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On the Bearing Capacity of Suction Bucket Foundations in Saturated Sand

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Abstract: The static bearing capacity of suction caisson with single- and four-caissons in saturated sand foundation is studied by experiments. The characteristics of bearing capacity under vertical and horizontal loadings are obtained experimentally. The effects of loading direction on the bearing capacity of four-caissons are studied under horizontal loading. The comparison of the bearing capacity of single-caisson and four-caisson foundation, the sealed condition of caisson's top and loading rate are analyzed.

Keywords: Caisson foundation, bearing capacity, saturated sand.

INTRODUCTION

A suction caisson is a closed-top steel tube that is lowered to the seafloor, allowed to penetrate the bottom sediments under its own weight first, and then pushed to full depth with suction force produced by pumping water out of the interior. In recent years, suction caissons have been used increasingly often for gravity platform jackets, jack-ups [1-3], they also have the potential of being used for several other purposes, such as offshore wind turbines, subsea systems and seabed protection structures [4-7]. The first advantage of suction caissons are attractive because of the convenient method of installation and repeatedly use. For an example, a suction caisson with a diameter of 9m and a height of 10m can be installed in 1~3 hours, by using only a pump. The second advantage is that it may mobilize a significant amount of passive suction during uplift. Despite some studies about the installation and bearing capacity have been studied, the detail responses of the suction caissons under dynamic loadings have remained unknown [8-10]. The dynamic loading condition is significant when suction caissons are used as the foundation of a platform. Wave loading, ice-induced or wind-induced dynamic loading cause the foundation to be subjected to cyclic loadings [11-14]. The lack of experience with these loading conditions lead to a proposal for a test program intended to gain a deeper understanding. The considerable expense and time consuming nature of prototype tests mean that the investigation of the bearing capacity of real scale devices under different circumstances is of limited practicality. It is much easier to change parameters in small scale tests. The soil type may be varied. The dimensions of the suction caisson and other process parameters may be varied conveniently also.

Only a few field tests of suction caissons have been reported in the open literature [15]. A number of investigators have tested scale models of suction caissons in geotechnical centrifuges [16].

Early experience with this technology often involved relatively stiff soils and axial compressive loadings applied at the top center of the caisson. Speed dependent loading tests on clay at 1g were performed by Jones *et al.* [17], Steensen-Bach [18].

Later designs for floating structures in deeper water, where horizontal or inclined mooring lines are attached to caissons, led to the need for increased lateral capacity. Although the offshore industry is deploying suction caissons in this configurations, a number of design issues remain unresolved [19, 20].

In the view point above, the static bearing capacity of single- and four-caissons in saturated sand layer are carried out. The effects of some factors are obtained.

INTRODUCTION OF EXPERIMENT

The single-caisson model is a steel cylinder caisson with an inner height of 7.2cm, a diameter of 4cm and a top's thickness of 0.2cm. The four-caisson foundation is consisted of four caissons connected by a plate (Fig. **1**). Each caisson has the same size as the single-caisson model. The distance between every two caisson's centers is 10cm. The Mongolia sand is used in experiments with a dry density of 1600kg/m^3. The sand is laid in an organic glass box with a size of 50×50×50 cm^3. The water level is 3cm over the sand layer surface. A dial gauge with a range of measurement of 0-30mm is used to measure the displacement of the caisson. A force transducer with a range of 0-6000N is used to measure the loading. The thickness of the sand layer is 40cm. Water is penetrated into the sand layer through a hole at the bottom of the model box. A thin coarse sand layer with a thickness of 2cm is laid on the bottom of the box for water penetrating uniformly and preventing piping. The sand layer is laid for 24 hours after finishing penetrating water.

EXPERIMENT'S OPERATION

The caisson is located at the center of the box. The pole at the caisson's top is connected with one end of the force transducer, and the loading head is connected with the other

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Fig. (1). The photos of four-caisson model.

Fig. (2). Layout of experiment.

end of the transducer. Two types of conditions are adopted in experiments when the caisson is applied on compressive or uplift vertical loading either the hole on the caisson's top is sealed or is not sealed. (1) When the hole is not sealed, the caisson is first penetrated into the sand layer by the gravity, and then is connected with the loading head. The LDVT is located at the caisson's top to measure the displacement of the caisson. The layout for experiments is shown in Fig. (**1**). (2) When the top is sealed, the caisson is first penetrated into the sand layer by the gravity, then penetrated into the sand layer fully by pressure. At last the hole is sealed by a screw and airproofed by glue.

The horizontal loading is applied on the caisson foundation by weight through a line. One end of the line is fixed on the pole at the caisson's top, the other end is connected with a salver. The weight is laid on the salver. The line is located at the sidewall of the box through a crown block. The layout of experiment is shown in Fig. (**2**). The loading is applied step by step. In each step, the data are recorded when the displacement does not change. When the displacement increases, while the force decreases or does not change, the experiment is finished Fig. (**3**).

EXPERIMENTAL RESULTS AND ANALYSIS

Fig. (3). Photos after experiments.

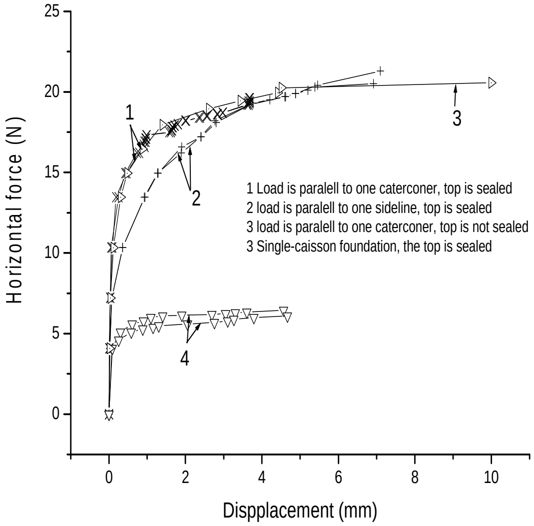


Fig. (4). Loading-displacement curves of four-caisson foundation in different directions under horizontal loading.

Fig. (**4**) shows the horizontal loading- displacement curves of the four-caissons when the loading is either in the direction of one sidewall or parallel to one catercorner of the quadrangle formed by the centers of four caissons. It is shown that the bearing capacity is almost the same in the two loading directions. Nevertheless, when the loading is in the direction of one catercorner, the slope of the loading-displacement curve is larger than that when the loading is parallel to one sideline. The bearing capacity is the same either the top is sealed or not sealed. The reason may be that the suction force can not be excitated under horizontal loadings.

CENTRIFUGAL EXPERIMENTS UNDER HORIZONTAL STATIC LOADING

In this section, centrifugal experiments are carried out by use of a three-bucket foundation under horizontal static loading (the data are all prototype in the following except for noting especially). The centrifugal experimental results are compared with the numerical results and the small scale experiments' results.

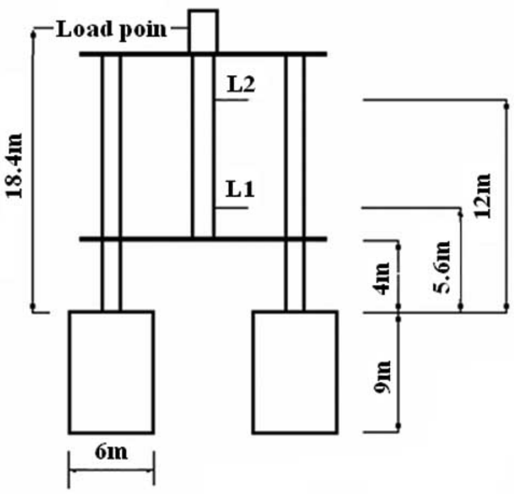
Layout of Centrifugal Experiments

Each bucket of the three-bucket foundation is made of steel and has a height of 9m and a diameter of 6m (Fig. **5**).

Fig. (**5**) is the sketch of layout for experiments. The soil layer is divided into three layers: the soil from 0m to 4m is the first layer and the dry density is 1.728g/cm^3, from 4m to 9m is the second layer and the dry density is 1.785 g/cm^3, from 9m−16.8m is the third layer and the dry density is 1.671 g/cm^3. During experiments, horizontal displacements are measured by three LVDTs, named L1, L2 and L3. The space between L1 and L2 is 6.4m. L3 is at the same level as the loading head (Fig. **6**). The distances between the top of bucket and L1, L2 and L3 are 12m, 5.6m, 18.4m, respectively. The force is measured by a force transducer made by 702 institute, China.

Consolidation and loading are both processed under 80g. The horizontal loading is applied on step by step immediately after consolidation. The increment in each step is 6400N. Increment of loading is applied on when the displacement is stable. One experiment is finished when anyone of the following conditions is satisfied: (1) Displacement keeps increase during one loading step. (2) Displacement increases but loading decreases.

(a) Layout



(b) Scale of bucket and LVDTs

Fig. (5). Layout of centrifugal experiments.

Experimental Results

Fig. (**6**) shows the loading-displacement curves. It can be seen that the relation between the loading and the displacement is nonlinear at the beginning and, with the increase of loading, there occurs a inflexion in the curve of loading-displacement. Displacements increase fast after the inflexion till the instability of bucket.

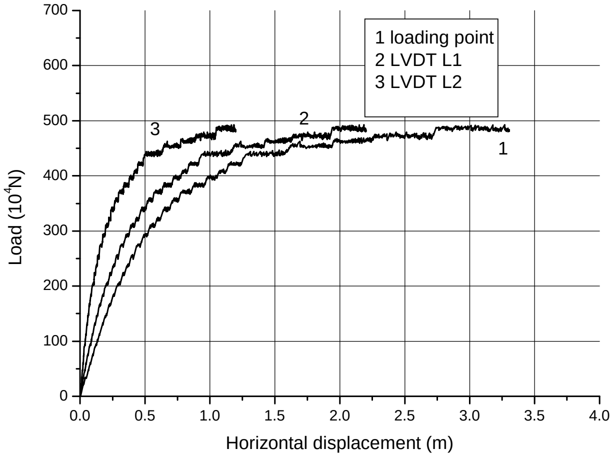


Fig. (6). Horizontal loading-displacement curve.

Numerical Simulation

Business software ABAQUS is adopted here to simulate the horizontal bearing capacity of the three-bucket foundation.

The scales of sand layer for simulation are 48m long, 28m wide and 16.8m thick, respectively.

The friction coefficient between the sand layer and the bucket is 0.6 which is determined by direct shear tests. The network is shown in Fig. (**7**). The boundary conditions are as follows: the bottom is fixed $u_x = 0, u_y = 0$, $u_z = 0$, it is normally fixed at the side $u_x = 0$, $u_y = 0$, it is free at the surface of the sand layer.

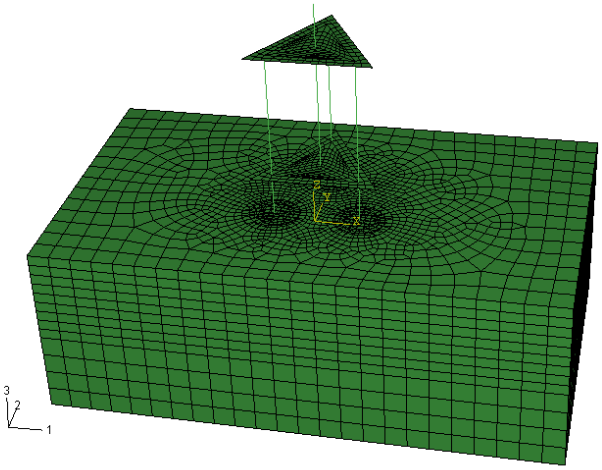


Fig. (7). Network for numerical simulation.

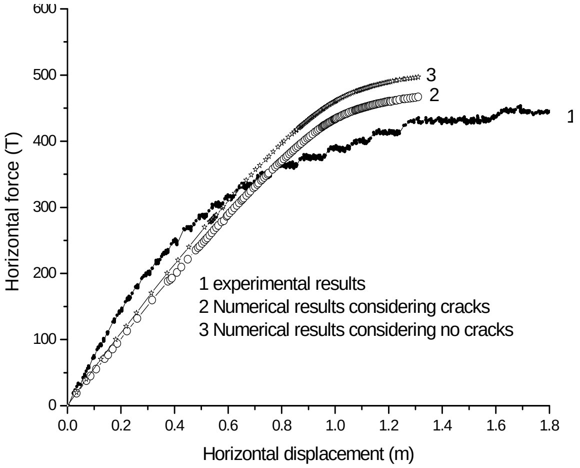


Fig. (8). Comparison of numerical and experimental results.

Table 1. Mechanical Parameters of Soil Layer

	Elastic Modulus E 10^{10}Pa	**Poisson's Ratio ν**	**Coh-esion C**	**Internal Friction Angle ϕ degree**	**Float Density kg/m^3**
The first layer (0-4m)	1.025	0.459	0	36.5	728
The second layer (4-9m)	2.88	0.45	0	40	785
The third layer (9-16.8m)	1.893	0.416	0	35	671

$$\begin{aligned} f &= (\sigma_1, \sigma_2, \sigma_3) \\ &= \frac{1}{2}(\sigma_1 - \sigma_3) + \frac{1}{2}(\sigma_1 + \sigma_3)\sin\phi - c\cos\phi \\ &= 0 \end{aligned} \tag{5-1}$$

The bucket is taken as elastic. The sand layer is taken as elasto-platic and obeys Mohr-Coulomb criterion, in which σ_1, σ_2, and σ_3, are the first, second and third principal stresses, respectively. c and ϕ are the cohesion and internal friction angle, respectively.

The elastic constants of bucket are $E = 2 \times 10^5 MPa$ and $\nu = 0.3$, respectively. The soil layer is divided into three layers: 0-4m is the first layer, 4-9m is the second layer, 9-16.8m is the third layer. The mechanical parameters of each layer is shown in Table **1**.

Comparison of Experimental and Numerical Results

In numerical simulations, two conditions, whether permit a crack occur or not between the bucket and the soil layer, are considered. The comparison is shown in Fig. (**8**). It is shown that the horizontal bearing capacity not permitting a crack occur is 7% higher than that permitting a crack occur. The numerical results permitting a crack occur is closer to the experimental results. The error is about 7.8%.

CONCLUSIONS AND DISCUSSIONS

It has no effect on the static compressive bearing capacity that if the top is sealed or not. The reason is that under static loadings, the soil layer is in drained condition whether the top is sealed or not. Nevertheless, if the loading is applied with some rate, the soil layer is in completely or partially undrained condition, that means, the strength of the soil layer will change with the loading rate, thus the bearing capacity will change with the loading rate.

With the increase of the internal friction angle and cohesion, the strength of the soil layer increases and so the bearing capacity of the bucket foundation increases also.

The main conclusions are as follows: The compressive bearing capacity is almost the same either the caisson's top is sealed or not. The uplift bearing capacity increases with the increase of the loading rate. The uplift bearing capacity when the caisson's top is not sealed while the loading rate is large may be bigger than that when the caisson's top is sealed while the loading rate is small. The horizontal bearing capacity of the four-caisson is almost the same when the loading is either parallel to a sidewall of the quadrangle formed by the centers of the four caissons or parallel to a catercorner of the quadrangle. Either the caisson's top is sealed or not, the horizontal bearing capacity is almost the same.

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