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Numerical study of piping limits for suction installation of offshore skirted foundations and anchors in layered sand

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ABSTRACT: Skirted foundations and anchors have proved to be competitive solutions for various types of fixed offshore platforms, subsea systems and an attractive foundation alternative for offshore wind turbines. One main design challenge for skirted structures in sand is to penetrate the skirted deep enough to obtain the required capacity. In order to overcome the high penetration resistance in sand suction assisted penetration is needed. Suction installation may cause the formation of piping channels, which break down the hydraulic seal and prevent further installation. This paper presents a numerical study of failure limits during suction installation in respect to both homogenous and layered soil profile. A numerical flow analysis is performed to determine the hydraulic gradients developing in response to the suction applied, and the results are presented as simple closed form solutions useful for evaluation of suction thresholds against piping. These closed form solutions are compared with large scale tests, performed in a natural seabed at a test site in Frederikshavn, Denmark. These solutions are also valid for penetration studies of other offshore skirted foundations and anchors using suction assisted penetration in homogeneous or layered sand.

Due to the complexity of the domain and the governing differential equation, the problem is solved numerically. A numerical solution can be obtained using either finite difference or finite element methods. In this paper, the problem is solved using the commercial finite difference program FLAC3D (Itasca, 2005).

1 INTRODUCTION

More than 485 suction anchors, had been installed for anchoring floaters at more than 50 different sites by the year 2004 (Andersen et al. 2005). Most of these anchors are in clay, but some are also in sand or layered soils. Examples of skirted foundations in sand are the offshore steel platforms at Draupner E and Sleipner T sites in the North Sea (Tjelta 1995). Skirted foundations in sand can also be used to increase the moment fixity and can be an attractive foundation alternative for offshore wind turbine as the bucket foundation installed in Frederikshavn has shown. (Ibsen 2008).

In order to overcome the high penetration resistance in sand, suction assisted penetration is needed. The suction creates a pressure differential across the caisson lid, effectively increasing the downward force on the caisson while reducing the skirt tip resistance.

This study has been a part of a research project whose aim is to develop a skirted foundation often referred to as the "bucket foundation" as a foundation for offshore wind turbines. At the time of writing, two bucket foundation have been installed, one at Horns Rev II and the other located in Frederikshavn, Denmark, (Ibsen 2008). Figure 1 shows an installation test of a 4 × 4 m bucket at the test site in Frederikshavn.

Figure 1. Installation tests on 4 × 4 m buckets in a natural seabed at the test site in Frederikshavn, Denmark.

The installation of bucket foundation for offshore wind turbines differs for several reasons. Compared to oil and gas jackets, the bucket foundation offers less self-weight to assist penetration and the offshore parks are predominantly located at shallow waters, <30 m, which reduces the maximum available suction capacity.

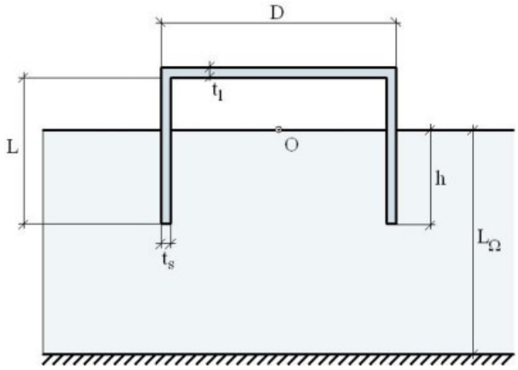

Figure 2. Definition of dimensions.

Figure 3. The critical suction has been achieved and soil failure by piping has occurred. The test was performed with a 4×4 m bucket.

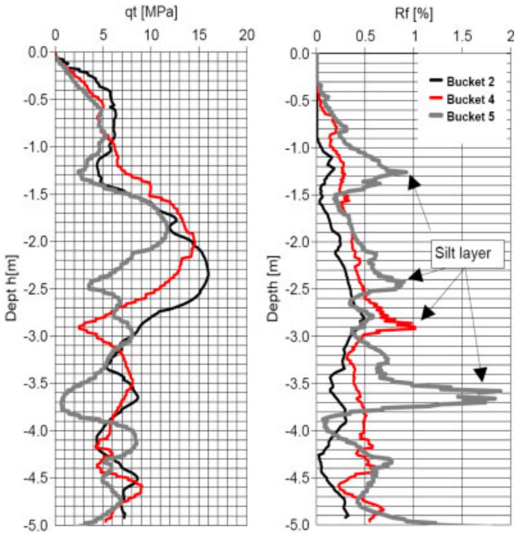

Figure 4. CPT test performed prior to the installation of the buckets.

The bucket foundation is a large diameter moment resistant structure and its cost efficiency is significantly improved by increasing the ratio of skirt length L over diameter D to approximately $L/D \approx 1$ while the wall thickness t is kept at a minimum. The geometric definitions are shown in Figure 2.

This paper presents a numerical study of the installation of large diameter thin-walled suction caissons in sand. The objective is to evaluate suction failure limits during installation in respect to piping in both homogeneous and layered sand. Steady-state flow analyses were performed to determine the flow and the hydraulic gradients developed in response to applied suction beneath the caisson lid. The results are presented as simple closed form solutions, valid for a wide range of boundary conditions, and useful for evaluation of suction thresholds against piping in homogeneous or layered sand. These closed form solutions are compared with a large scale field test, installed in a natural seabed at the test site in Frederikshavn, Denmark.

2 FIELD TEST DATA

Since installation data from field installation of suction caissons in sand are limited this project has conducted a substantial amount of installation tests on 2×2 m and 4×4 m buckets which have been performed at the offshore test site in Frederikshavn, Denmark, Ibsen (2008). One of the focus points for these installation tests has been to study the critical suction causing piping.

Failure during suction assisted installation occurs when certain thresholds are exceeded. The failure may be caused by either formation of piping channels or cavitation of pore water. The formation of piping channels occurs when the applied suction increases and causes an upward flow, reducing the effective stresses within the caisson, and eventually liquefying parts of the internal soil matrix. Local piping channels break down the hydraulic seal and prevent further installation, as shown in Figure 3.

Three installation tests are studied in this paper. They are all installed within a test site of 13×14 m. The results of the CPTs performed prior to the installation are shown in Figure 4. The applied suction p needed to install the 2×2 m buckets can be seen in Figure 5. In the figure, the normalized suction p/γ' is plotted against the normalized penetration depth h/D where γ' is the submerged unit weight of the soil and D is the diameter of the bucket. In the figure 5 it is also seen that installation failure by piping did occur during the installation of bucket 4, at a depth 1.56 m. The piping channels were filled with sand and the outer soil surface leveled, in order to restart the installation. A new failure occurred at a depth of 1.7 m and the test was stopped.

Figure 5 shows that the suction needed to install bucket 5 is higher than the suction resulting in piping

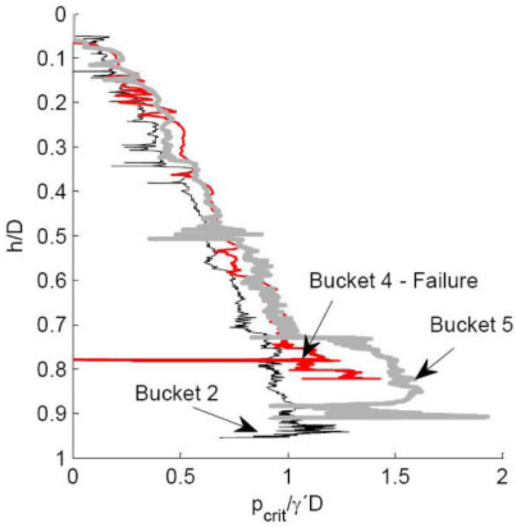

Figure 5. The applied suction p needed to install the three buckets. The diameter and skirt length is 2 m × 2 m.

during the installation of bucket 4. The only difference between the installation tests is the presence of silt layers, see Figure 4.

- Bucket 2 is installed in a homogeneous sand layer.
- Bucket 4 is installed where one thin silt layer is present at a depth of 2.7 m.
- Bucket 5 is installed in a layered soil profile with thin silt layers at depth of 1.2, 2.4 and 3.5 m.

It is assumed that these thin silt layers act as impermeable flow boundaries and change the steady-state flow field around the skirt tip as it approaches the layer. The theory is that the presence of these impermeable flow boundaries will increase the suction thresholds against piping as it was observed from the installation test with Bucket 5. The influence of the flow boundary is modeled and studied in the following sections.

3 NUMERICAL MODEL

The pumping action results in the suction p inside the bucket, which then causes a steady-state flow field to evolve in the soil, as shown in Figure 6. This yields a constant influx of water, which must be pumped out to maintain a constant level of suction.

Assuming isotropy the seepage problem reduces to the well-known Laplace's differential equation, $\nabla^2 h = 0$. It may conveniently be expressed in terms of pore pressure, $u = \gamma_w h$ and cylindrical coordinates (r, z, ϕ) due to the circular geometry of a suction caisson:

$$\nabla^2 u = \frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} + \frac{\partial^2 u}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 u}{\partial \phi^2} = 0 \tag{1}$$

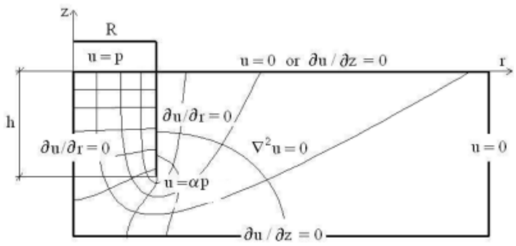

Figure 6. Schematic illustration of the axisymmetric flow do-main during suction installation.

The term $(1/r^2)\partial^2 u/\partial\phi^2$ vanishes due to the axis-symmetry of the caisson. The differential equation must be solved with appropriate boundary conditions to determine the hydraulic gradient field which arises from the pressure difference, between the ambient seabed water pressure, $\gamma_w h_w + p_a$ and the pore pressure beneath the lid, $\gamma_w h_w + p_a + p$. p_a is the atmospheric pressure.

Due to the complexity of the domain and the governing differential equation, the problem is solved numerically. A numerical solution can be obtained using either finite difference or finite element methods. In this paper, the problem is solved using the commercial finite difference program FLAC3D An axisymmetric model was created with a grid consisting of a total of 5,904 zones and an outer boundary located, in the distance, $20R$ the caisson, as shown in Figure 6. The case where $L_\Omega \to \infty$ is simulated as $L_\Omega = 20R$. The boundary conditions along the caisson skirt, the bottom boundary and the axisymmetric axis are Neumann's conditions, preventing a flow orthogonal to the boundary. The boundary conditions of the soil surface in the caisson, the free surface and the outer boundary are Dirichlet conditions with prescribed pore pressures. The steady-state flow model computes the exit hydraulic gradient i next to the skirt and that gradient is used to calculate the seepage length s in terms of the applied suction p as:

$$s = \frac{p}{\gamma_w i} \tag{2}$$

The normalized seepage length s/h is a unique function of the relative penetration length h/D.

4 NUMERICAL RESULTS

The steady-state flow simulations were conducted for two different cases at various embedment depths $0.1D > h > 1.2D$. In the first case, simulations were conducted to investigate bucket installation in homogeneous soil, the results are shown in Figure 7a. The second case simulates a bucket installed in sand over a impermeable flow boundary, located in the depth L_Ω. The results are shown in Figure 7b.

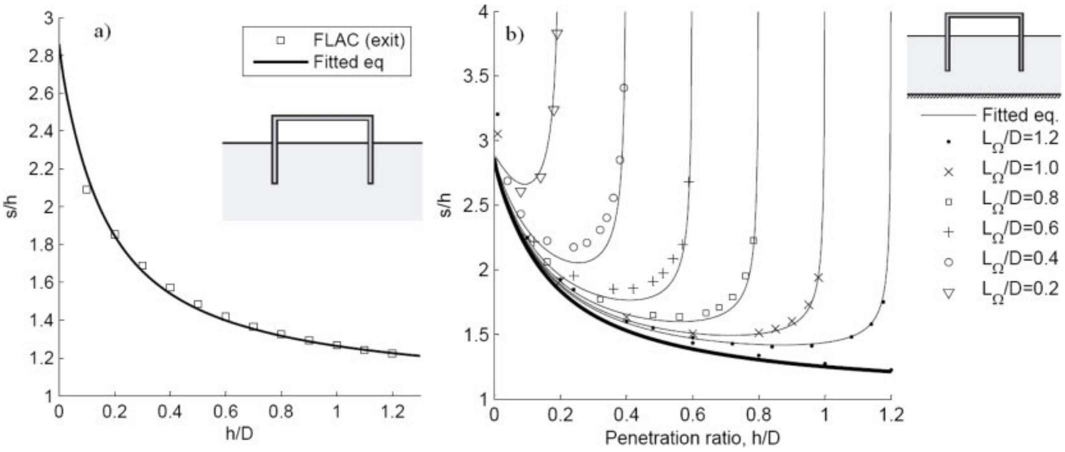

Figure 7. The results of the FLAC calculation are plotted as normalized seepage length for exit gradient versus relative penetration. a) Installation in homogenous sand. b) Installation in sand over a flow boundary.

4.1 *Installation in homogeneous sand*

The following empirical expression is given to approximate the numerical data for the installation in homogeneous sand.

$$\left(\frac{s}{h}\right)_{ref} = 2.86 - \arctan\left[4.1\left(\frac{h}{D}\right)^{0.8}\right]\left(\frac{\pi}{2.62}\right) \tag{3}$$

Equation (3) is fitted to two boundaries. For a very small h/D ratio, equation (3) approaches 2.86, a theoretical solution for a sheet-pile wall, suggested by Hansen (1978). For an infinitely long bucket, all the hydraulic head loss occurs inside the bucket with evenly spaced horizontal equipotential lines. Therefore, the normalized length tends to unity.

For installation in homogenous sand the internal hydraulic gradients have been investigated by several researchers using finite element programs as Plaxis and SEEP.

Senders & Randolph (2009) performed calculations with the finite element programme Plaxis and proposed a similar expression for the exit gradient:

$$\left(\frac{s}{h}\right) = \pi - \arctan\left[5\left(\frac{h}{D}\right)^{0.85}\right]\left(2 - \frac{2}{\pi}\right) \tag{4}$$

For very small h/D ratio equation (4) approaches π, which is a theoretical solution for a sheet-pile wall, suggested by Scott (1963).

Feld (2001) performed calculations with the finite element program SEEP and proposed that the seepage length could be estimated as:

$$\left(\frac{s}{h}\right) = 1.32\left(\frac{h}{D}\right)^{0.75} \tag{5}$$

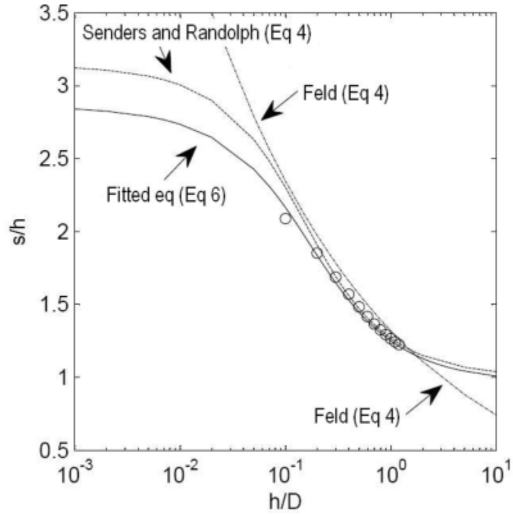

Figure 8. Seepage length for exit gradient versus relative pene-tration predicted by equation (4), (5) and (6).

Figure 8 show that these three different formulations predict similar seepage length for penetrations of practical interest $0.1 \le h/D \le 1$.

4.2 *Installation in sand over a flow boundary*

The following empirical expression is given to approximate the numerical data for the installation in layered sand:

$$\left(\frac{s}{h}\right) = \left(\frac{s}{h}\right)_{ref} + 0.1\left(\frac{D}{L_\Omega}\right)\left(\frac{h}{L_\Omega - h}\right)^{0.5} \tag{6}$$

where $(s/h)_{ref}$ is calculated from equation (3). It is seen that equation (6) approaches equation (3) if the distance to the flow boundary L_Ω is large in comparison to the diameter of the bucket *D*.

5 CRITICAL SUCTION

The formation of local piping channels occurs when the exit hydraulic gradient, next to the caisson wall, exceeds the gravitational force, and thereby reduces the effective stresses to zero. The critical gradient is:

$$i_{crit} = \frac{\gamma'}{\gamma_w} \tag{7}$$

The exit hydraulic gradient *i* can also be expressed in terms of the applied suction *p* and the seepage length *s* as:

$$i = \frac{p}{\gamma_w s} \tag{8}$$

where γ_w is the unit weight of water and γ' is the submerged unit weight. The critical suction resulting in formation of local piping channels are therefore

$$p_{crit} = s\gamma_w i_{crit} = s\gamma' \tag{9}$$

By combining equation (6) with equation (9) the critical suction can be expressed as:

$$\frac{p_{crit}}{\gamma' D} = \frac{h}{D}\left(\frac{s}{h}\right) \tag{10}$$

Figure 9 shows the critical suction calculated by equation (10) with different ratios L_Ω/D. If L_Ω/D is large then the critical suction approaches the threshold for penetration in homogeneous sand. It is also seen that the presence of a flow boundary will increase the threshold where critical suction will occur.

6 PREDICTION OF FIELD TEST DATA

In Figure 10, the suction needed to install the bucket is plotted against equation (3) and (10). The figure shows that suction close to or higher than critical, predicted by equation (3), can be applied without significant consequences. This is particularly seen in the installation test with bucket 5.

It is seen that the suction needed to overcome the resistance during the installation of the bucket 2 never violated the critical suction predicted by equation (10) with the flow boundary at 2.7 m. This was not the case in the installation test with bucket 4. At a depth of 1.56 m the applied suction violated the failure criterion predicted by equation (10) and piping channels were formed and observed during the test. At the test with

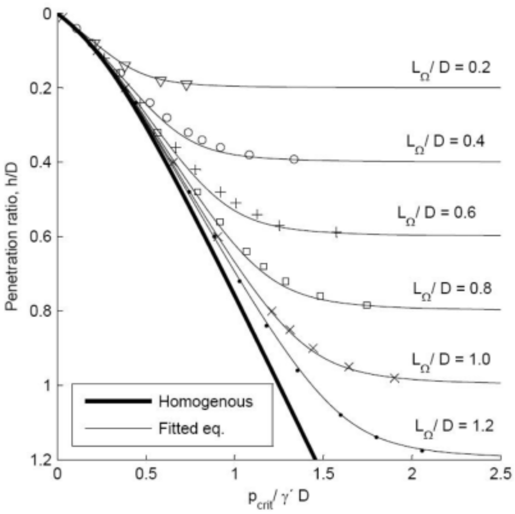

Figure 9. Normalized critical suction versus relative penetration. The critical suction is calculated with different ratios L_Ω/D.

bucket 5 the flow boundary was at a depth of 1.2 m. This increases the suction capacity and the bucket was penetrated with the highest applied suction without any failure occurring. It is shown that these thin silt layers act as flow boundaries and increase the suction thresholds against piping.

7 CONCLUSION

By comparing the numerical studies with the installation tests it is shown that it is the exit gradient next to the skirt which controls when piping will occur.

For installation in homogeneous sand, the internal hydraulic gradients have been investigated by several researchers using computer programmes such as Plaxis, SEEP and FLAC. These studies have resulted in different formulations, but the empirical expressions predict similar critical suctions for skirt penetrations of practical interest.

However, experience from installation of prototype foundations have shown that gradients close to critical, predicted by the expressions for homogenous sand, can be applied without significant consequences.

The same was observed in the field test reported in this paper. It is stated that the presence of thin silt layers will act as flow boundaries and increase the suction thresholds against piping.

The influence of the flow boundary was studied in this paper. The results are presented as simple closed form solutions and shown to predict thresholds against piping in homogeneous or layered sand.

Future studies have to be performed in order to establish the thresholds against piping when the skirt penetrates through a flow boundary.

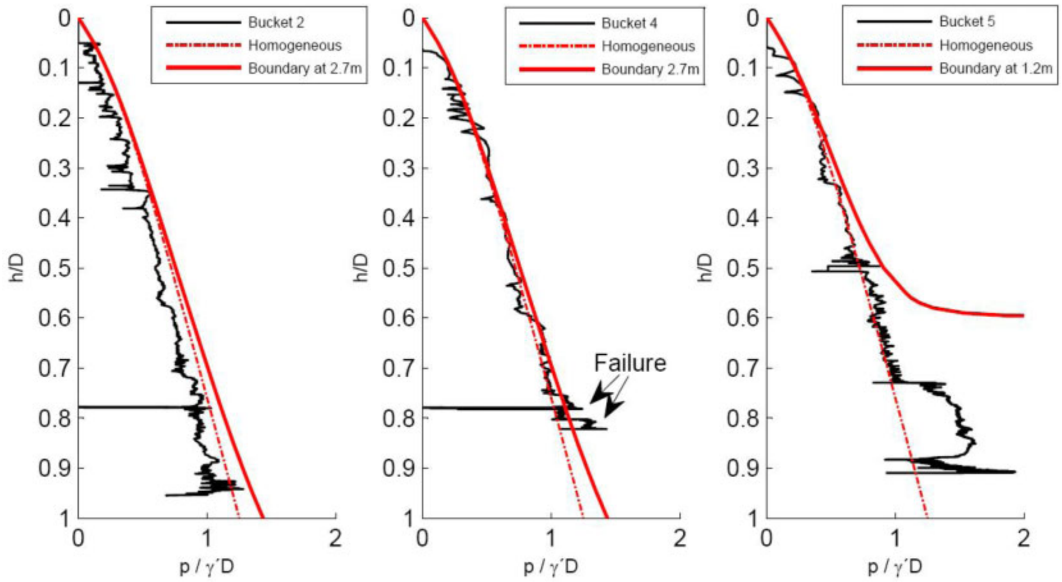

Figure 10. Installation tests analyzed using equation 10 with the flow boundaries interpret from the CPT tests in Figure 4.

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