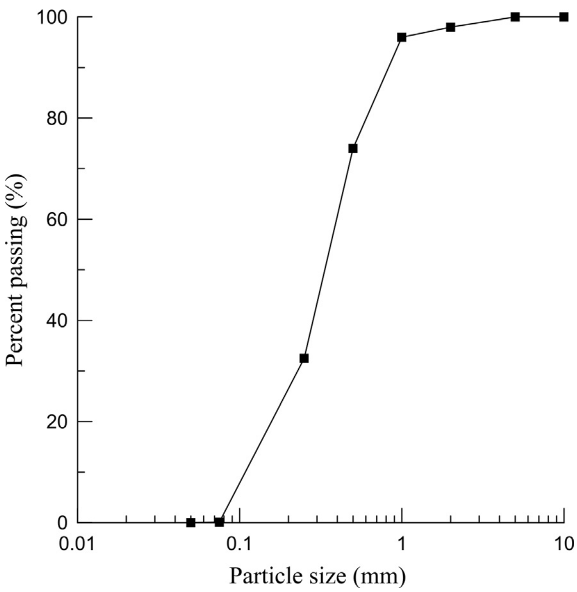

Fig. 1. Grading curve for the sand bed.

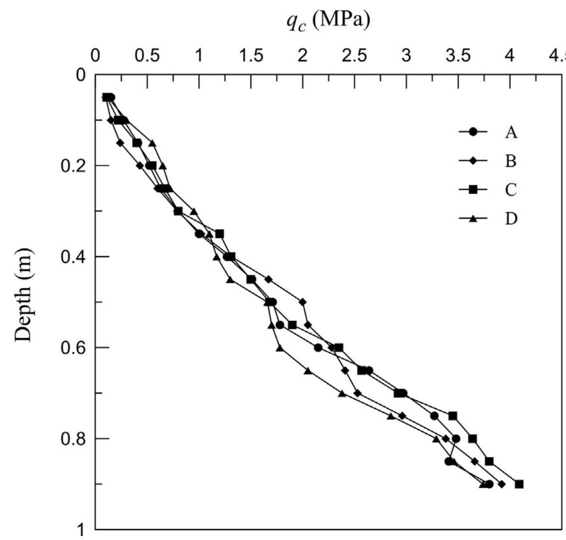

Fig. 2. CPT results of the sand bed: cone resistance, q_c (MPa).

Table 1
Details of the caisson dimensions.

Diameter D (cm)	Skirt length L (cm)	L/D ratio	Skirt thickness (cm)	Self-weight (kg)
50	50	1.0	1	113.5

due to the lack of special field and laboratory observations. In China, several wind farms have been proposed in the eastern offshore areas, for example, eastern coasts of Fujian, Jiangsu and Tianjin. At many of the proposed sites, the seabed soils comprise sand (with relative density of 0.65–0.70) at shallow depths, which we stress in this paper.

In the present study, the installation process was researched based on two conditions, jacking condition and suction condition. The main objectives of this study were to investigate the (1) soil–skirt interaction during both jacking installation and suction installation; (2) mechanism of the penetration resistance reduction due to suction and seepage; (3) calculation methods for the jacking penetration resistance, suction penetration resistance and the required suction. The arrangement of this paper is as follows. In Section 2, the equipment and the approach used for the tests are presented. The results of the jacking installation tests are presented in Section 3 and the results of the suction installation test are in Section 4. The comparisons with the previous studies and discussions are given in Section 5, and the conclusions of the paper are given in Section 6.

2. Materials, equipments, and procedures

2.1. Materials and equipment

Sand used in the laboratory tests was collected at a site off the east coast of Tianjin City, where a wind farm was proposed. The grading curve of the sand is shown in Fig. 1. It can be seen that the sand is mainly composed of 75% medium sand with the grain size in a range of 0.25–0.5 mm, and 22% coarse sand with the grain size >0.5 mm. The dry sand was firstly evenly rained into the testing platform (4 m $\times$ 4 m $\times$ 2.5 m), and each layer was prepared elaborately with a thickness of 0.2 m. The sand was saturated by elevating the water level in the bed with a water supply and drainage system with a velocity of 0.5 m/day. The purpose of using this slow velocity is to avoid uneven seepage or piping in the sand. And then the sand bed was fully and evenly vibrated with a penetrating vibrator-vibrating rod, to release the gas in it. After that the sand bed was left for static settlement for 30 days. The final form of the bed is about 2.0 m in depth overlaid by 0.15 m fresh water to keep the sand saturated during the tests.

Soil parameters of the soil bed, such as the cone resistance, saturated density, effective internal friction angle, saturated moisture content, void ratio and relative density were tested as well. All the tests were completed in the geotechnical laboratory of the Tianjin University with sand samples except the cone resistance, which was tested directly in the sand bed. The CPTs were carried out by using a 35.7 mm diameter cone (with a section area of 10 mm^2), penetrating at a rate of 0.2 cm/s. The relation of the cone resistance q_c to depth is shown in Fig. 2 and the values of the saturated density, effective internal friction angle, saturated moisture content, void ratio and relative density are 2.05 t/m^3, 38°, 0.26, 0.60 and 0.68, respectively. The friction angle was measured in slow direct shear tests, at stress levels of 50 kPa, 100 kPa, 150 kPa and 200 kPa, respectively.

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 dimensions of the caisson are listed in Table 1. There are eight soil pressure sensors with a diameter of 0.02 m embedded in the skirt wall of the caisson, with four toward inside and the remaining four toward outside (see Fig. 3). The sensors are used for monitoring the interaction between the skirt of the caisson and the sand. The sensors with the same subscripts are in the same height from the skirt tip. The distances from the skirt tip to the soil pressure sensors are 6 cm, 18 cm, 30 cm, and 42 cm. There are four valves on the top lid of the caisson, which are used for pumping, gas exit in the self-weight penetration stage, the vacuum gauge and the vacuum transducer, respectively (see Fig. 4a).

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. 4b. A hydraulic cylinder provides the reaction forces used in the jacking installation tests. The hydraulic cylinder is fixed on the steel reaction beam attached to the side walls of the platform (see

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