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Experimental investigation on the effect of skirt chamfer on the soil plug heave inside the bucket foundation

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ABSTRACT: Bucket foundations are widely used in offshore engineering. As foundations, the bucket foundation is used to support fix platforms such as offshore wind turbines (OWT) and tidal energy converters (TEC). As anchors, the bucket foundation can be used to secure tension leg platforms. The bucket foundation is jacked or suction-assisted installed, during which the soil displaced by the skirt may flow inside the skirt compartment to form a soil plug heave. This study conducted model tests to investigate the effect of the chamfer set on the skirt tip on the soil plug heave. Test results indicate that all the soil displaced by the skirt flows inside the skirt compartment if the skirt tip is equipped with an internal chamfer. However, 80% volume of soil displaced by the skirt flows outside the skirt compartment for the bucket with an external chamfer. Moreover, a half-model was adopted to investigate the effect of installation methods (jacked and suction-assisted installation) on the soil plug heave. It is found that a majority of soil flows outside the skirt for the bucket with an external chamfer even the bucket is suction installed. Overall, the external chamfer set on the skirt can reduce the soil plug heave, which is beneficial for increasing the uplift resistance and restraining the potential scour.

Keywords: bucket foundation; soil plug heave; clay; soil resistance; skirt foundation

1 INTRODUCTION

Bucket foundations, or termed skirt foundations, are widely used in offshore engineering. The bucket foundation can be used to support fixed platforms, offshore wind turbines (OWT) or subsea structures (Erbrich and Tjelta, 1999; Houlsby et al., 2005; Mana et al., 2013), and can also be used as anchors to secure floating platforms (Christophersen, 1993). The bucket foundation is comprised of a peripheral skirt with thin thickness and a top lid to create sealed conditions inside the skirt compartment. During installation the skirt is penetrated into the seabed to a certain embedment under the self-weight of the foundation, and then the foundation is installed further by pumping out water within the skirt compartment. The drainage valve using to pump water from inside the skirt is sealed after installation to ensure the mobilisation of suction when the bucket foundation is subjected to vertical or inclined uplift loading during operation.

A certain volume of soil that displaced by the skirt flows inside the skirt compartment, resulting in a soil plug inside the bucket, as shown in Figure 1. The soil plug heave prevents the bucket from being installed to the predetermined embedment depth. By cutting an external bevel on the skirt tip may change the soil flow mechanism, and helps the majority of displaced soil to move outside the skirt (Newlin, 2003). The chamfer angle, β, depicted in Figure 2, can be used to described the geometry of the skirt tip. $\beta > 0$ and $\beta < 0$ represent an external chamfer and internal chamfer, respectively.

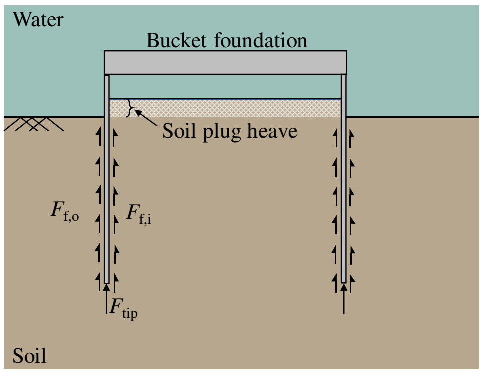

Figure 1. Sketch showing the soil plug heave inside the skirt compartment

Many researchers have conducted laboratory tests (Houlsby et al., 2005; Mana et al., 2012; Ragni et al., 2020; Peng et al., 2024; Westgate et al., 2009) and numerical simulations (Liu et al., 2025) to investigate the soil resistance during installation of the bucket foundation. However, the skirt of the model bucket was usually set as flat, such that the effect of the chamfer set on the skirt on the soil plug heave could not be investigated. This study aims at investigating the skirt chamfer on the soil plug heave by conducting 1g laboratory tests. Two categories of model tests were designed: the first is to investigate the effect of chamfer on the soil resistance and soil plug heave; and the second is to investigate the effect of installation methods (jacked or suction-assisted installation) on the soil plug heave.

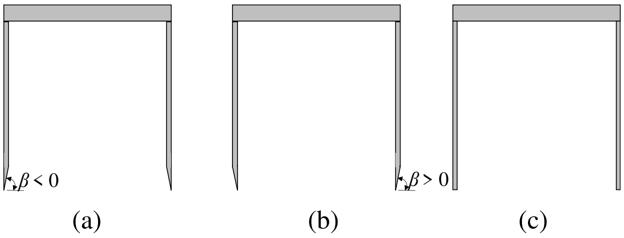

Figure 2. Chamfer at the skirt tip: (a) internal chamfer; (b) external chamfer; and (c) no chamfer

2 EXPERIMENT ARRANGEMENT

Model tests were conducted in a strong box with internal dimensions of 2 m (length) × 0.4 m (width) × 0.4 m (height). Both the front and back sides of the strong box are made from tempered glass.

As stated above, the model tests are divided into two categories. A full model was used in the first series of model tests. The full model was jacked installed to the soil by an actuator shown in Figure 3. The test was terminated when the soil resistance measured by the load cell right above the model bucket suddenly increased, meaning the soil inside the skirt compartment touched the lid. In the second series of model tests, a half model was used, which was vertically installed to the soil along the inner side of the tempered glass. Therefore, the soil plug heave could be captured using a digital camera.

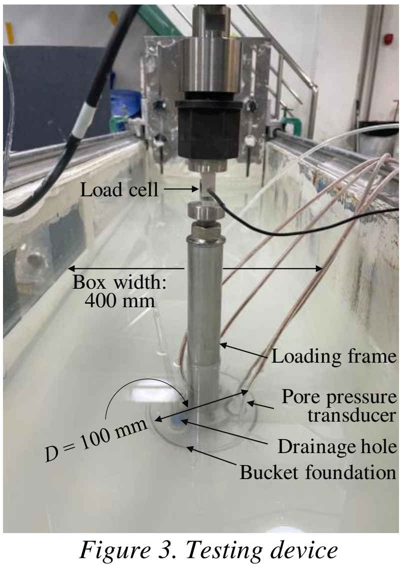

Figure 3. Testing device

The scale laws of the 1g experimental tests are briefly summarised as follows. Martin and Houlsby (2000) pointed out that reasonable modelling accuracy could be achieved by 1g tests for undrained geotechnical problems where the loads depend primarily on cohesive soil strength, and not on gravitational forces. The undrained strength in 1g tests should be reduced with a scale factor that is equal to the length scale factor, such that the dimensionless strength ratio, $\gamma' D/s_u$ (γ' is the submerged unit weight of the soil, D is the foundation diameter, s_u is the undrained strength of the soil), governing the soil flow mechanism around the foundation, in model scale is equal to that in prototype. The reasonability of 1g tests associated with displacement-capacity issues of foundations in clayey soils has been validated by many researchers (Martin and Houlsby, 2000; Wallace and Rutherford, 2018; Han et al., 2023).

2.1 Soil preparation

SpesWhite kaolin was adopted to prepare clayey samples. The soil properties are summarised as below: specific gravity G_s = 2.60, plasticity limit PL = 35% and liquid limit LL = 65%. The clay powder was mixed with fresh water to form a homogeneous slurry (with the initial water content of 120%), and then the slurry was transferred to a vacuum mixer to be deaired under a pressure of 30 kPa (i.e., vacuum degree of 70%) for 5 h. Subsequently, the deaired slurry was carefully poured into the strong box for consolidation using the hydraulic gradient method (Zelikson, 1969), allowing artificial unit weight to be created on the soil grains. The consolidation period was about three weeks, ensuring the settlement of the sample to reach a plateau.

The undrained shear strength s_u was measured by a ball penetrometer with a diameter of D_{ball} = 24 mm. The undrained strength was obtained by dividing the net soil resistance by a bearing capacity factor. A bearing capacity factor of 12.0 was adopted to represent a medium rough ball-soil interface condition based on the analytical solutions in Randolph et al. (2000). The penetration and extraction rate of the ball penetrometer was 4.5 mm/s, corresponding to a dimensionless velocity V of 830. The dimensionless velocity is larger than 30, ensuring undrained conditions of the soil (Finnie and Randolph, 1994). A layer of surficial soil was scrapped off after measuring the undrained strength, such that a lightly over-consolidated (LOC) sample was obtained. The undrained strength can be characterised by $s_u = s_{um} + kz$, where s_{um} is the undrained shear strength at the mudline, k is the strength gradient and z is the embedment depth of the LOC soil. The mudline strength and strength gradient are about 0.16–0.29 kPa and 3.0 kPa/m, respectively.

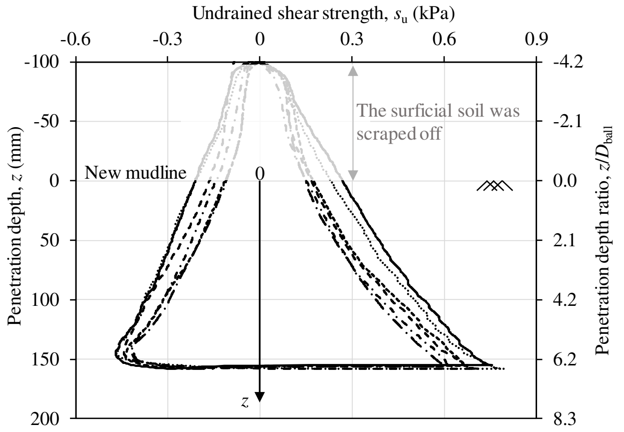

Figure 4. Undrained shear strength profiles

2.2 Model bucket foundation

The full bucket models were fabricated from aluminium. Two model foundations, with chamfer angles of 77° and −77° respectively, were adopted in model tests. The bucket models are 100 mm in diameter. The skirt is 100 mm in length and 2.0 mm in thickness.

Three half models were designed in the model tests, with the chamfer angles of 77° (external chamfer), 0 (flap skirt), and −77° (internal chamfer), respectively. The half models have the same dimensions with that of the full model. Note the half models were fabricated from plexiglass, such that the soil plug heave inside the skirt could be observed more clearly.

The surface roughness was measured by a profilometer, as plotted in Figure 5. The surface of the half model is smoother than that of the full model.

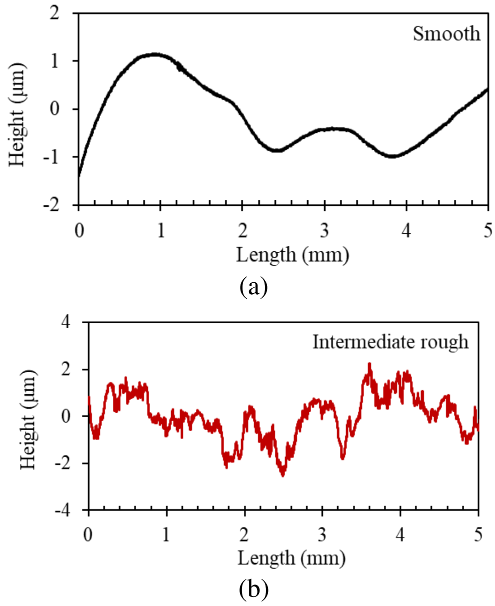

Figure 5. Surface Roughness of: (a) plexiglass (half-model); and (b) aluminium (full-model).

2.3 Test arrangement and cases

For jacked installation, the model bucket foundation was lowered below the water surface using the actuator, as shown in Figure 3. When the skirt tip was flush with the mudline, the load cell (type: KD24s, ME; scale: ± 200 N) was reset to zero to eliminate the submerged weight of the bucket. Then the bucket foundation was pushed into the soil under displacement control with a constant rate of v = 0.1 mm/s, during which the drainage valve on the lid was vented (i.e., unsealed), as shown in Figure 3. The dimensionless velocity $V = vt_s/c_v = 77$ (t_s is the skirt thickness) is higher than 30, ensuring undrained conditions during installation (Finnie and Randolph, 1994).

Table 1. Summary of test cases.

Case Name	**Model bucket**	**Chamfer**	**Installation method**	**Soil plug heave h_{soil}/L**
F-in-J	Full model	Internal	Jacked	0.12
F-ex-J		External		0.02
H-in-J	Half model	Internal		0.10
H-flap-J		Flap		0.04
H-ex-J		External		0.02
H-in-S		Internal	Suction-assisted	0.10
H-flap-S		Flap		0.08
H-ex-S		External		0

For suction-assisted installation, the half model anchor was first pushed into the soil under displacement control with a constant velocity of 0.1 mm/s until to the predetermined embedment of 0.4L (i.e., 40 mm), simulating the self-weight process. Then the drainage valve was connected to a syringe pump for suction installation. The flow rate of the pump was 1600 mm^3/s, forcing the bucket to further penetrate into the soil under the pressure difference inside and outside the lid.

A total of eight tests was designed, with the results summarised in Table 1. In the case name, 'F' and 'H' represent the full-model and half-model, respectively; ‘in’ and ‘ex’ represent internal and external chamfer, respectively; ‘J’ and ‘S’ represent jacked and suction installation method, respectively. The case name F-in-J means the full anchor model with an internal chamfer is jacked installed to the soil.

3 TEST RESULTS AND DISCUSSION

3.1 Soil resistance on the skirt during installation

When the bucket foundation is pushed into the soil, the net reaction force F_{net} (the measured soil resistance minus the surcharge) on the skirt comprises the end bearing force F_{tip} on the skirt tip and the frictional force F_f inside and outside the skirt. The net soil resistance q_{net} is derived by

$$q_{net} = F_{net}/A \quad (1)$$

where A is the cross-sectional area of the bucket. The variation of q_{net} with the normalised skirt embedment z/L (z is the embedment of the skirt tip and L is the length of the skirt) is plotted in Figure 6. It can be seen that the soil plug heave h_{soil} is $0.12L$ for the bucket foundation with an internal chamfer (β = −77°), indicating all of the soil displaced by the skirt flows inside the skirt compartment. However, for the bucket foundation with an external chamfer (β = 77°), the overall inward soil flow ratio is about 20%, meaning the external chamfer encourages the soil to flow outside the skirt wall. Overall, the skirt tip is suggested to be fabricated with an external chamfer for bucket foundations and suction caissons in practical engineering.

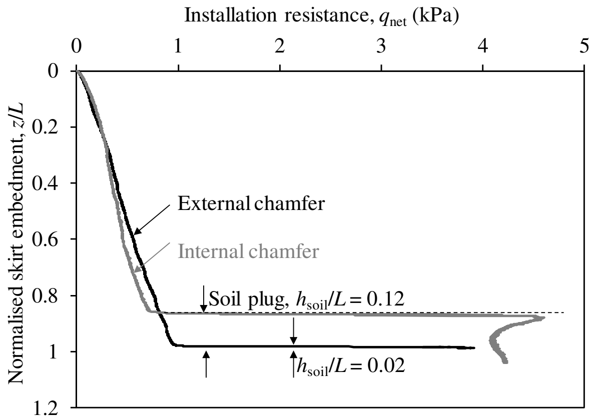

Figure 6. Net soil resistance during installation

The net soil resistance q_{net} increases with the embedment depth, as shown in Figure 6, due to the increase of the undrained strength with the embedment and the increase of the skirt-soil contact area. The net soil resistance of the bucket foundation with an external chamfer is slightly higher than that with an internal chamfer. The difference may be resulted from the end bearing resistance F_{tip} on the skirt tip. The soil flow mechanism is affected by the chamfer at the skirt tip, changing the tip bearing capacity factor and hence the end bearing resistance on the skirt. Further numerical simulations should be conducted to accurately establish the relationship between the bearing capacity factor and the chamfer angle.

3.2 Soil plug heave of jacked installed bucket foundation

Figure 7 shows the photographs at the moment when the soil inside the skirt compartment touches the lid of the bucket foundation. The soil plug heave is h_{soil}/L = 0.02, 0.04 and 0.10 for the bucket with an external chamfer, no chamfer, and internal chamfer, respectively.

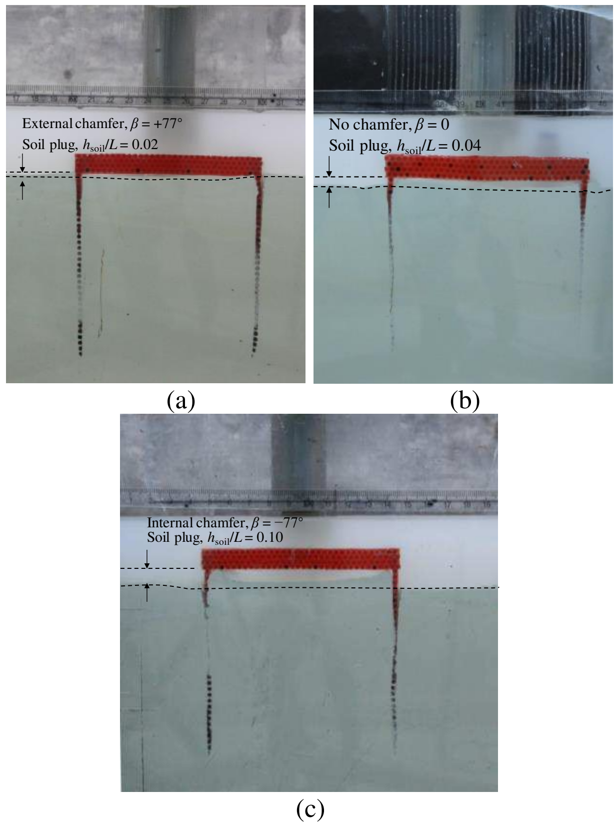

Figure 7. Effect of chamfer at the skirt tip on the soil plug heave (jacked installed bucket): (a) external chamfer; (b) no chamfer; and (c) internal chamfer

3.3 Soil plug heave of suction installed bucket foundation

The photos in Figure 8 show three typical moments of the bucket foundation with an external chamfer during combined self-weight and suction installation. The mudline is plat when the skirt initially touches the soil as shown in Figure 8a. The soil displaced by the skirt primarily moves outside the skirt as shown in Figure 8b during the jacked installation (mimics the installation under self-weight). Therefore, a soil heave around the bucket foundation is observed. During the subseqent suction installation, no soil plug heave is observed inside the skirt as shown in Figure 8c. This indicates that the displaced soil flows outside the skirt even the bucket foundation is suction installed.

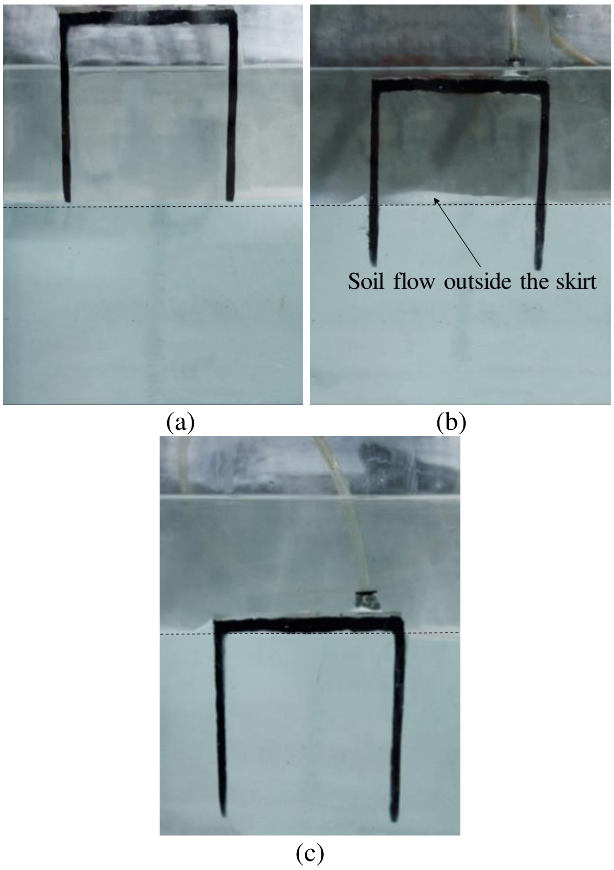

Figure 8. Photos showing three typical moments of the bucket foundation with an external chamfer: (a) z/L = 0; (b) z/L = 0.4; and (c) z/L = 1.0

Figure 9 shows the photographs at the moment when the soil inside the skirt compartment touches the lid of the bucket foundation. The soil plug heave is $h_{soil}/L = 0$, 0.08 and 0.10 for the bucket with an external chamfer, no chamfer, and internal chamfer, respectively.

It is assumed that the soil plug heave inside the bucket foundation under suction installation is higher than that under jacked installation. However, there exists a contradiction of the soil plug heave for the bucket foundation with an internal chamfer. Therefore, more sophisticated tests, particle image velocimetry (PIV) test for instance, should be designed to investigate the soil flow mechanism around the skirt during installation. Moreover, the soil plug heave may depend on the over-consolidation ratio (OCR), which also needs to be investigated further.

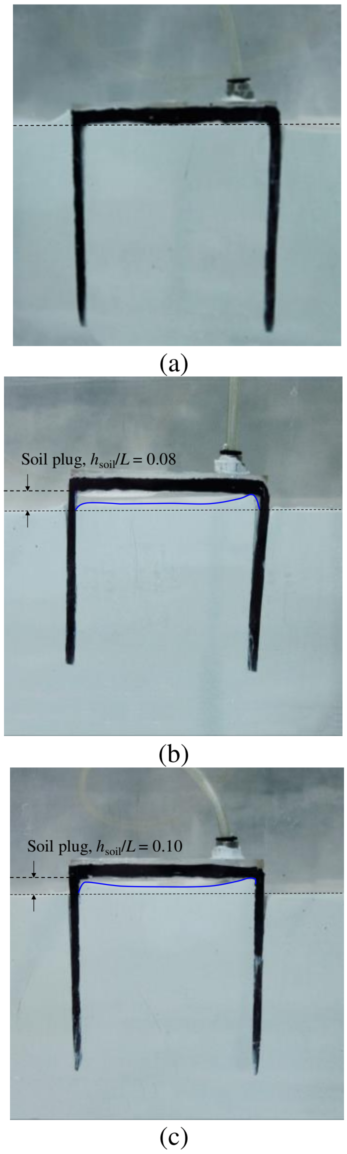

Figure 9. Effect of chamfer at the skirt tip on the soil plug heave (combined self-weight and suction installation): (a) external chamfer; (b) no chamfer; and (c) internal chamfer

4 CONCLUSIONS

This study conducted model tests to investigate the effect of the chamfer set on the skirt tip on the soil plug heave. Test results indicate that all the soil displaced by the skirt flows inside the skirt compartment if the skirt tip is equipped with an internal chamfer. However, 80% volume of soil displaced by the skirt flows outside the skirt compartment for the bucket with an external chamfer. For LOC soils used in the present study, it is found that the soil plug heave is largely unaffected by the installation methods (jacked or suction-assisted installation). Overall, the external chamfer set on the skirt can reduce the soil plug heave, which may be beneficial for increasing the uplift resistance and restraining the potential scour. Further studies should be conducted to quantify the effect of soil plug heave on the uplift capacity of the bucket foundation.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, Writing- Original draft. **Other Author**: Conceptualization, Supervision. **Additional Authors**: Methodology, Supervision. **Last Author**: Investigation, Writing- Reviewing and Editing.

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