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Ocean Engineering 33 (2006) 964–973
OCEAN ENGINEERING
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Technical note

# The response of bucket foundation under horizontal dynamic loading

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Received 8 December 2004; accepted 25 July 2005
Available online 28 November 2005

**Abstract**

The experimental investigation of the response of suction bucket foundation in fine sand layer under horizontal dynamic loading has been carried out. The developments of settlement and excess pore pressure of sand foundation have been mainly studied. It is shown that the sand surrounding the bucket softens or even liquefies at the first stage if the loading amplitude is over a critical value, at later stage, the bucket settles and the sand layer consolidates gradually. With the solidification of the liquefied sand layer and the settlement of the bucket, the movement of the sand layer and the bucket reach a stable state.


*Keywords:* Suction bucket foundation; Saturated sand; Liquefaction; Dynamic loading

## 1. Introduction

Because of many virtues, such as economy and being used repeatedly, the bucket foundations have attracted much attention of oil companies in recent years (Dyme and Houlsby, 1998; Aas and Andersen, 1992; Senpere and Auvergne, 1982; Tjelta et al., 1990; Bye et al., 1995). Suction foundations are attractive first because of the convenient method of installation and repeated use. For an example, a bucket foundation with a diameter of 9 m and a height of 10 m can be installed in 1–3 h by using only a pump. The second advantage is that it may mobilize a significant amount of reverse-end bearing or passive suction during uplift. Despite several studies about the installation and static bearing

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0029-8018/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.oceaneng.2005.07.005

capacity have been studied, the detail responses of the suction bucket foundations under dynamic loadings have remained unknown. 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. The lack of experiences with these loading conditions leads 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 (Allersma et al., 1997, 1998, 2000; Clukey et al., 1995).

Up to now, the bearing capacity characteristics of this type of foundation, especially under dynamic loadings, are not clarified. Many platforms have been or will be constructed on saturated sand foundations or on the foundations with saturated sand interlayers. When wave loading or ice-induced dynamic loading act on the upper structures of a platform, the sand surrounding the bucket will be perturbed by the loadings transmitted from the bucket. Under dynamic loadings, the excess pore pressure in the saturated sand may accumulate and the sand may even liquefy. With the degradation of the sand layer strength and the drainage of the pore water, the bucket and the sand surrounding the bucket will sink gradually, the pore pressure may rise and even lead to liquefaction of sand layer around the bucket foundation (Lu et al., 2003).

On the viewpoints of above, the responses, especially the deformations of the bucket and the sand surrounding the bucket and the excess pore pressure under horizontal dynamic loadings, are investigated in this paper.

## 2. Introduction of the experiments

The experiments were carried out in a tank of length × width × height = 50 cm × 50 cm × 50 cm. The sizes of three model buckets were (diameter × pure height (not

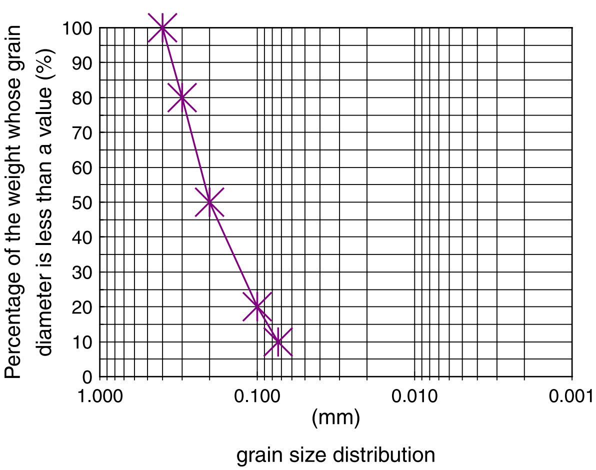


Fig. 1. The grain size series.

including the height of the top plate)): 5 cm × 10 cm, 10 cm × 10 cm and 5 cm × 7.5 cm. The upper side was closed, while the lower side was opened. The thickness of the top plate was 1 cm. The thickness of the side wall was 0.2 cm. A small hole was on the top plate for drainage during penetrating the bucket into the sand layer. When the bucket penetrates fully, the hole was closed. A fine pipe with an inner diameter of 0.8 cm and an outer diameter of 1 cm was welded with the bucket on the centre of the top plate.

The saturated Zhangzhou (in Fujian province, China) fine sand was adopted in the experiments. The internal friction angle of the sand was 38° at the stress level of 100–500 kPa. The dry density was 1.55–1.70 g/cm$^3$. The grain size series is shown in Fig. 1.

The sand foundation was prepared by sand raining method layer-by-layer. Each layer is 5 cm thick and was compacted by a steel plate. Water was penetrated into the sand layer through a hole at the bottom of the tank when the sand layer thickness reached 45 cm. A 1 cm thick layer of coarse sand was laid on the bottom of the tank to increase the permeability and to prevent piping. The water altitude was 1 cm over the sand surface after finishing penetration water.

An electro-oil server loading facility was developed and adopted in our experiments. This system may output loadings with frequencies 0.1–5 Hz, and amplitudes 0–80 kg. The maximum of the permitted displacement of the loading head was 50 mm. The dynamic horizontal loading was applied on the fine pipe at the point of 12 cm over the top plate. A force transducer was connected with the load head and the fine pipe. When the responses of model bucket foundations do not develop anymore, the loading was halted. The pore pressure, the horizontal displacements 12 cm above the bucket's top plate, the vertical displacements of the bucket and of the sand layer surface, the loading amplitude were measured in each experiment. The pore pressure was measured by a PPT which was located 1 cm away from the bucket's side wall and 2 cm below the sand surface. The displacements were measured by LVDTs (Fig. 2). The loading amplitudes adopted in our experiments were 10–40 N. The loading amplitude and the horizontal displacement of the bucket were shown in Figs. 3 and 4.

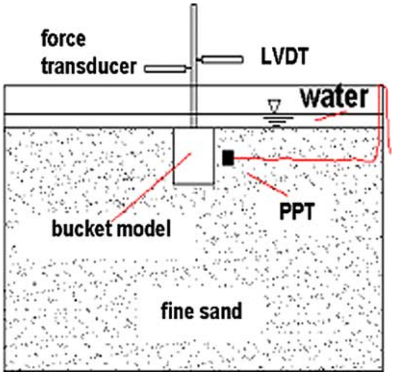


Fig. 2. The layout of the model.

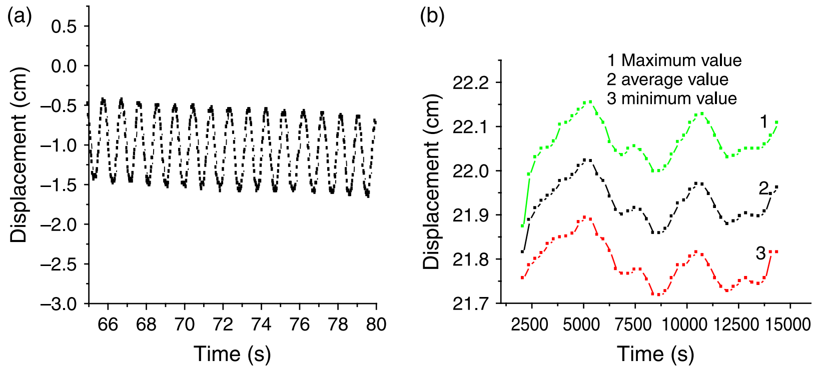


Fig. 3. The responses of displacement. (a) Date in some continuous cycles. (b) Data shown are 500 cycles between each point.

## 3. Experimental results

The steel model buckets were penetrated into the sand at the center of the tank in the beginning of each experiment by two ways: penetrating by pressing into or by suction, in this way, to investigate the effects of penetration method. The loading was applied on in two ways: immediately or waiting for half-an-hour after finishing the bucket's penetration, to investigate the effects of the diffusion of pore pressure generated during the penetration of the bucket. The results shown in next sections are in the condition of penetration by pressing into and applying loading waiting for half-an-hour after finishing the bucket's penetration if there is no note.

It was shown that when the loading amplitude was small enough, there were not obvious responses. With the increase of loading amplitude, even if no liquefaction occurred, the sand layer surrounding the bucket settled gradually and a horse-saddle-type pit was formed (Fig. 5). The scope of the pit was bigger in the loading direction than that perpendicular to the loading direction. The pit developed to a steady-state gradually.

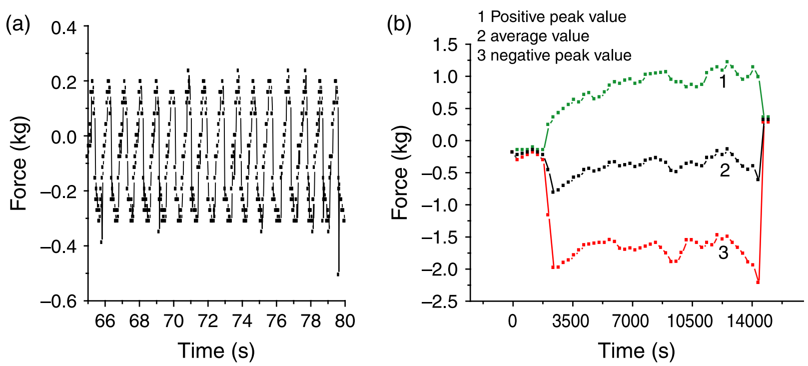


Fig. 4. The force applied on the bucket. (a) Date in some continuous cycles. (b) Data shown are 500 cycles between each point.

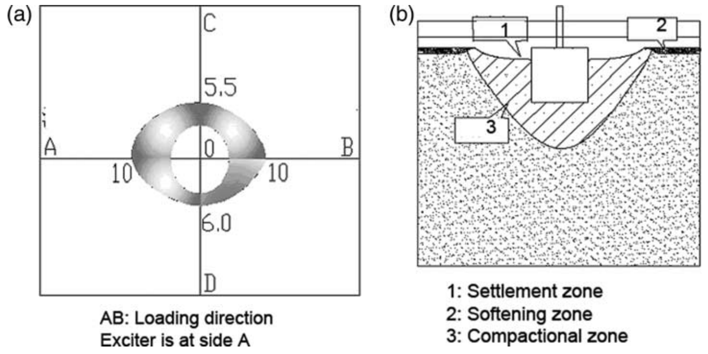


Fig. 5. The effected area. (a) Down-looking figure. (b) Side-glance figure.

The sand layer surrounding the bucket about one times of the diameter of the bucket in the loading direction softened or liquefied, while 50% of the diameter of the bucket perpendicular to the loading direction softened or liquefied.

The bucket settled gradually after the loading was applied on. It was caused by the liquefaction or the softening of the sand layer surrounding the bucket. With the settlement

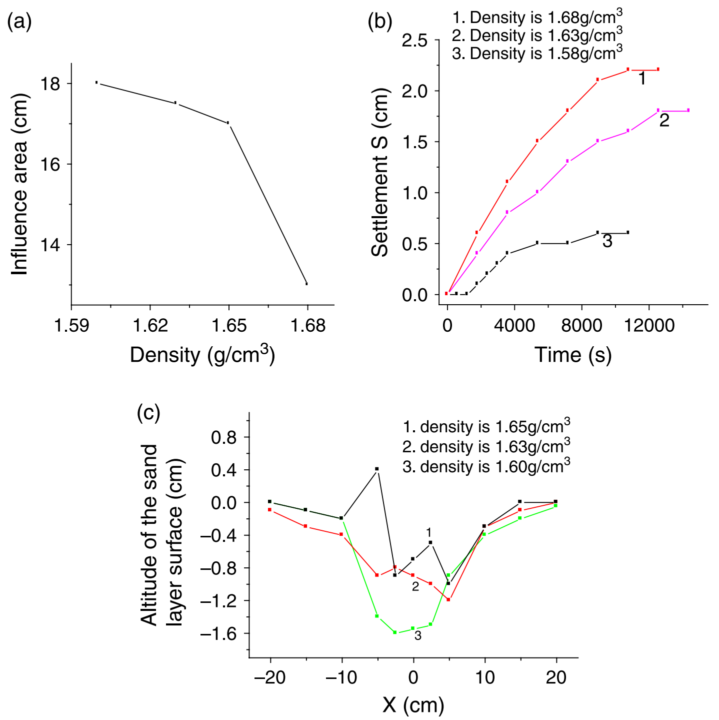


Fig. 6. The influences of density (the force is $f = 25$ N). (a) Density versus influenced area. (b) Development of settlement. (c) The altitude of sand layer surface in loading direction ($X$ is the coordinate in the loading direction).

of bucket and the diffusion of excess pore pressure, the reinforcement of the sand to the bucket became stronger and stronger. Therefore, the settlement development of the bucket became smaller and smaller, and stopped eventually. When the loading amplitude was big enough, which may produce big displacement, an obvious sliding face appeared in the sand layer. The sand near the slide face was dilatant and produces cracks (this phenomenon is seen when the bucket is located near one side wall of the tank). The softened and liquefied sand were pressed away in this case.

At the place some distance away from the bucket, the responses of the sand layer degrade to an elastic state or even there are no responses. Thus the effected area is limited. When the effected area (having obvious displacement) did not develop anymore, the movements of the bucket and the sand foundation reached a steady state.

The results of the effect of density are shown in Fig. 6. It is shown that with the increases of the sand density, the effected area and the settlement decreased. It may be explained by the fact that the strength of sand layer increases with the increase of the density. That means, the ratio of the loading amplitude to the sand layer strength decreases, therefore, the effected area decreases. When the density increase to some value, the responses caused by the applied loading is elastic, therefore the effected area does not occur.

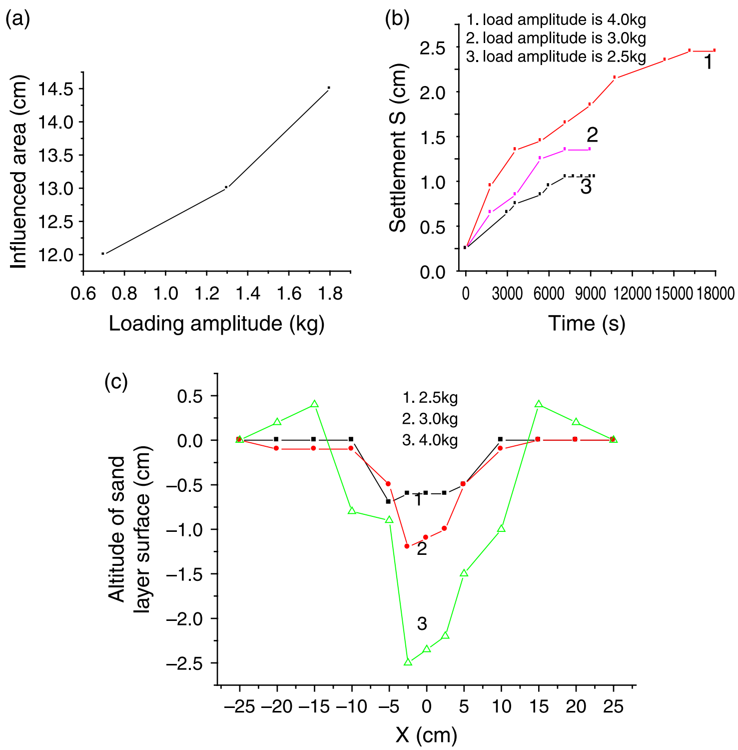


Fig. 7. The influences of the loading amplitude (the dry density is 1.6 g/cm$^3$). (a) Loading amplitude versus influenced area. (b) Development of settlement. (c) The settlements in loading direction.

The results of the effect of loading amplitude are shown in Fig. 7. It is shown that with the increase of the loading amplitude, the effected area and the settlement increase. The reason is that with the loading amplitude increasing, the ratio of the loading amplitude to the sand layer strength increases also.

The results of the effects of loading frequency are shown in Fig. 8. It is shown that with the increase of the loading frequency, the effected area increase and the settlement decreases. The reason is that with the increase of loading frequency, the water is more difficult to drain, the reason is that the dimensional permeability ($k/\omega H$, $k$ is Darcy permeability coefficient, $\omega$ is loading frequency, $H$ is sand layer height.) becomes smaller and smaller with the increase of frequency. Therefore, the effected area and settlement decreases.

The results of the effect of size of bucket are shown in Fig. 9. It is shown that at a critical value of the ratio of the bucket's height to the diameter, the effected area increased and the settlement is the biggest. When the ratio is over the value or less than the value, the responses decrease. The reason may be that at a given loading level, the responses of the sand layer is correlated to the contact area between the sand and the bucket's side wall and the bottom wall, so there exists an optimized ratio of the bucket's height to the diameter, at this condition, the sand bears the strongest loading in unit contact area, which makes the responses the heaviest.

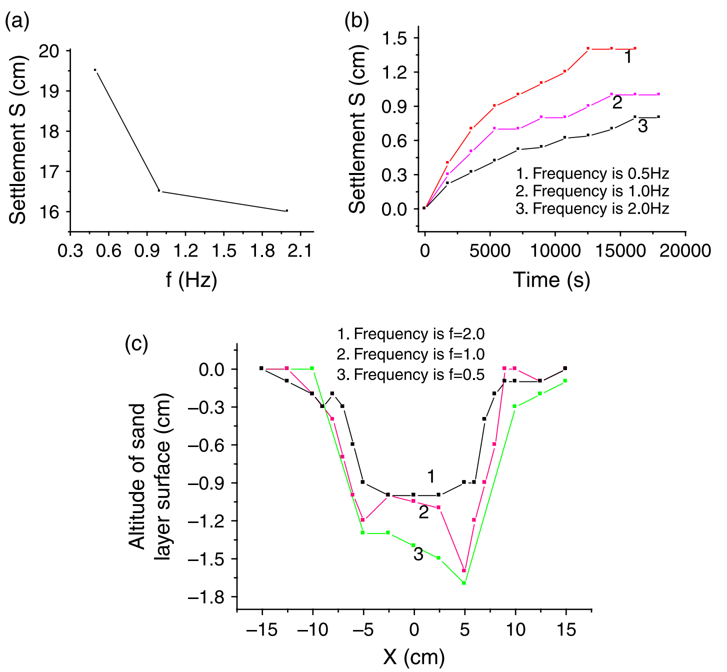


Fig. 8. The influences of the loading frequency (the dry density is 1.6 g/cm$^3$). (a) Force frequency versus influenced area. (b) Development of settlement. (c) The settlements in loading direction.

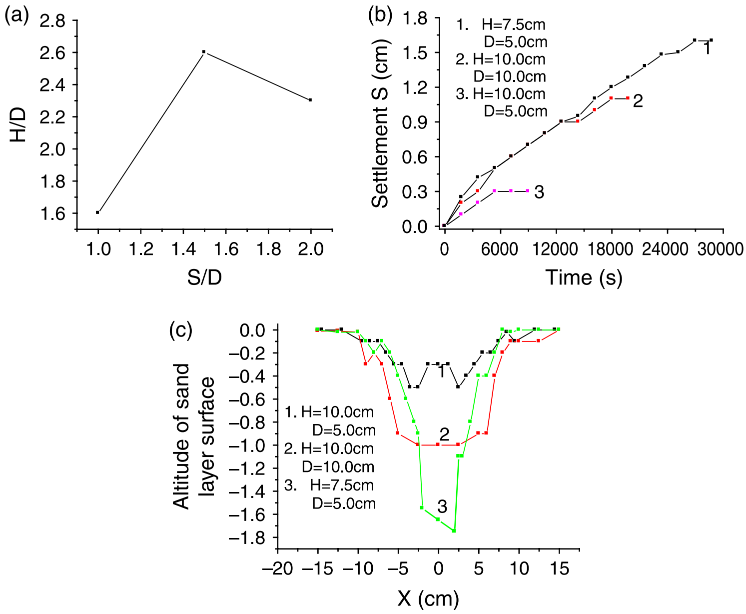


Fig. 9. The influences of the bucket size. (a) Bucket's size versus effected area. (b) Development of settlement. (c) The settlements in loading direction.

The comparison of the responses of the bucket in the conditions of applying loading immediately (Style I) or half-an-hour (Style II) after the bucket arrived at the given place by suction is given in Fig. 10. It is shown that the settlement is smaller in the condition of Style II than that in the condition of Style I. The reason is that the pore pressure have diffused in the condition of Style II, so the strength of the sand layer has recovered, while

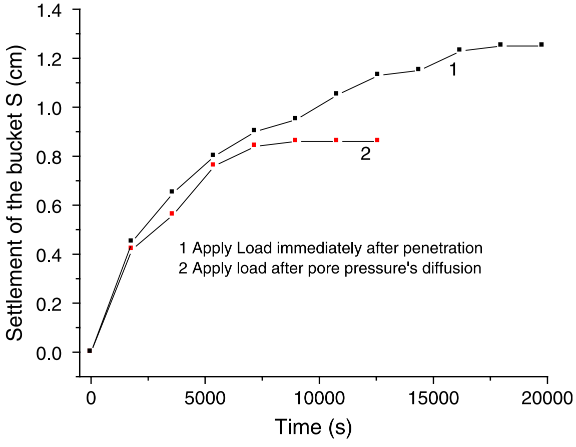


Fig. 10. The effect of pore water pressure diffusion on the settlement of the bucket.

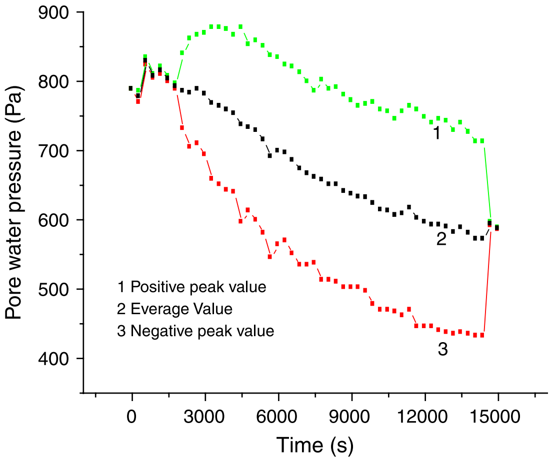


Fig. 11. The pore pressure development.

in the condition of Style I, the strength of the sand layer is small because of the pore pressure increase and disturbance of the skeleton caused during penetration.

During loading, the pore pressure increases at the first stage and then decreases gradually (Fig. 11). The reason is that at the first stage, the sand layer intents to contract, but the water is difficult to drain, so the pore pressure increase. With the increase of pore pressure, the strength of the sand decreases, so the sand begins to consolidation, the pore pressure decreases gradually.

## 4. Conclusions

The experimental investigation of the response of suction bucket foundation under horizontal dynamic loading has been carried out. It is shown that there is no liquefaction occurring when the amplitude is smaller than a critical value. Nevertheless, when the amplitude is bigger than the critical value, the sand surrounding the bucket softens or liquefies, and settles gradually to form a saddle-type hole. The size of the hole is bigger in the direction of loading than that perpendicular to the loading direction. The settlement of the bucket is bigger than that of the sand, thus the bucket is below the sand layer surface after experiments. The non-uniform settlement of the sand surrounding the bucket makes a cycle crack occurring between the effected area and the non-effected area. There is about one times size of the same as the bucket's diameter liquefies in the loading direction; while about 50% size of the bucket's diameter liquefies perpendicular to the loading direction. The influenced area increases with the decrease of the sands' density and the increase of the loading amplitude and the decrease of the loading frequency. It is shown that there exists an optimized ratio of the bucket's height to the diameter, at this condition, the sand bearing the strongest loading in unit contact area, which makes the responses acute.

The responses of the bucket in the conditions of applying loading immediately is heavier than that half-an-hour after the bucket arrived at the given place.

## Acknowledgements

This program is supported by the fund of Chinese Ocean Oil Co. and Chinese Academy of Sciences 'KJCX2-SW-L03-01' (40025103) and National Natural Science Fund (No. 10202024).

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