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Experimental study on the plug heave of bucket foundation in clay during suction installation

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ABSTRACT: Suction installation is the key to successful adaptation of bucket foundation, but plug heave during installation often leads that the foundation cannot be sunk to the design depth which decreases the bearing capacity. Therefore, prediction method of plug heave height becomes one of the key study in the design of bucket foundation. In this paper, a series of model tests on the suction installation of bucket foundation in clay were performed to study the phenomenon of plug heave in clay. Based on test results, the mechanism of plug heave in clay was revealed, and the influence of installation velocity (v) and thickness-to-diameter ratio (t/D_o) on plug heave rate was studied. Then, the prediction method of plug heave height of suction bucket foundation is proposed with considering s installation velocity (v) and thickness-to-diameter ratio (t/D_o) in clay.

Keywords: Bucket foundation; suction installation; plug heave; installation velocity; thickness-to-diameter ratio

1 INTRODUCTION

Bucket foundations offer significant advantages in offshore wind projects due to their high overturning resistance and rapid installation. Successful application hinges on precise suction installation, with a critical concern being "plug heave" – the excessive filling of the bucket's interior with soil before reaching the design depth. This results in the internal soil plug extending above the external mudline, preventing the foundation from reaching its intended depth and thus preventing full utilization of its bearing capacity. Researchers internationally have investigated this phenomenon, although a consensus on its underlying mechanisms remains elusive.

The plug heave was first discovered during the bucket installation in the Gorm oil field in the Danish sector of the North Sea(Senpere, 1982). It has been repeatedly observed in subsequent engineerings and tests, such as the installation of bucket foundation at the Girassol field in Angola(Dendani, 2002) and centrifuge model tests conducted by Gaudin and Chen(Gaudin, 2014 and Chen., 2009).

Most of studies on the plug heave focused on sand and silt. Yang and Tran investigated the plug heave during the installation of bucket foundations in sand and silt through model tests(Yang, 2003). They found that the skirt thickness of the bucket and the velocity of installation influence the plug heave, demonstrating that the greater skirt thickness resulted in larger plug heave, and the increasing of velocity of installation decreased the plug heave. Conflicting findings have emerged from studies on plug heave in clay. Chen's (2009) clay tests indicated a plug heave volume less than the soil volume displaced by the bucket skirt. However, Rauch (2003) reported an essentially equal volume, and Andersen (2005) found that the plug heave volume exceeded the displaced volume at bucket penetrations greater than half its height.

In summary, research on plug heave in clay has yielded inconsistent or conflicting results. Therefore, this study investigates the mechanisms of plug heave in clay, the factors influencing it, and methods for its evaluation. This research provides a basis for the design and construction of relevant engineering projects.

2 1G MODEL TEST FOR PLUG HEAVE

2.1 Test apparatus and soil preparation

(1) Test apparatus

The test apparatus for studying the plug heave, including the model tank (1m×1m×1m), the control system for negative pressure and the data acquisition system, were shown in Figure 1. The maximum diameter of the test model was 0.3m. The space between bucket edge and tank was more than 1*D*, which avoids boundary effect. (Li, 2023).

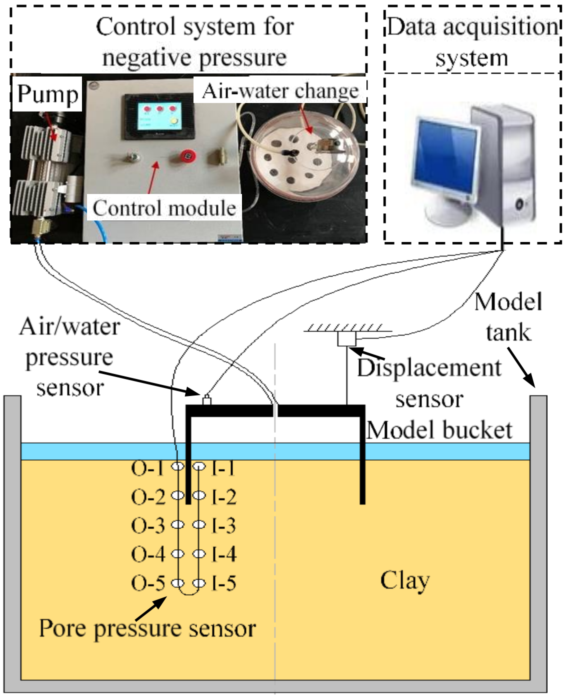

Figure 1. Diagram of model test for plug heave

(2) Soil preparation

The clay was from the reclamation area in Tianjin. The clay was prepared by vacuum preloading method, shown in Figure 2. During the preparation, vane shear tests were performed to test the undrained shear strength of clay. Vacuum preloading stopped when the strength reached 9 kPa. Soil parameters were shown in Table 1.

Table 1. Physical and mechanical parameters of clay

Soil	Saturated unit weight γ_{sat}/(kN/m^3)	Moisture content ω/%	Void ratio e	Permeability coefficient k/(cm/s)	Undrained shear strength s_u/kPa
Clay	18.6	23.5	0.893	2×10^{-5}	9

2.2 Test arrangements and test schemes

(1) Test arrangements

Table 2 shows the outer diameter (D_o), height (L), skirt thickness (t), and installation velocity (v) for tests N1-N8. N2 and N3 were used to verify the test repeatability. Tests N1-N6 were used to study the influence of installation velocity on plug heave. N4, N7, and N8 were to study the effect of bucket dimensions on plug heave.

Table 2 Test arrangements

Tests	Dimensions D_o×L×t(mm)	t/D_o	L/D_o	v (mm/s)
N1	200×150×5	0.025	0.75	0.38
N2	200×150×5	0.025	0.75	0.20
N3	200×150×5	0.025	0.75	0.20
N4	200×150×5	0.025	0.75	0.12
N5	200×150×5	0.025	0.75	0.09
N6	200×150×5	0.025	0.75	0.07
N7	300×150×5	0.017	0.50	0.12
N8	100×150×5	0.050	1.50	0.12

(2) Sensors schemes

Sensors included air/water pressure sensors (range -0.1MPa-0.1MPa), displacement sensors (range 0 to 1m), and pore pressure sensors (ranges of 0-10kPa and 0-100kPa). Arrangements were shown in Figure 1. The depth between two pore pressure sensors was 5 cm.

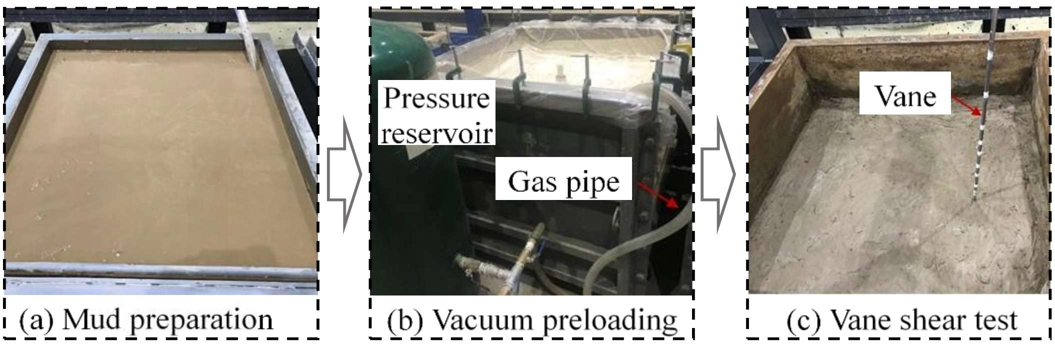

Figure 2. Soil preparation process

2.3 Test process

First, the model bucket was installed under its own weight. After the self-weight installation, the bucket was connected to the control system of negative pressure. Then the vacuum pump was used to extract water inside the bucket to create suction pressure to install the model bucket (shown in Figure 3). Each two tests had 48-hour resting period, and different test was performed at different location in the tank. The space between tests was more than 1D, which avoid the interaction effect.

Figure 3. Suction installation test of bucket foundation

The data of installation depth and internal pressure with time for tests N2 and N3 were shown in Figure 4.

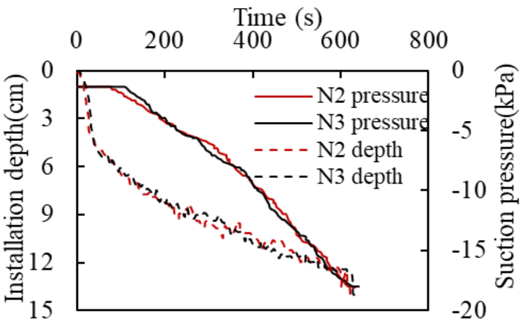

Figure 4. Installation depth and Pressure of N2 and N3

Fig. 4 shows that the curves of N2 and N3 largely overlap, which verified of tests reproducibility.

3 INFLUENCE OF PLUG HEAVE

3.1 Influence of installation velocity

Tests N1 to N6 studied the influence of installation velocity (v) on the plug heave and its height. Curves of installation depth and installation depth were shown in in Figure 5 and Figure 6 respectively.

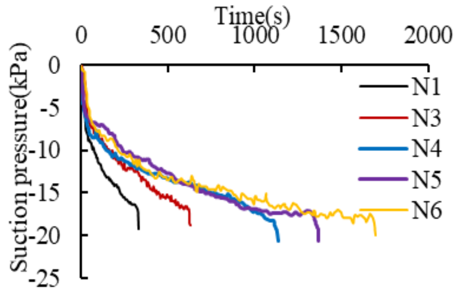

Figure 5. Relationship between suction pressure and time

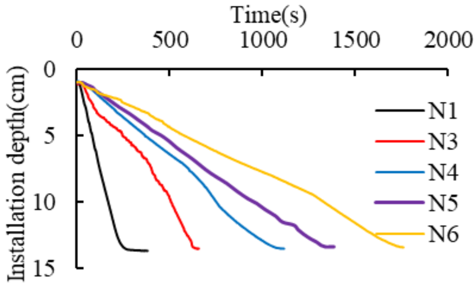

Figure 6. Relationship between installation depth and time

Fig. 5 shows that during the early stage, the suction pressure dropped rapidly, followed by the linear change. When the bucket lid contacted the soil, there was a sudden drop of pressure, indicating the end of installation. Fig. 6 shows that during the suction installation, the installation depth increases linearly with time, indicating the constant installation velocity.

The permeability of clay was much lower than sand. Therefore, the clay can be considered the impermeable layer. The height of extract water equivalent to the volume of water extracted from the bucket equals the sum of the ground uplift height and the subsidence depth of the bucket. Thus, plug heave height can be calculated through formula (1).

$$h_s(t) = h_w(t) - h_b(t) = W_w(t) / \rho_w A_{in} - h_b(t) \qquad (1)$$

In formula, $h_s(t)$-plug heave height. $h_w(t)$-equivalent height of extract water. $h_b(t)$-installation depth. $W_w(t)$-weight of extract water. ρ_w-water density. A_{in}-area of bucket lid. t-installation time.

Tests clearly showed the phenomenon of plug heave, as shown in Figure 7. Plug heave height was calculated through formula (1). Relationships between installation depth and plug heave height were shown in Figure 7.

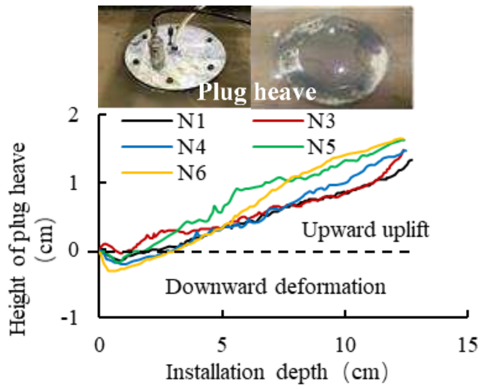

Figure 7. Plug heave height vs. installation depth

Figure 7 shows that trends of five tests were generally consistent. During the early stage, ground surface began to sink downward. As the installation continued, the soil inside the bucket started to uplift. The uplift height showed the linear increasing trend relative to the installation depth.

To study the influence of installation velocity on plug heave, the ratio of plug heave *m* was defined as the ratio of plug height to skirt embedment. Relationships between installation velocities of N1 to N6 and ratio of plug heave was shown in Figure 8.

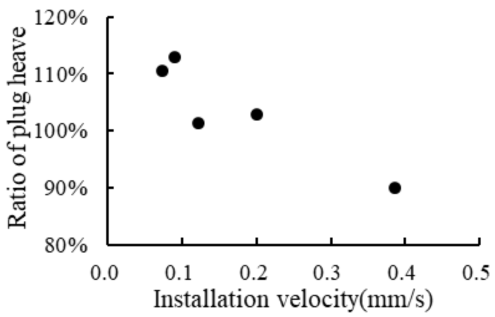

Figure 8. Ratio of plug heave vs. installation velocity

Figure 8 shows that the ratio of plug heave decreased with the increase of installation velocity. As the installation velocity increased from 0.07 mm/s to 0.38 mm/s, the ratio of plug heave decreased from 113% to 90%. The reason was that during the suction installation, the plastic zone at the bucket bottom occurred due to seepage and penetration disturbance. The plastic soil flowed into the bucket due to the rheological effect. As installation velocity decreased, suction pressure lasted longer, making more soil flow into the bucket, thereby increasing the ratio.

3.2 Influence of thickness-to-diameter ratio

N4, N7, and N8 studied the influence of thickness-to-diameter ratio (t/D_o) in clay on the plug heave. Relationships between the plug heave height and installation depth were shown in Figure 9.

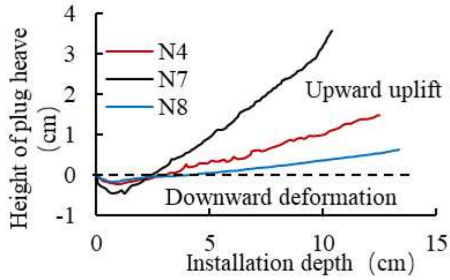

Figure 9. Plug heave height vs. installation depth

Figure 9 shows that trends of different bucket foundations dimensions were generally consistent. However, different dimensions had much influence on rate of plug heave. The plug heave height with the smallest thickness-to-diameter ratio(N7) showed the largest initial downward deformation and the highest upward uplift. The relationship between the ratio of plug heave and the thickness-to-diameter ratio (t/D_o) was shown in Figure 10.

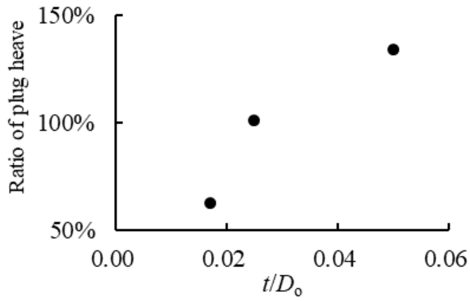

Figure 10. Ratio of plug heave vs. t/D_o

Figure 10 shows that as thickness-to-diameter ratio increased, the ratio of plug heave increased. When the thickness-to-diameter ratio increased from 0.017 to 0.05, the ratio of plug heave increased from 63% to 134%. The reason was that the drag reduction effect due to seepage in clay was much weaker than it in sand. As the thickness-to-diameter ratio increased, the resistance at the bottom of bucket increased, requiring higher suction pressure. Under the same installation velocity, the larger negative pressure occurred stronger seepage effect at the bucket bottom, leading to the expansion of the plastic zone and the more intense rheological effect. It resulted in more soil flowing into buckets and exacerbating plug heave.

4 CALCULATION METHOD FOR CLAY

The analysis shows that the ratio of plug heave(m) was negatively correlated with the installation velocity and positively correlated with the thickness-to-diameter ratio. Relationships can be approximately represented by the logarithmic function. Therefore, the fitting formula was given by formula (2). In formula (2), v_0 is the minimum installation velocity 0.07mm/s.

$$m = 1.05[-0.125\ln(\frac{v}{v_0}) + 1.12] \times [0.641\ln(\frac{t}{D_o}) + 3.29] \quad (2)$$

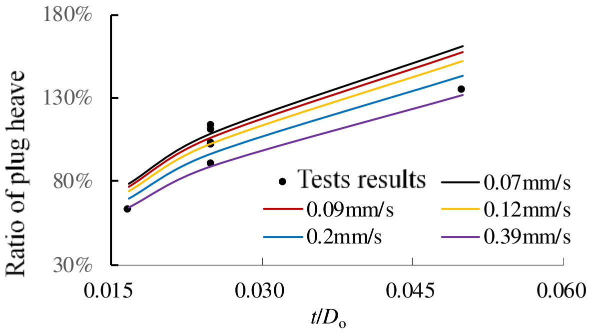

Figure 11. Test results vs. calculation results

According to formula, the ratio of plug heave with t/D_o=0.0167 to 0.05 and installation velocity v= 0.07 mm/s to 0.39 mm/s were calculated and compared with test results, as shown in Figure 11.

Figure 11 shows that the test data is well-fitted by equation (2). The ratio of the test result to calculation result ranged from 0.88 to 1.07, which shows that formula (2) can accurately calculate the ratio of plug heave in clay.

The plug heave volume V_{soil} can be calculated by formula (3).

$$V_{soil} = m \cdot \left(\frac{\pi D_o^2}{4} - \frac{\pi D_i^2}{4} \right) \left(H - h_{soil} \right) = \frac{\pi D_i^2}{4} h_{soil} \quad (3)$$

In formula, H is bucket height. D_i is inner diameter. D_o is outer diameter. h_{soil} is plug heave height.

According to formula (3), the plug heave height can be calculated by formula (4).

$$h_{soil} = \frac{mH\left(D_o^2 - D_i^2\right)}{D_i^2 + m\left(D_o^2 - D_i^2\right)} \quad (4)$$

The h_{soil} can be calculated by formula (2) and formula (4). The h_{soil} for tests were calculated by this method. Comparisons were shown in Table 3.

Table 3 Test results vs. calculation results of h_{soil}

No.	Test /mm	Calculation /mm	m	Ratio
N1	13.3	13.2	0.901	1.01
N2	14.8	14.2	1.015	1.04
N3	15.0	14.2	1.028	1.06
N4	14.8	15.0	1.013	0.99
N5	16.3	15.5	1.128	1.05
N6	16.0	15.8	1.105	1.01
N7	35.9	39.4	1.341	0.91
N8	6.3	7.4	0.625	0.85

Table 3 shows that the ratio ranged from 0.85 to 1.06, demonstrating that the calculation method can accurately assess the plug heave height.

5 CONCLUSIONS

Model tests of suction installation of bucket foundations were performed in clay. Based on test results, the influence of installation velocity and thickness-to-diameter ratio on the ratio of plug heave were analyzed. Considering these factors, the calculation method of the plug heave height was proposed. Conclusions were as follows:

(1) The ratio of plug heave m was negatively correlated with the installation velocity v. The smaller installation velocity v resulted in the longer duration of suction pressure, which made more plastic soil due to seepage occur and flow into the bucket.

(2) The ratio of plug heave m was negatively correlated with the thickness-to-diameter ratio t/D_o. The likely mechanism was that the increasing of t/D_o increases the resistance at the bucket bottom. It required greater suction pressure. This enhanced the seepage at the bucket bottom, and increased more plastic soil. These made more soil flow into the bucket.

(3) Ratio of plug heave m was approximately logarithmically related to the installation velocity v and the thickness-to-diameter ratio t/D_o. Based on test results and fitting formulas, the calculation method for the plug heave height in clay was proposed. Ratios between calculation results and test results were between 0.85 and 1.16, which indicated the method appears to fit the trends in the data.

It is acknowledged that strict adherence to scale laws is challenging in 1G model tests. Specifically, it is difficult to directly extrapolate the measured soil plug heave height in the 1G tests to the field scale using simple scale factors. Therefore, this study focuses on conducting a series of model tests, while maintaining reasonable equivalence in terms of height to diameter ratio and normalized velocity, to investigate the influence of installation velocity and bucket dimensions on plug heave height and to study the regularity. Further centrifuge tests or prototype-scale tests should be performed to apply the research to specific field engineering projects.

AUTHOR CONTRIBUTION STATEMENT

Chengfeng Li: Data curation, Formal analysis, Writing-original draft, Writing – Review & Editing. **Run Liu**: Conceptualization, Methodology. **Chao Liang**: Supervision, Validation. **Wenguan Ma**: Resources, Software, Visualization. All authors have read and agreed to the published version of the manuscript.

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