Evaluation of soil disturbances due to the installation of a suction bucket on sand using centrifuge model tests

Évaluation de la perturbation du sol due à l'installation de caissons sur du sable à l'aide d'essais sur maquette dans une centrifugeuse géotechnique.

Jae-Hyun Kim & Dong-Soo Kim
Department of Civil and Environmental Engineering, KAIST, Republic of Korea, zlawogus@kaist.ac.kr

ABSTRACT: Suction bucket foundations are widely used in offshore areas due to the various benefits they offer. However, seepage flows generated by the pumping out of water at the lid can cause significant soil plug loosening and can lift up the sand plug, thereby hindering the penetration of the bucket to the target depth. Despite this effect, soil plug heave inside the bucket during the suction installation process has not been studied thoroughly. Therefore, in the present study, to investigate the mechanism of soil plug heave during the suction installation process and its effects on the suction pressure, two types of centrifuge model tests were performed: half-section (2D) model tests and total-section (3D) model tests. From these tests, the mechanisms related to the suction bucket installation process and the characteristics of seepage flows during the suction bucket installation were investigated. Cone penetration tests were also conducted to evaluate the effect of soil plug loosening indirectly.

1 INTRODUCTION

Suction buckets are considered as an alternative foundation in offshore areas due to the numerous benefits offered by these devices, such as easy installation and no need for special devices during the installation process (Tjelta et al. 1986). A suction bucket is installed using self-weight and the hydraulic pressure difference across the lid generated by the pumping out of water from inside the bucket (Houlsby and Byrne 2005, Tran and Randolph 2008). The pressure difference, called the suction pressure, creates additional driving force and allows the bucket to be installed into the seabed. When suction buckets are installed in highly permeable soils such as a sand layer, upward seepage flow occurs around the bucket tip and the bucket interior, leading to a decrease in the effective stress in the soil at the bucket tip as well as along the inner skirt wall. This process reduces the tip resistance and inner-wall skin friction, resulting in a significant reduction of the driving force.

However, the soil inside and outside the bucket can be disturbed due to the applied suction pressure as well as skirt penetration, possibly leading to shear failure of the soil. This can change the soil properties around the bucket. In addition, any upward seepage flow can create significant soil plug loosening and lift up the sand plug, thereby hindering the penetration of the bucket to the target depth. These phenomena can also influence the long-term behavior of the foundation. Despite these effects, soil disturbances and soil plug heave inside the bucket created by suction installation are not well understood.

This study aims to investigate the behavior of soil during the installation of a suction bucket and the effect of the behavior on the installation process. Two types of centrifuge model tests were designed: half-section (2D) model tests and total-section (3D) model tests. From the half-section model tests, the mechanisms of the suction bucket installation process and sand heave formation were investigated by means of an image analysis method. In the total-section model tests, the characteristics of the suction pressure, which is directly related to the upward seepage flow, were assessed. Cone penetration tests (CPT) were also conducted for an indirect evaluation of the effect of soil plug loosening. From a series of tests, the significant effects of a disturbance to the soil plug on the suction bucket installation process were identified.

2 HALF-SECTION MODEL TEST

To investigate the mechanism of soil disturbance during the installation of the suction bucket, a half-bucket model was made to penetrate the sand with a container equipped with a Perplex window, and the soil movements around the bucket during the suction installation process were captured by a digital camera.

The half-bucket model had a diameter of 100 mm (D_c), a length of 100 mm (L), and a tip thickness of 1 mm (t), corresponding to a prototype 5 m (D_c) * 5 m (L) * 0.05 m (t) in size at the 50 g level. A thin rubber pad was glued onto the flat surface of half-bucket model to prevent water leakage during the suction installation process. In addition, a guide rail was attached to the rear surface of the box so that the half-bucket model could be installed onto the front window surface. The half-bucket model was pushed by a guide rail toward the front window. This prevented soil ingress through the contact surface between the bucket and the window. Silicon grease was spread along the contact surface to minimize the friction.

Silica sand was used in this study. The soil properties of the sand are as follows: G_s = 2.65; mean grain size, D_{50} = 0.237 mm; maximum dry density, γ_{max} = 1.64 t/m^3; minimum dry density, and γ_{max} = 1.24 t/m^3. A soil model with a height of 400 mm and a relative density (D_r) of 60 % was prepared by a water pluviation method. The water level was 200 mm from the soil surface. The suction installation test was performed at 50 g.

The captured images were analyzed by a GeoPIV tool (White et al., 2003). Figure 1 illustrates the evolution of the soil displacement vectors with an increase in the degree of bucket penetration at z/D_c = 0.5 (where z denotes the bucket penetration depth from the soil surface) with an incremental penetration of $\Delta z/D_c$ = 0.03. The results clearly show considerable sand movements both near the skirt tip and in the plug center. In addition, a large soil plug heave was observed (about 3% of the bucket diameter). There is a clear trend in which the soil beneath the skirt tip moves into the interior of the bucket while the outer soils move outward (see the close-up view near the skirt tip in Figure 1). This indicates that the majority of the sand heave is the result of the volume expansion of the soil plug, not sand inflow from outside of the skirt. This can have an effect on the installation process because the soil plug heave increases the permeability of the intact soil, which in turn can affect the suction pressure (Houlsby and Byrne 2005).

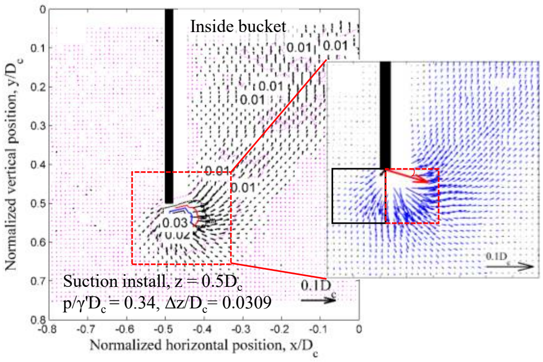

Figure 1. Incremental soil displacement vectors at the bucket penetration of $z/D_c = 0.5$ with $\Delta z/D_c = 0.03$.

3 TOTAL-SECTION MODEL TEST

To investigate the characteristics of seepage flows and soil disturbances during the suction bucket installation process, total-section model tests were performed on sand. A bucket model with prototype dimensions identical to those of the half-section model was used for the model tests. The model tests were performed in a cylindrical container 700 mm in height and 900 mm in diameter. A differential pressure transducer and pore water pressure transducers were used to measure the suction pressure at different elevations along the inner skirt. Suction pressure was applied to the interior of the bucket by pumping out the water. Water pumping was simulated by a gravity flow created by the head difference between the water level in the container and the elevation of the hose outlet which was directly connected to the interior of the bucket. Installation tests were started at 25 g by opening a water discharge valve.

Figure 2 presents the measured seepage gradients (i) along the inner skirt wall with the penetration depth. It can be seen that all of the measured seepage gradients rapidly increased to approximately 1 initially and remained at that level during the entire installation process. Note that the critical hydraulic gradient, $i_c = \gamma'/\gamma_w$, was close to 1 for soil, and the seepage gradients along the inner skirt wall correspond to a critical gradient for all depths. Soil plug heaves of approximately 12.5 % of the bucket diameter were also observed.

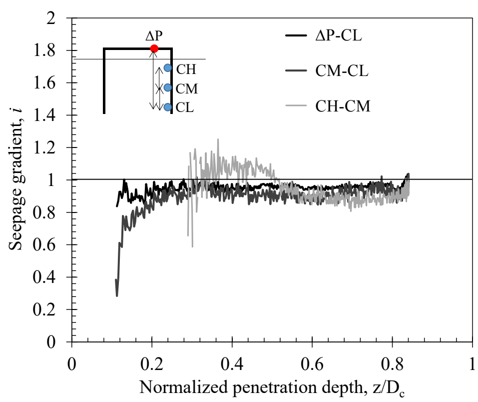

Figure 2. Seepage gradient along the inner bucket wall during suction installation.

Soil disturbances due to the installation of the suction bucket were also evaluated by performing a cone penetration test (CPT) at locations inside the bucket after removing the suction-installed bucket. Subsequently, the measured cone tip resistance was compared to the value measured at intact soil. In this study, a miniature cone with a 10 mm diameter and a 60° conical tip was used. The results showed that the tip resistance measured inside the bucket is much lower than that in the intact soil up to a penetration depth of 4 m (Figure 3). Thereafter, the tip resistance measured inside the bucket increased to that of the intact soil. The measured cone tip resistance values were also compared to the prediction proposed by Kim et al. (2016). The q_c profile for intact soil was in good agreement with the prediction assuming a soil density level with $D_r = 62$ % which corresponds to the prepared soil density. Moreover, the q_c profile inside the bucket matches the prediction of $D_r = 25$ %. This indicates that the soil density inside the bucket was decreased by 9 %.

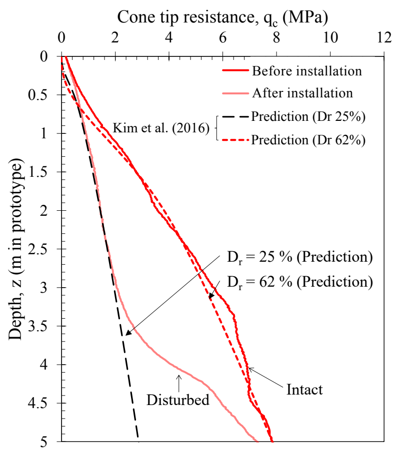

Figure 3. Results of cone penetration test at locations inside (disturbed soil) and outside (intact soil) the bucket.

4 CONCLUSION

In this study, the soil disturbance due to the installation of a suction bucket on sand was evaluated using centrifuge model tests. Half- and total-section model tests were conducted for this purpose. The mechanisms related to the installation of the bucket, the suction pressure, and soil loosening induced by an upward seepage flow were studied. The results demonstrate the effect of soil plug loosening during the installation process.

5 ACKNOWLEDGEMENTS

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