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Model tests of modified suction caissons in marine sand under monotonic lateral combined loading

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ABSTRACT

This paper presents a novel type of offshore foundation, a modified suction caisson (MSC), consisting of an internal caisson in an external short-skirted structure. A series of small-scale model tests were conducted to investigate the lateral bearing capacity of the MSC embedded in saturated marine fine sand. The lateral loading was carried out on the MSC at load eccentricity ratios of 1.0, 1.5, 2.0 and 2.5. Experimental results show that the MSC significantly increases the lateral bearing capacity and reduces the lateral deflection, compared to its corresponding conventional suction caisson. Parametric studies indicate that the bearing capacity of the MSC increases with increasing the external skirted structure dimension and the internal caisson aspect ratio, while decreases with increasing the load eccentricity. The lateral deflection decreases when the size of the external skirted structure increases. It was also found that rotation center of the MSC moves with loading conditions and the variation in the external skirted structure dimension. In the limit state, the rotation center is located at a depth of about 0.5–0.7 length of the internal caisson and is 0.15 diameter of the internal caisson away from its centerline.

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1. Introduction

In order to reduce environmental pollution and solve fossil energy crisis, offshore wind energy has received much attention in recent years. Compared to onshore wind turbines, placing wind turbines offshore not only avoids noise pollution and esthetic issues, but also allows the turbines to benefit from the higher wind speed at sea [1].

Lateral loads such as the horizontal load and moment resulted from wind and waves play a predominant role in the design of offshore wind turbine foundations [2]. Suction caissons are increasingly applied to offshore wind turbines due to their low cost, easy construction and reuse [3]. In order to increase the lateral bearing capacity and reduce the lateral deflection, a modified suction caisson (MSC) was proposed [4]. It consists of an internal caisson (which can also be viewed as a conventional suction caisson) combined with an external short-skirted structure, as shown in Fig. 1(a). There is a hole on the internal caisson lid for connecting to the vacuum pump and four holes permanently opened in the external skirt lid to reduce the water resistance during the penetration process of the MSC. In this paper, MSCs with various external skirt length and width were investigated.

The concept of the MSC is similar to a hybrid-skirted foundation proposed by Bienen et al. [5] and Gaudin et al. [6]. Bienen et al. [5] investigated the effects of the internal caisson dimension and the soil shear strength on the bearing capacity under combined loading by conducting a three-dimensional analysis. It was concluded that the hybrid-skirted foundation could provide higher lateral capacity.

Although the MSC is a new type of foundation, we can borrow some ideas from the conventional suction caisson to explore its lateral bearing behavior. Zhu et al. [7] carried out a series of large-scale model tests on suction caissons embedded in silt to investigate the deformation mechanism and soil–structure interaction. They suggested that the instantaneous rotation center of the suction caisson at failure was at the depth of about four-fifths of the skirt length, almost directly below the caisson lid center. Achmus et al. [8] used the finite element method to study the bearing behavior of suction bucket foundations in very dense and medium dense sand. It was found that the suction bucket experiences a heave during horizontal loading, which leads to the formation of a gap between the bucket lid and the soil with the increasing load. The ultimate capacity and initial stiffness of the bucket-foundation system were strongly dependent on the bucket dimensions and the load eccentricity. Kumar and Rao [9] suggested that the lateral bearing capacity of the suction caisson is a function of undrained shear strength, embedment depth ratio and load eccentricity ratio. There is a good correlation between the lateral load and the maximum earth pressure mobilized. Wakil [10] conducted a comparative study between skirted footings and unskirted footings on sand based on small-scale model tests. He concluded that the skirted structure could improve the horizontal bearing capacity and change the failure mode of circular shallow footings from slide mechanism into rotation mechanism. El-Sherbiny [11] investigated the bearing behavior of suction caissons in normally consolidated clay and found that the rotation center was at a depth of about 2/3–3/4 of the skirt length. Villalobos et al. [12] carried out a series of moment capacity tests to investigate the effects of different installation procedures on the response of suction caisson foundations in saturated dense sand. It was found that the use of suction beneficially reduced the penetration resistance of the caisson and the moment resistance of a suction caisson depended on the method of installation.

From the aforementioned literature review, it can be found that little attention has been paid to the deformation of the sand around the suction caisson. In addition, it is necessary to explore the lateral bearing capacity and the rotation center of the MSC.

The objective of this study is to investigate the response of MSCs subjected to monotonic lateral combined loading through a series of model tests conducted in saturated marine fine sand. Loading-deflection curves were established to study the influence of some parameters such as the dimensions of the external skirted structure, aspect ratios of the internal caisson and load eccentricities on the bearing behavior. The rotation center of the MSC was examined by considering various dimensions of the external skirted structure and load eccentricities. The deformation of the sand around the MSC during loading process was also explored.

2. Model test

2.1. MSC models

The caisson models (Fig. 1) are made of steel and the dimensions are given in Table 1. Caisson No. II is a conventional suction caisson, caisson Nos. II-1A and II-2A have zero external skirt length, which are only as references for the study. Our tests showed that the MSC can easily penetrate into the saturated fine sand to a desired depth, provided that the reasonable dimension of the MSC is given.

2.2. Sand used

Natural marine sand collected from the Gold Beach of Qingdao of East China, was used in the experiments. The physical properties of the sand, which were obtained from standard tests, are listed in Table 2. According to the particle size distribution curve shown in Fig. 2, the fine sand used is poorly graded with diameters of all grains less than 0.37 mm and greater than 0.075 mm. It may be regarded relatively uniform, so that the testing conditions can be consistent.

2.3. Test setup

The sand tank (1 m long, 1 m wide, and 0.8 m high) was designed large enough to eliminate the size effects, and its sidewalls were strengthened using square steel to prevent any lateral deformation.

The schematic diagram of the experimental setup is shown in Fig. 3. Gravel was first scattered uniformly to a thickness of 10 cm in the tank. It assured that the water level decreased uniformly during draining by opening the valve at the bottom of the tank. A sheet of geotextile was then used as a cover to avoid washing away the fine sand during draining. Enough water was then poured into the tank, and dry marine fine sand was sprayed into the water to ensure the homogeneity of sand formation. During this process, the water level should be always kept higher than the sand surface. Finally, the sand bed reached a height of 60 cm. This procedure of sand bed formation adopted here was proved to be satisfactory [13].

Lateral load was applied to the caisson through a lubricated soft steel wire over a frictionless pulley connected to weights. Two LVDTs with an interval of 12 cm were placed horizontally on the loading rod to measure the corresponding lateral deflections. The