Centrifuge model tests on installation of suction caissons in sand

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ABSTRACT

When suction caissons are installed in sand layer, upward seepage flow occurs within sand due to the generation of hydraulic gradient. Upward hydraulic gradient (and hence upward seepage flow) significantly reduces the soil resistance and facilitates the caisson installation. However, this can create significant plug loosening and uplift the sand plug inside the caisson. However, the behavior of seepage flow and soil plug heave during suction installation are not yet fully understand. Therefore, this study aims to investigate the soil behavior during suction installation of caissons in sand and its influence on the installation process using the centrifuge model tests. To investigate the effect of suction installation on soil behavior, two types of centrifuge model tests were designed: half-section model test and total-section model test. From the half-section model test, the mechanism of sand heave formation was analyzed using image based technique. In the total-section model test, variation of suction pressure which was directly related with seepage flow was assessed. CPT tests were also conducted after removing the suction-installed caisson and found the evidence of soil plug loosening. The results emphasize the effect of soil plug loosening not only for the installation but also for the further performance.

Keywords: suction caisson, suction installation, sand, centrifuge

1 INTRODUCTION

Recently, offshore development in deep-sea is growing for oil and gas extractions as well as construction of wind farms. Suction caissons, which are cost effective and have many advantages such as quick and easy installation, have been considered as an alternative to the conventional foundation.

A suction caisson is installed by self-weight and a hydraulic pressure difference induced by pumping out the water inside the caisson. Hydraulic pressure difference between the inside and outside the caisson creates additional driving force. Especially, this causes upward seepage flow which reduces the effective stress of soil inside the caisson and hence reduces the penetration resistance of caisson. However, the sand inside the caisson is loosened by upward seepage flow because of reduction in effective stress of the soil. This soil loosening creates soil plug heave. This soil heave eventually interrupts the penetration of caisson to the target depth, and hence introduces scoring around the caisson and adversely affects on its further performance.

In the field trials, very different degrees of soil plug heave were formed. The internal soil heave about 40 % of penetration depth was reported in the Gorm project (Senpere and Auvergne, 1982) while negligible soil plug heave was observed in the Draupner E platform installation (Tjelta, 1995). The formation of soil plug during suction installation was also observed in the lab tests. Tran et al. (2007) reported that the typical soil heave was approximately 7 to 9 % of skirt penetration depth in homogeneous sand. Moreover, the soil heave in the layered soils, comprising sands and silty sands, was found to vary between 15 and 20 % of wall penetration. Although soil heave formation is important role in the installation and further performance, the mechanism of soil plug heave and its effect on the seepage flow (and hence suction pressure) are not yet fully understood.

This paper, therefore, aimed to investigate the mechanism of soil plug heave and variation of suction pressure in the result of seepage flow from a series of centrifuge tests in sand. Two types of centrifuge test were planned: half-section model test and total-section model test. From the half-section model test, the mechanism of sand heave formation was analyzed by directly observing the soil movements thorough the transparent window equipped in the model box. In the total-section model test, suction pressure and seepage flow created by suction installation were assessed. CPT tests were also conducted at the location inside the caisson after removing the suction-installed caisson and
found the evidence of soil plug loosening. The results emphasize the effect of soil plug loosening not only for the installation but also for the further performance.

2 TEST PROGRAM

2.1 Half-section model testing system

To observe the formation of soil plug heave, half-section model testing setup was planned. The test was simulated by a specially designed container equipped with transparent Perspex window in front face. The inner dimension of the container is 140 mm width, 580 mm length and 650 mm height as shown in Figure 1. The soil and caisson movements can be captured through a transparent window on one side. In addition, guide rail system was set up to ensure caisson to be penetrated into soil without tilting and to prevent water leakage through the contacting surface by pushing the model caisson toward the window.

Half-section caisson model with 100 mm × 100 mm×1 mm (Dc×L×t, where Dc indicates diameter; L is length; and t is thickness of model caisson), equivalent to 5 m × 5 m × 50 mm in prototype dimension at 50 g, was designed. Rubber pad was attached along the sliding surface to reduce the friction and to block the water leakage. Thin hose was connected to the fitting in the caisson lid to pump out the water. Water pumping can be achieved by gravity flow created by head difference between the water level inside the container and the elevation of hose outlet. Pumping was started and stopped by opening and closing water discharged valve which was operated pneumatically.

Two pore water transducers (PPTs) were used for measuring the suction pressure (one inside and the other outside the caisson at the same elevation). Vertical displacement of caisson was measured by a laser sensor. Soil movement was observed from CMOS camera which was remotely controlled in front of the model container.

2.2 Total-section model testing system

To investigate the variation of suction pressure and seepage flow during suction installation, total-section model testing system was set up (Fig. 2). A guiding system which allows the caisson to vertically move freely but to prevent lateral movement using two linear bearings and hollow rod was connected to the top of caisson lid.

Model tests are performed in a cylindrical container with dimensions of 700 mm (height) and 900 mm (diameter). The model caisson with 200 mm×200 mm×2 mm, equivalent to 5m×5m×50mm in prototype dimension at 25 g, was used in this study. This has same prototype dimension with that of half-section caisson model.

Differential pressure transducer (DPT) was used for measuring the suction pressure. In addition, three PPTs were attached inside the caisson along the wall at different elevations to measure the change of pressure depending on the location. Vertical displacement was measured by a laser sensor and flowmeter was also used for recording the seepage flow. Installation method is same with the half-section model test.

2.3 Preparation of sand layer and test procedure

Silica sand was used in this test. This sand is mainly comprised with quartzite. The soil properties of the sand are; specific gravity Gs = 2.65, mean grain size (D50) = 0.237, maximum dry density, γmax = 1.64 and minimum dry density, γmin = 1.24. The sand permeability (k) was ranged from k = 5.3×10-5 to 2.1×10-4 m/s. Friction angle was 40° (at relative density of 60 %). Details of tested soil can be found in Kim et al. (2015).

Soil models were prepared by a pluviation method. Total two soil models with relative density, Dr = 60 %, were prepared. One is for half-section model test and
the other is for total-section model test. The test conditions were summarized in Table 1. Total soil model height was 400 mm for half-section model test and 450 mm for total-section model test. The prepared soils were saturated by applying the water. Total water height above the soil surface was set to be 200 mm for both tests. After soil preparation, the testing setup was installed.

In each test, the caisson was fully submerged before being positioned to the soil surface to ensure that there was no air trapped inside the caisson. Then, the model caisson was lowered by hand until the skirt wall was reached to 20 mm below the soil surface at 1g. After connecting the water pumping hose into the outlet located at the caisson lid, the test-ready container was spun up to the target g-level. Once the caisson settled down and no further movement was recorded at the target g-level, the camera was activated and continuous images were captured at a rate of 0.5 Hz (only for half-section model test). Then, suction installation was started by opening the pumping valve.

| Table 1. Test conditions. |
|---------------------------|
| Test ID | g-level | Dc×L×t | Dc×L×t | γ' sub* |
|---------|---------|--------|--------|---------|
| T1, (Half) | 50 | 100×100×1 | 5×5×0.05 | 9 (60) ** |
| T2, (Total) | 25 | 200×200×2 | 0 | |

* submerged soil unit weight  
** soil relative density in % unit (Dr)

3 TEST RESULTS

3.1 Formation of soil plug heave during installation (T1)

In the half-section test, suction pressure measured during installation is not presented here.

Continuous images captured during installation were analyzed to trace the soil movement around the caisson during installation. The PIV analysis was performed by GeoPIV (White et al., 2003).

Figure 3 shows PIV analysis results of suction installation for z/Dc = 0.5 (where, z indicates caisson penetration depth) with an incremental penetration of about Δz/Dc = 0.03 superimposed on the captured images. The results clearly show the trend of soil movements. Considerable sand movements were observed not only close to the skirt tip but also plug center, indicating soil plug heave. Large upward soil movement occurred near the soil surface and was attenuated with the closer to the level of skirt tip (Fig. 3a). There is clear trend that the soil particles just beneath the skirt tip move into the interior of caisson while the outer soils move outward. It indicates that the majority of sand heave is the result of soil plug own expansion in volume, not a sand inflow from the outside skirt wall (Fig. 3b).

Figure 4 shows the accumulated normalized horizontal and vertical displacement increments (Δx/Dc...
and Δy/Dc, where, x and y indicate vertical and horizontal position from the soil surface in the plug center) in different elevations along the penetration axis. Significant vertical upward displacements were observed at plug center and these are accelerated toward the end of penetration (Δy/Dc = -0.027, negative value means soil plug heave). In addition, the amount of soil plug heave attenuates with depth. Overall, soil plug largely loosens with caisson penetration, causing sand plug to expand in volume during suction installation. It would be significantly influenced on the suction installation because soil plug heave increased the permeability of soil plug than that of the intact soil which is important parameter for estimating suction pressure and seepage flow.

3.2 Variation of suction pressure and effect of soil plug loosening (T2)

Figure 5 presents the measured suction pressure with penetration depth. The measured suction pressure linearly increased with penetration depth after sharp increase in the very initial stage of installation. This trend is quite similar to the previous study (Tran and Randolph, 2008). It was noted that the penetration of caisson was terminated at z/Dc = 0.76 (3.8 m) due to the lack of water pumping rate. However, this does not affect the observed trend. It can be seen that the differential pressures measured by P1 and P2 (as shown in Fig. 5) were lower than suction pressure obtained from DPT located at caisson lid because head difference occurred as the sensor penetrated into the soil with caisson penetration (measurement of P2 was diverged from suction pressure recorded at around 1.6 m, indicating embedment of the sensor into the soil).

Evidence of the soil plug loosening was also assessed by conducting cone penetration tests (CPT) in the locations inside (loosen) and outside (intact) the caisson after removing the suction-installed caisson. In this study, the cone diameter was 10 mm and the tests were performed at the penetration rate of 1 mm/sec. Figure 7 shows the comparison of cone penetration results (q_c) inside and outside the caisson. It is observed that the tip resistance is much lower in soil inside the caisson up to 4 m depth, compared with that in intact soil. However, tip resistance measured in soil inside the caisson is closer to that of non-loosened soil after 4 m penetration depth. This provides an indication of the level of sand plug loosening inside the caisson.

The results emphasize the effect of soil plug loosening not only for the installation but also for the further performance.

4 CONCLUSIONS

This study aims to investigate the soil behavior during suction installation of caissons in sand and its influence. In this study, half-section and total-section model tests were performed to evaluate variation of

![Fig. 5. Variation of suction pressure with penetration (P3 is not in the graph due to malfunction of the sensor).](image)

![Fig. 6. Variation of suction pressure with penetration (P3 is not in the graph due to malfunction of the sensor).](image)
suction pressure and soil loosening induced by upward seepage flow. The objectives of physical simulation are to investigate the effect of suction installation on the soil conditions and mechanism of soil loosening. Interesting conclusions were derived from a series of centrifuge model tests as follows:

1) The majority of sand heave occurred by suction installation is the result of soil plug own expansion in volume, not a sand inflow from the outside skirt wall.

2) Considerable sand movements were observed not only close to the skirt tip but also plug center.

3) Significant vertical upward displacements were observed at plug center and it is accelerated toward the end of penetration.

4) The suction pressure linearly increased with penetration depth after sharp increase in the very initial stage of installation.

5) Pore pressure ratio, $\alpha$, is close to the previously proposed value when $k_f = 2$ to 3, indicating increment of soil permeability.

![Cone tip resistance, $q_c$ (MPa)](image)

**Fig. 7.** CPT test inside (loosen soil) and outside (intact soil) the caisson.

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