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A Dynamic Loading Device for Suction Foundations in Centrifuge Modeling*

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Abstract: Suction bucket foundations are widely used in the offshore platform for the exploitation of the offshore petroleum and natural gas resources. During winter seasons, ice sheets formed in Bohai Bay will impose strong impact and result in strong vibration on the platform. This paper describes a dynamic loading device developed on the geotechnical centrifuge and its application in modeling suction bucket foundation under the equivalent ice-induced vibration loadings. Some experimental results are presented. It is shown that when the loading amplitude is over a critical value, the sand at the upper part around the bucket softens or even liquefies. The excess pore pressure decreases from the upper part to the lower part of the sand foundation in vertical direction while decreases from near to far away from the bucket's side wall in the horizontal direction. Large settlements of the bucket and the sand around the bucket occur under the horizontal dynamic loading. The dynamic responses of the bucket with smaller size are heavier.

Key words: suction bucket foundation; dynamic loading device; ice-induced vibration; centrifuge modeling

0　Introduction

In recent years, suction bucket foundations have been applied increasingly often in offshore engineering (Clukey et al[1], 1995; Allersma et al[2,3], 1997, 2000). The first advantage of suction bucket foundations are attractive because of the convenient method of installation and repeatedly use. For an example, a suction bucket foundation 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 several studies on the installation and static bearing capacity have been carried out, the detail responses of suction bucket foundations under dynamic loadings have remained unknown (Senpere et al[4], 1982; Aas et al[5], 1992; Dyme et al[6], 1998). The dynamic loading condition is significant when suction buckets are used as the foundation of a platform. Wave loading and ice-induced dynamic loading cause the foundation to be subjected to cyclic loadings (Tjelta et al[7], 1990; Bye et al[8], 1995). The lack of experiences under these loading

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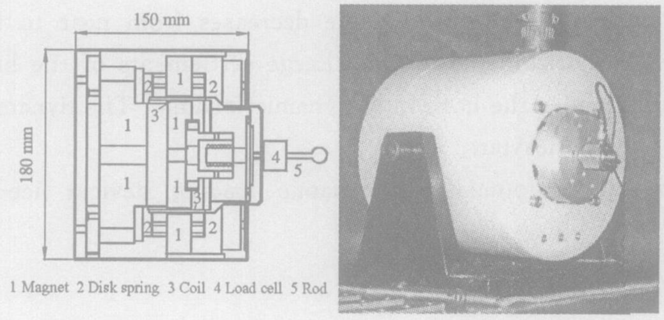
conditions led to a proposal for a test program intended to gain a deeper understanding. The considerable expense and time consuming nature of prototype tests mean that the investigation of the bearing capacity of real scale devices under different circumstances is of limited practicality. It is much easier to change parameters in small scale tests. But problems arise concerning the stress-dependent behavior of soil that the measured loadings are so low that measurements are not sufficiently accurate to visualize differences in design. These restrictions can be overcome if performing the tests in a geotechnical centrifuge. In a centrifuge the soil stresses over a similar depth are the same as in the prototype situation. For an example, at 100g (100 times the Earth's gravity), a suction foundation with a diameter 9m and a height of 9m may be simulated with a foundation with a diameter of 0.09m and a height of 0.09m. The scaling factor of the prototype to the model is 100 :1.

The ice-induced dynamic loading is the controlling loading in Bohai Bay in China. This type of horizontal dynamic loading is translated to the soil layer by platform and causes the parameters, e.g. strength and modulus of the soil layer, to degrade. As a result, the bearing capacity of bucket foundations decreases. Therefore, it is important and necessary to clarify the dynamic behavior of bucket foundations under this type of loadings in order to provide practical design method and parameters (Ding et al[9], 2003; Lu et al[10], 2003).

In this paper, we first introduced a set of dynamic loading devices designed for simulating the horizontal dynamic loadings. Then some experimental results of the ice-induced cyclic behavior of suction bucket foundations are presented. The effects of the loading amplitude, the size of the bucket and the structural weight are mainly investigated.



(a) Schematic diagram (b) Picture

Fig. 1 The electro-magnetic actuator

1 Dynamic loading device

The dynamic loading device is composed primarily of an electro-magnetic actuator as shown in Fig. 1. This actuator consists of a permanent magnet, a cylindrical silver coil, two copper disk springs, a load cell and a steel rod connected to the coil. There are two main technical challenges associated with the design of the actuator. (1) The cylindrical coil is suspended in a prefabricated space in the permanent magnet. The space is very tiny in order to avoid magnetic loss. However, since this cylindrical coil moves horizontally, it is orthogonal to the gravitational force, the deformation of the coil under this gravity may lock it in this tiny space. In order to avoid this situation a linear bearing and two disk springs are installed to make the coil move linearly without being locked. This technique has been demonstrated to be very effective. (2) The weight of the coil should be minimized to increase its deformation in the direction of loading. Silver wire is used to form the cylindrical coil so as to enhance the performance and limit the weight within 0.5 kg. The total weight of the device is 14 kg. Consequently, the vibration of the 0.5 kg coil would not impose significant impact on the strong box whose weight is 150 kg. The coil moves back and forth to apply cyclic loading on the model bucket through a rigid rod.

Fig. 2 is the controlling system for the loading device. The loading function is fed from a computer signal generator into a servo amplifier. The latter in turn generates the necessary electrical signals to control the intensity of electric current in the actuator. The output from the actuator in the form of loading is continuously monitored by the loading cell and fed back through a charged amplifier to the oscillograph. Output signal from pore pressure transducer (PPT) and linear variable displacement transformers (LVDT) were passed across the centrifuge slip-ring and converted to digital data.

With this device, different amplitudes and the frequencies of horizontal cyclic forces are reproduced at centrifugal acceleration of 80 g. Therefore, the scaling factor of the load frequency of the prototype to the model is 1∶80, and the scaling factor of the load amplitude of the prototype to the model is 6400∶1. In the centrifuge, the peak cyclic loading of 100 N and 64 Hz represents a prototype loading of 640 KN and 0.8 Hz. Table 1 shows the technical specifications of this actuator. The force-electricity relation at 80 g is shown in Fig. 3.

Tab. 1　Technical specification of the electromagnetic actuator

Diameter (mm)	Length (mm)	Weight (kg)	Frequency range (Hz)	Peak cyclic load (N)
180	260	14	1～120	100

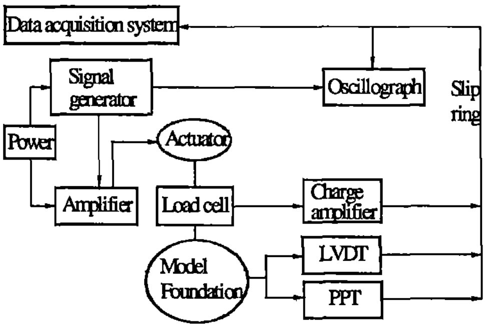


Fig. 2　Controlling system of the actuator

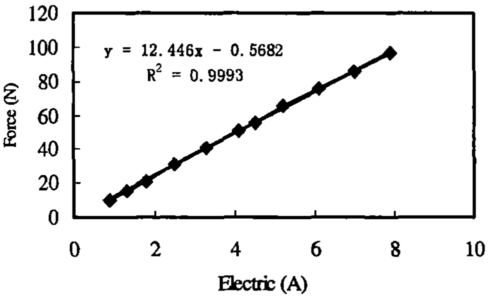
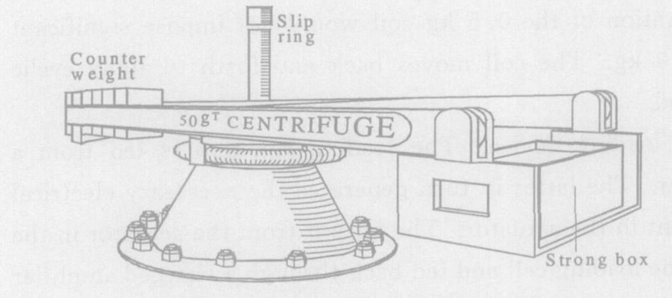


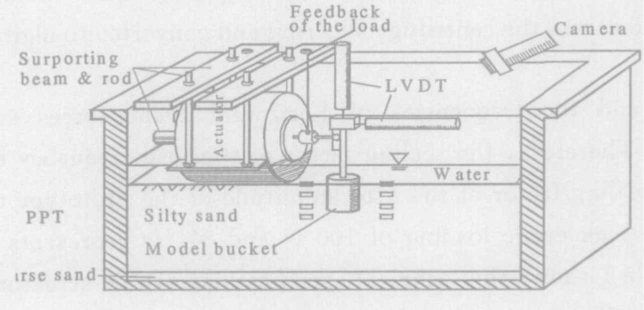
Fig. 3　Force-electricity relation at 80 g

2　Centrifuge system configuration

Fig. 4 shows the configuration of the centrifuge and the model. The internal area of the aluminum strong box measures 600 mm × 350 mm and height is 350 mm. The thickness of the silty sand is 210 mm, underlain by 20 mm coarse sand which is to prevent the piping during penetration of water. There is 20 mm high water above the soil surface. The actuator is supported by two steel beams fastened on the flange. Two rods fix the back of the actuator against the side of the strong box as shown in Fig. 4. A miniature TV camera was attached to the flange of the model container to monitor the motion of the model bucket. The model bucket is a steel cylinder which has an external diameter of 60 mm, an internal diameter of 56 mm, and a height of 72 mm. The dead weight of the platform was simulated by a ballast mounted on the top of the shaft. The movement of the bucket was monitored by two LVDTs. When the centrifuge model is tested under 80 g, its behavior would primarily correspond to that of a prototype footing with a diameter of 4.8 m.



(a) 50 g-t centrifuge at Tsinghua University



(b) Schematic diagram of centrifuge model

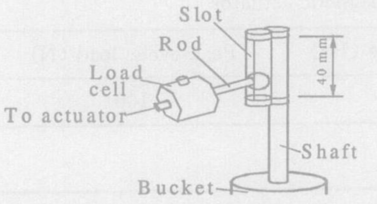


Fig. 4 The layout of the model

3 Preparation of the experiments

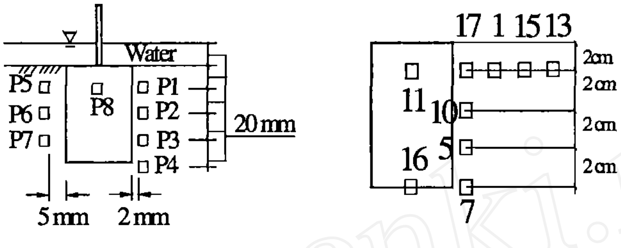
The experiments are performed in the 50 g-tons centrifuge in Tsinghua University. The maximum of the centrifuge's acceleration is 200g. The payload is 250kg under 200g. The experimental material is fine sand whose special gravity is 2.69 and the average grains diameter is 0.14mm. The permeability is 5×10^{-3} mm/s. Three model buckets made by steel are used in experiments. The inner depths (do not include the top cap thickness) are 48mm, 72mm and 90mm, respectively, the inner diameters are all 60mm, the thicknesses of the wall and the top cap are both 2mm. A fine pipe with an outer diameter of 10mm, an inner diameter of 8mm and a height of 100mm is welded at the center of the top cap. A sliding groove permitting a ball moving up and down to adapt the settlement of the bucket is connected with the pipe closely. One end of a steel pole is jointed with a ball, the other end of the pole is connected with the electromagnetic vibration actuator. Thus the pole cannot be dragged when the bucket settles. One LVDT is located at the top of the fine pipe to measure the vertical displacement. One LVDT is located at the fine pipe at the same level as that of the steel pole to measure the horizontal displacement. The other two LVDTs are located on the sand surface to measure the settlements of the sand surface at different positions. Ten PPTs made in Druck Co. (English), are buried in the sand around and in the bucket (Fig. 5). The PPTs are not fixed but suspended in the sand.

In order to guarantee the repeatability, 210mm thick model sand layer is divided into five layers to create and be compacted gently by hand striking. This course is controlled by dry density. The water depth over the sand surface is 1cm.

After the dry sand sample has been prepared, the sand layer is saturated by penetrating water into from the bottom of the tank through a vulva. A 20mm thick coarse sand layer is deposited at the bottom of the tank to guarantee the water rise uniformly and preventing the piping. When the water level is over the sand surface, a vacuum pump is used to pump the gas in the sand for 38 hours to increase the saturation.

Two types of PPT layout are adopted in the tests. The first type: one row PPTs are disposed in the sand along depth at the actuator side and 2mm away from the bucket's side wall. The upper one is 20mm below the sand surface. The others have a 20mm distance one by one from the upper to the lowest. Two rows are disposed in the sand at the opposite side. One row is 2mm away from the bucket's wall and the other row is 52mm away from the bucket's wall. The second type: two rows are both 2mm away from the bucket's side wall on the opposite side in the loading direction. A row of PPTs are disposed in the horizontal direction 20mm below the sand surface. Except for the PPTs disposed outside of the bucket, one PPT is put in the bucket 20 mm below the top and one is put at the bottom of the bucket (Fig. 5).

It is difficult to make real ice in a centrifuge and drive it to interact with platform, thus an equivalent ice-induced dynamic loading is adopted in the experiments. The measured frequency of the platform caused by the dynamic ice-induced loading is 0.8～1.2 Hz in Bohai bay, China. Accordingly, the frequency in experiments is adopted as 0.8 Hz. The loading position is 8cm over the top of the bucket at the beginning. This relative position will change a little with the development of the settlement. Steel blocks with different weights are located at the top of the fine steel pipe to simulate the effects of the structural weight.



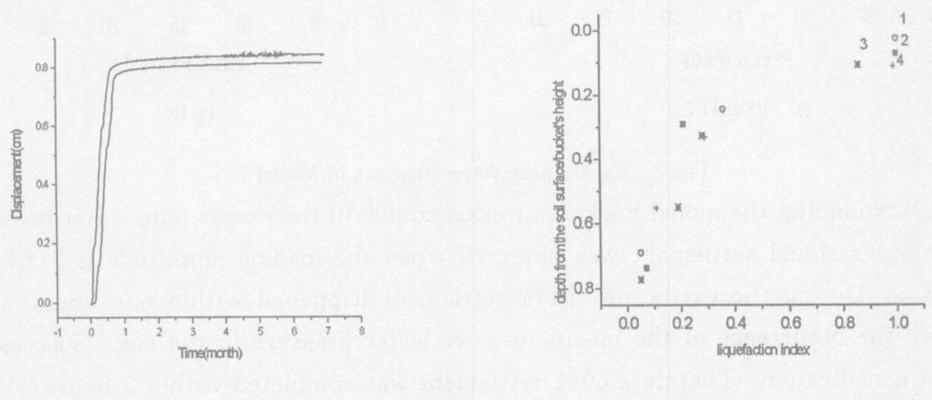
Model 1　　　Model 1

Fig. 5　Two types of the pore pressure translators

4　Experimental results

4.1　The repeatability of the experiments

In order to guarantee the repeatability, some experiments are repeated three or more times. In Fig. 6, the repeated results under the condition: the loading amplitude is 60N, the frequency is 0.8 Hz. The bucket is with an inner diameter of 60mm and an inner height of 72mm, there is not a steel block placed at the top of the fine steel pipe, are shown. The consolidation course is under 80g and lasts for 40 minutes. The dry densities before and after consolidation are 1520g/mm^3 and 1600g/mm^3, respectively. The buoyant unit density is γ'= 971g/mm3 and the settlement is 8mm after consolidation finished. (If there is no indication, the data are all in the model in the this paper.) It is shown that the consolidation course has good repeatability (Fig. 6(a)).



(a) Settlement (Prototype)　　(b) Pore pressure along the depth

Fig. 6　The repeatability of the experiments results

The repeatability of the pore pressure along the depth of the sand foundation is shown in Fig. 6 (b). It is shown that the repeatability is good also.

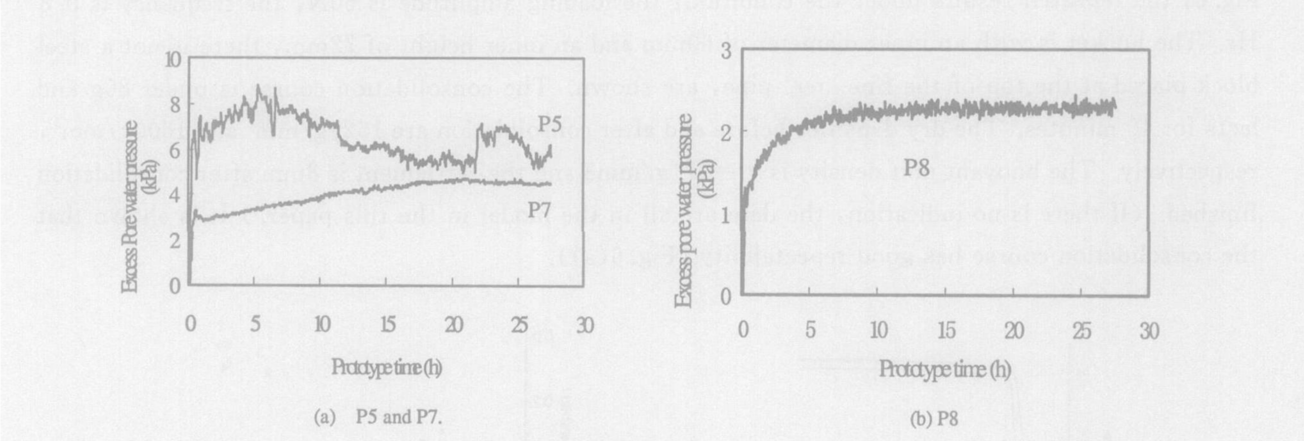
Although a total of 40 experiments were performed in the centrifuge, some of the results were discarded during the analysis as centrifuge performance related problems occurred including PPTs′ being not work.

4.2 The dynamic responses

The results presented here is in the following conditions: The cyclic loading amplitude is 60 N and frequency is 64 Hz, which corresponds to a prototype load of 384 kN and 0.8 Hz. The model bucket has a diameter of 60 mm and a height of 72 mm. Fig. 7 shows the excess pore water pressure during excitation (prototype scale, PPT is placed as Model 1 in Fig. 5). It is shown that the excess pore pressure recorded by P5, P7 and P8. The ratio of the maximum excess pore water pressure Δu_m, over the vertical effective stress in the soil is approximately to be 1.0 at P1, as shown in Table 2. Liquefaction potential may exist within a depth of 1.5 m (in prototype). Also when centrifuge was stopped, fine soil particles were observed at the surface of the ground on the edge of the bucket. Since P1 is located near the surface, it also presents sharp variation, indicating fast dissipation of excess pore water pressure. Both the maximum and residual excess pore pressure profiles, $\triangle u_m$ and $\triangle u_r$, decrease with the soil depth.

Fig. 7a shows that the excess pore pressure recorded by P5 and P7. These two transducers were installed at 5 mm distance to the opposite side of the bucket, they present distinct peaks. The ratio of $\triangle u_m / \sigma_v'$ at P5 is 0.94, being very close to 1.0. However, since it is located comparatively far from the bucket, the peak comes up slowly. P5 also experiences sharp variation and then decreases to a lower value. The two PPTs have their residual values $\triangle u_r$ decrease with the soil depth.

Fig. 7b shows that the excess pore pressure generated inside the model bucket. Positive pore pressure instead of suction is generated, indicating that this horizontal loading leads to shear compression of the inside soil.



(a) P5 and P7.

(b) P8

Fig. 7 Excess pore water pressure in Model 1

The soil surrounding the model bucket is weakened due to the excess pore water pressure. 80 cm (prototype scale) residual settlement was observed when the loading amplitude is 3.84×10^5 N, as shown in Fig. 8. During the excitation, 61 % settlement happened within one hour, which seems associated with the occurrence of the maximum pore water pressure in the soil. Successive shaking makes the silt densification. Therefore 80 % settlement was completed within 5 hours when the pore water pressures tend to be stable. Since the model bucket is connected to the actuator. It is shown that the settlements decrease from the bucket to far away. The settlement at 20m (in prototype) away from the bucket′s side wall is not obvious, while the settlement 8m away is nearly half of that at the top of the bucket. This may be caused by the heterogeneous settlement. The prototype residual settlement of the bucket is 37 cm, as shown in Fig. 8. 95 % settlement of Model 2 happened within three hours.

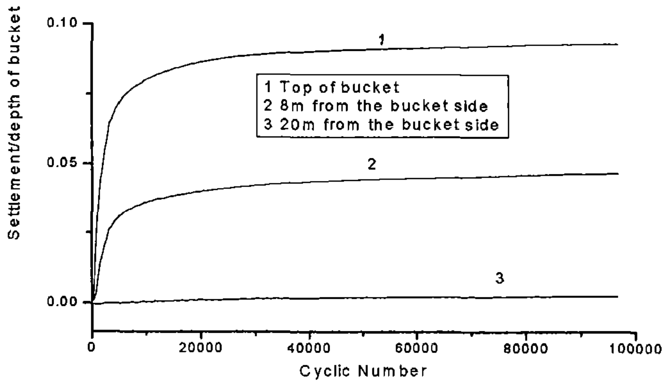


Fig. 8 Settlement of the bucket foundation

5 Discussions and conclusions

A dynamic loading device composed primarily of an electromagnetic actuator has been developed. With this device, the amplitude and the frequency of a horizontal cyclic force is reproduced at centrifugal acceleration of 80 g.

Centrifuge tests have been carried out to investigate the behavior of a suction bucket under horizontal cyclic loading for a duration of prototype 26.7 hours. The experimental results indicate that excess pore water pressures were generated in the silt surrounding the bucket. The maximum excess pore water pressure is approximately equal to the vertical effective soil stress, e. g. $\triangle u_m/\sigma'_v$ ratio is 0.94～0.96. Liquefaction potential exists within a depth of 1.5 m. The residual pore water pressure decreases with the depth. Since the soil is weakened during long time excitation, great settlement was observed.

As we all know, the disturbance bear by the sand layer will become heavier with the increase of loading amplitude. Therefore, the excess pore pressure and the settlement increases fast and high. At the first stage, the pore water is difficult to drain, so the pore pressure increases. The strength of the sand layer decreases and even liquefies with the increase of excess pore pressure. Nevertheless, the diffusion of the excess pore pressure will be over the generation gradually with the increase of the gradient of pore pressure. Accordingly, the sand layer settles and the pore pressure decreases.

It may be explained by the fact that the bucket with smaller size has smaller inertial moment and structural weight, that is say, the bucket with small size has smaller cost of energy under the same amplitude than the bucket with large size. The bucket with small size has smaller bucket-sand interface than the bucket with larger size also. Therefore, the sand layer bears more loading around the bucket with smaller size than with bigger size.

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用于吸力式基础离心机模拟的动力加载设备

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摘要: 吸力式桶形基础广泛地应用于海洋油气开发的海洋平台。在冬季,渤海冰排会对平台产生强烈的冲击,引起振动。本文介绍了一套用于土工离心机实验的动力加载设备,并介绍了该套设备在模拟吸力式桶形基础在受到等效动冰载作用下的响应的实验研究情况及实验结果。结果表明,当载荷幅值超过一个临界值时,地基上部会发生软化甚至液化。超孔隙水压从土体上部到下部,从桶形基础壁面到远处逐渐减小。在动载荷作用下,桶形基础和临近土体会发生大的沉降。桶形基础尺寸越小,动载荷响应越大。

关键词: 吸力式桶形基础; 动力加载设备; 冰致振动; 离心机模拟

中图分类号: TU411.5 **文献标识码**: A