Proceedings of the Nineteenth (2009) International Offshore and Polar Engineering Conference
Osaka, Japan, June 21-26, 2009

ISBN 978-1-880653-53-1 (Set); ISSN 1098-618

Experimental Study on the Bearing Capacity of Suction Caissons in Saturated Sand

Bintian Jiao[1] *Xiaobing Lu*[1] *Jin Zhao*[1] *Ailan Wang*[1] *Zhongmin Shi*[2] *Zeng X H*[1]
[1]Institute of Mechanics, Chinese Academy of Sciences, Beijing, China
[2]Research Centre, China National Offshore Oil Co., Beijing，China

ABSTRACT

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

KEY WORDS: 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 (Clukey et al, 1995; Allersma et al, 1997, 2000), they also have the potential of being used for several other purposes, such as offshore wind turbines, subsea systems and seabed protection structures (Housby et al, 2000; Byrne et al, 2002; Byrne et al, 2004; Andersen et al, 1999). 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 loads have remained unknown (Senpere et al, 1982; Aas et al, 1992; Dyme et al, 1998). The dynamic load condition is significant when suction caissons are used as the foundation of a platform. Wave load, ice-induced or wind-induced dynamic load cause the foundation to be subjected to cyclic loads (Tjelta et al, 1990; Bye et al, 1995; Wang et al, 2006; Zhang et al, 2007). The lack of experience with these load 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 (Tjelta et al, 1986). A number of investigators have tested scale models of suction caissons in geotechnical centrifuges (Clukey et al, 1995)

Early experience with this technology often involved relatively stiff soils and axial compressive loads applied at the top center of the caisson. Speed dependent load tests on clay at 1g were performed by Jones et al (Jones et al, 1994), Steensen-Bach (Steensen-Bach, 1992).

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 (Clukey, 2001; Luke et al, 2005.)

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. The main aim of this paper is to obtain the characteristics of the bearing capacity of suction caissons, thus small size buckets are adopted in experiments, which causes the experimental results can not be applied to full-scale caissons.

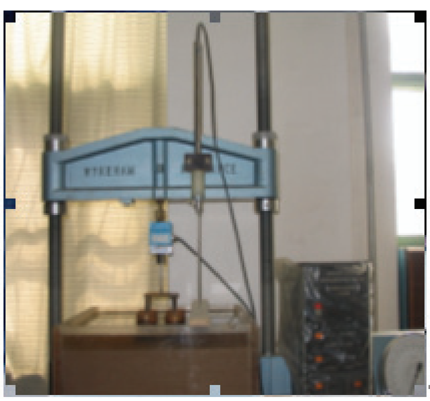
INTRODUCTION OF EXPERIMENT

The single-caisson foundation 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 foundation. The distance between every two caisson's centers is10cm. The Mongolia sand is used in experiments with a dry density of $1.6\ g/cm^3$. The sand is laid in an organic glass tank 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 $0-3cm$ cm is used to measure the displacement of caisson. A force transducer with a range of measurement of $0 - 6000\ N$ is used to measure the load. The thickness of sand layer foundation is 40cm. Water is penetrated into the sand layer through a hole at the bottom of the model tank. A thin coarse sand layer with a thickness of $2\,cm$ is laid on the bottom of the tank for water penetrating uniformly and preventing piping. The sand layer is laid for 24 hours after finishing penetrating water.

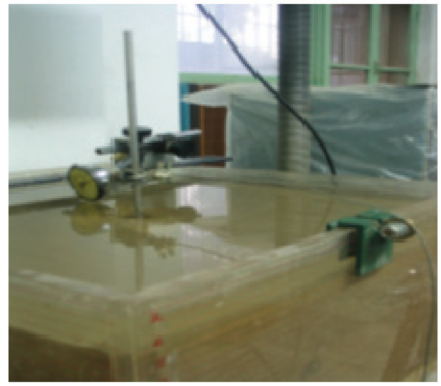
(a)

(b)

Fig. 1 The photos of single-caisson foundation and four-caisson foundation: (a)Single-caisson foundation; (b) Four-caisson foundation



(a)



(b)

Fig. 2 Layout of experiment: (a) Layout of experiment for applying vertical load; (b) Layout of experiment for applying horizontal load

EXPERIMENT PROCEDURES

The caisson is located at the center of the tank. The pole at the caisson's top is connected with one end of the force transducer, and the load head is connected with the other end of the transducer. Two types of conditions are adopted in the experiments when the caisson foundation is applied on pressing or uplift vertical load: either the hole on the caisson's top is sealed or is not sealed. When the hole is not sealed, the caisson is first penetrated into the sand layer by the gravity, and then is connected with the load 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. 1a. 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.

Because of the limit of load apparatus, the vertical load is controlled by displacement increment. The increase ratio is $0.04\,cm/\min$. The force and displacement are recorded once the displacement increases $0.02\,cm$.

The horizontal load is controlled by force increment. The load 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 hook hanging the weight. The line is located at the sidewall of the tank through a crown block. The layout of experiment is shown in Fig. 2b. The load 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. The design of experiments are shown in Table 1.

EXPERIMENTAL RESULTS AND ANALYSIS

Vertical Load

In the experiments applying on compression vertical force, it is shown that there is slightly apophysis on the sand layer surface near the caisson with the caisson penetrating into the sand layer. The sand flows towards the caisson's top and the apophysis disappears when the caisson's top is below the sand layer surface. It is shown that a concave pit forms near the caisson's side wall with the settlement of sand layer under vertical load, while the caisson foundation is failed in inclined way under horizontal load. Figs. 4 and 5 give the curves of compression load-displacement either the caisson's top is sealed or not. It is shown that the capacity increases gradually to a maximum (the bearing capacity) with the increase of displacement. The bearing capacity is almost the same in these two conditions. In the present experiments, the bearing capacity of four-caisson foundation is nearly 4 times that of single-caisson in our experiments.

The reason is that under static load, the soil layer is in drained condition whether the top is sealed or not. Nevertheless, if the load is applied with some rate, the soil foundation is in completely or partially undrained condition, that means, the strength of the soil foundation will change with the load rate, thus the bearing capacity will change with the load rate.

Table 1 Scheme of experiment

Exp. No	Sum of caisson	Type of load	Increase rate of load	Remark
1	Single	VUP	Step by step	not sealed
2	Single	VUP	Step by step	sealed
3	Four	VUP	Step by step	not sealed
4	Four	VUP	Step by step	sealed
5	Single	VUP	1mm/min	sealed
6	Single	VUP	10mm/min	sealed
7	Single	VUP	20mm/min	sealed
8	Four	VUP	1mm/min	sealed
9	Four	VUP	10mm/min	sealed
10	Four	VUP	20mm/min	sealed
11	Four	VUP	0.6mm/min	sealed
12	Four	VUP	40mm/min	not sealed
13	Single	HL	Step by step	sealed
14	Four	HL	Step by step	S-S
15	Four	HL	Step by step	S-D
16	Four	HL	Step by step	NS-D

Note: The four-caisson's centers form a quadrangle. S-S denotes sealed, load in one sideline direction of the quadrangle（Fig.3）, S-D denotes sealed, load in one diagonal direction of the quadrangle, NS-D denotes not sealed，load in one diagonal direction of the quadrangle（Fig.3）, VUP denotes vertical uplift load, HL denotes horizontal load.

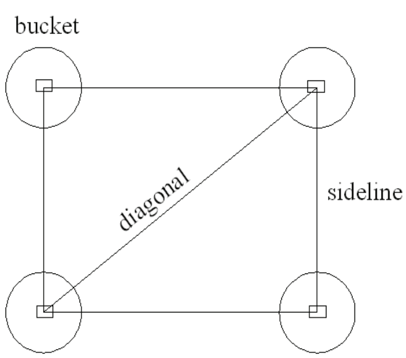


Fig.3 Sketch of sideline and diagonal

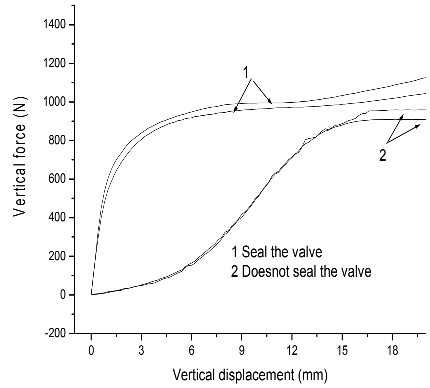


Fig. 4 comparison of results of four-caisson foundation under vertical compression load

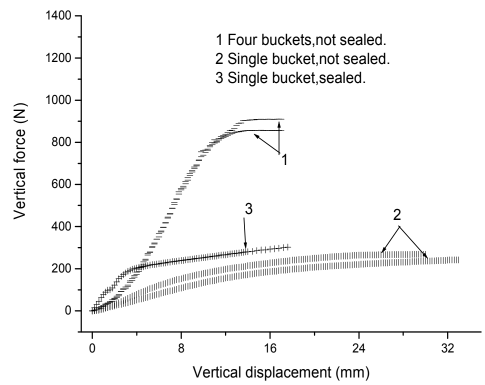


Fig.5omparison of results of single-bucket and four-caisson foundation under vertical compression load

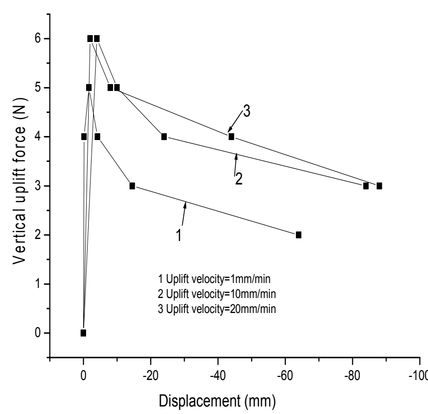


Fig.6 Load-displacement curves of single-caisson foundation under uplift load

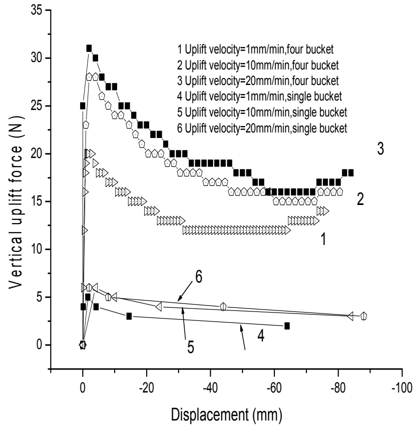


Fig.7 Load-displacement curves of single and four-caisson model under uplift load

Figs. 6 and 7 give the curves of uplift load-displacement either the caisson' top is sealed or not. It is shown that the bearing capacity increases with the increase of incremental rate of load. The bearing capacity of four-caisson is almost 6 times that of the single-caisson under the same incremental load rate when the caisson's top is sealed under our experimental conditions (noting here that it is not correct for all the loading rates.), which means, there is obvious strengthening effect of four-caisson. The load rate has large influence on the bearing capacity. In the experiments of the four-caisson bearing uplift load, the bearing capacity is $200N$ when the top is sealed and the load rate of is $0.1cm/\min$, while the capacity is $210N$ when the top is not sealed and the load rate of is $4cm/\ \min$.

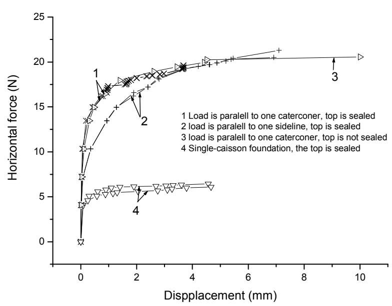


Fig.8 Load-displacement curves of four-caisson foundation in different directions under horizontal load (The two directions are: diagonal and sideline of the quadrangle formed by the four caisson's centers.)

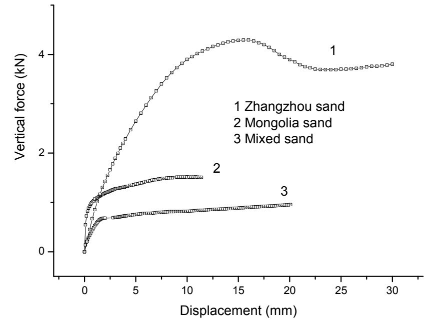


Fig.9 Comparison of the bearing capacity of different kinds of sand layer

Horizontal Load

Fig. 8 gives the horizontal load-displacement curves of the four-caissons when the load is either in the direction of one sidewall or parallel to one diagonal of the quadrangle formed by the centers of four caissons. It is shown that the bearing capacity is almost the same in the two load directions. Nevertheless, when the load is in the direction of one diagonal, the slope of the load-displacement curve is larger than that when the load is parallel to one sideline of the quadrangle formed by the four bucket's centers. The bearing capacity is the same either the top is sealed or not sealed. The reason may be that suction force can not be excitated under horizontal load.

Comparison of the Bearing Capacity of Different Kinds of Sand Layer

In order to compare the bearing capacity of different sand layer foundation, Experiments with three kinds of sand layer foundations (Zhangzhou sand, Mongolia sand and mixed sand which is mixed by Zhangzhou sand and clay.) and with single-caisson foundation under vertical load are carried out. The results are shown in Fig.9. It is shown that the bearing capacity is different obviously with different sand layer foundation. Zhangzhou sand has the biggest bearing capacity since it has the biggest internal friction angle and the coarsest particles, while the mixed sand has the smallest capacity since it has the smallest internal friction angle and the finest particles. The basic soil index properties are as follows: Zhangzhou sand: the grain series is $4\times10^{-2}-7.5\times10^{-3}cm$ (Fig.10), the gravity ratio is 2.66, the cohesion and the internal friction angle are $c=0,\varphi'=39.7^{\circ}$, respectively. Mongolia sand: the grain series is shown in Fig.10, the gravity ratio is 2.65, the cohesion and the inner friction angle are 0 and 38°, respectively. Mixed sand: the grain series is shown in Fig. 10, the gravity ratio is 2.69，the cohesion and the inner friction angle are 0 and 36°, respectively. All the sand layer foundations in experiments have the saturated density $1.6g/cm^3$ .The main index properties of the three kinds of sand are shown in Table 2.

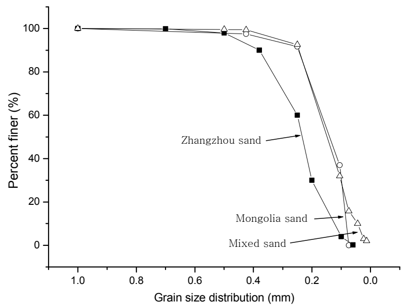


Fig. 10 Grain size distribution

Table 2 The index properties of the three kinds of sand

	Specific gravity	D_{50} (mm)	$e_{\min}$	$e_{\max}$	$c\,(Pa)$	$\varphi\left(^{\circ}\right)$
Zhangzhou sand	2.66	0.23	0.617	0.949	0	39.7
Mongolia sand	2.65	0.14			0	38
Mixed sand	2.69	0.15	0.454	0.949	0	36

CONCLUSIONS

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

ACKNOWLEDGEMENT

This paper is supported by the program of Chinese Academy of Sciences & China National Offshore Oil Co. "Study on Some Key Problems of Science and Technology in ocean oil exploitation" (KJCX2-SW-L03-01).

REFERENCES

Aas, PM, Andersen, KH (1992). "Skirted Foundation for Offshore Structure," *9th Offshore South East Asia Conf.*, Singapore.

Allersma, HGB, Plenevaux, FJA, Wintgens, JFPCME(1997). "Simulation of Suction Pile Installation in Sand in a Geocentrifuge," *7th Int. Offshore and Polar Engrg. Conf. , Honolulu, Hawaii, ISOPE,* Vol.1, pp 761-765.

Allersma, HGB, Kierstein, AA, Maes, D (2000). "Centrifuge Modeling on Suction Piles Under Cyclic and Long Term Vertical Loading," *Proc. Tenth Intl. Offshore and Polar Engrg. Conf,* Seattle, USA, ISOPE, Vol 2, www.isope.org .

Andersen, KH and Jostad, HP(1999). "Foundation Design of Skirted Foundations and Anchors in Clay," *OTC 10824, Proc. Offshore Tech. Conf.*, Houston, Texas, 3-6 May, 1-10.

Bye, A, Erbrich, C, Earl, K, et al. (1995). "Geotechnical Design of Bucket Foundation," *OTC7793,* 869-883.

Byrne, BW, and Housby, GT, Martin, CM., and Fish P. M.(2002). Suction caisson foundations for offshore wind turbines. Wind Engineering, 26(3), 145-155.

Byrne, BW, and Houlsby, GT(2004). "Experimental Investigations of the Responses of Suction Caissons to Transient Combined Loading," *ASCE J. Geotech. And Geoenviron. Engrg.,* 130(3), 240-253.

Clukey, EC, Morrison, MJ, Garnier, J，et al. (1995). "The Response of Suction Caissons in Normally Consolidated Clays to Cyclic TLP Loading Conditions," *OTC 7796*, 909-918.

Clukey, EC(2001). "Suction Caisson Design Issues," *Proc. OTRC 2001 Inter. Conf. Geotech., Geological and Geophysical Properties of Deepwater Sediments,* Houston, April, 163-181.

Dyme, W, Houlsby, GT(1998). "Drained Behavior of Suction Caisson on Very Dense Sand," *OTC10994*, 765-782.

Hous, GT, and Byrne, BW(2000). "Suction Caisson Foundations for Offshore Wind Turbines and Anemometer Masts," *Wind Engineering*, 24(4), 249-255.

Jones, WC, Iskander, MG, Olson, RE, et al. (1994). "Axial Capacity of Suction Piles in Sand," *Proc. 7th Int. Conf. On the Behavior of Offshore Strucutres, Ed.* Chryssostomidis C., Pergamom. 63-75.

Luke, AM, Rauch, AF, Olson, RE, et al (2005). "Components of Suction Caisson Capacity Measured in Axial Pullout Tests," *Ocean Engineering,* 32, 878-891.

Senpere D, Auvergne GA (1982). "Suction Anchor Piles-a Proven Alternative to Driving or Drilling," *OTC4206*, 483-493.

Steensen-Bach, JO, (1992). "Recent Model Tests With Suction Piles in Clay and in Sand," *Proc. 24th Offshore Technology Conference, Houston, USA, OTC6844*, 323-330.

Taylor, RN(1995). "Geotechnical Centrifuge Technology," *Blackie Academic & Professional*, London.

Tjelta, TI, Guttormsen, TR, Hermstad, J(1986). "Large-Scale Penetration Test at a Deepwater Site," *Proceedings,Offshore Technology Conference, OTC 5103,* 201-212.

Tjelta, TL, Hermstad, J, Andenaes E(1990). "The Skirt Piled Gullfaks c Platform Installation," *OTC6473*, 453-462.

Wang,YH, Lu, XB, Wang, SY, et al. (2006). "The Response of Bucket Foundation Under Horizontal Dynamic Loading," *Ocean Engineering,* 33(7): 964-973.

Zhang, JH, Zhang, LM, Lu, XB(2007). "Centrifuge Modeling of Suction Bucket Foundations for Platforms Under Ice-sheet-Induced Cyclic Lateral Loadings," *Ocean Engineering*, 34(8-9): 1069-1079.