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Installing offshore bucket foundations – insights from hydro-mechanical large deformation numerical modelling

W. Zhang
Department of Engineering, Durham University, Lower Mount Joy, South Road, Durham DH1 3LE, UK
wangcheng.zhang@durham.ac.uk (corresponding author)

ABSTRACT: Offshore wind (OSW) development is crucial for net-zero target and energy security. Rapid OSW development requires the installation of offshore foundation solutions tailored to the seabed and loading conditions. Suction bucket foundation is one of alternative offshore wind foundation solutions to the commonly used monopiles particularly for floating wind developments at deep seas. The key advantage of suction caisson is that its installation can be aided by suction loads produced through a pump reducing noises and carbon footprints. Difficulties have arisen at several sites with installation hazard such as piping, tilting and soil plug failure. This study aims to investigate suction aided installation performance of suction caissons by using a developed large-deformation and mechanical-hydraulic coupled finite element method. An existing Arbitrary Lagrangian-Eulerian Finite Element framework with remesh and interpolation techniques will be extended to account for i) continuing large-deformation penetration, ii) solid-fluid coupling that dominates the installation, and iii) suction interface. The computational tool enables observations of details behind the mechanism-based prediction method.

Keywords: Bucket foundation; suction aided installation; Finite Element method; numerical modelling

1 INTRODUCTION

Many countries have committed to achieving net-zero carbon emissions by the middle of the century, with offshore wind energy development playing a pivotal role in reaching this goal. The rapid expansion of offshore wind energy necessitates the installation of foundation anchorages designed to suit varying seabed conditions and loading requirements. Among these, suction caissons have emerged as a promising foundation solution.

Suction caissons offer several advantages over conventional offshore foundations. They are quicker and more environmentally friendly to install than deep foundation piles and can be more easily removed during decommissioning. Their installation relies on the self-weight of the structure combined with hydraulic pressure generated by a pump, providing a cost-effective and efficient alternative (Tjelta et al. 1986, Ragni et al. 2020).

Once installed and connected to the wind energy superstructure, suction caissons are subjected to environmental loads from wind and waves. These loads induce hydraulic pore pressure in the surrounding sand, with dissipation rates varying depending on soil conditions (Stapelfeldt et al. 2020). This behaviour underscores the importance of tailoring foundation designs to site-specific environmental and geotechnical conditions to ensure the stability and longevity of offshore wind installations.

Estimating installation resistance is critical for selecting an appropriate vessel for the installation operation, thereby optimizing costs effectively. Several methods exist for this estimation, including hand calculations based on bearing capacity theory (Houlsby and Byrne 2005, Alluqmani et al. 2019) or empirical correlations with CPT (cone penetration test) results (Senders and Randolph 2009). However, these approaches rely on simplifications and assumptions, such as ideal drainage conditions, which may not fully capture the complexities of real-world scenarios. CPT-based methods, while practical, require verification and careful engineering judgment due to uncertainties such as the location and quality of CPT data, penetration rates, size effects, and soil spatial variability (Le et al. 2014). These factors can significantly influence the accuracy of resistance predictions.

Numerical modelling, when the model accurately represents real-world conditions, offers a more robust means of predicting installation resistance by accounting for complex and realistic mechanical and hydraulic behaviours. However, numerical studies on suction caisson installation resistance remain limited due to several challenges:

- Large deformations involved during the installation process.
- The need to model coupled mechanical and hydraulic behaviours of soils.
- The complex interaction between the structure and soil, particularly at the suction interface, which requires precise implementation.

2 METHODOLOGY

The RITSS (Remeshing and Interpolation Technique with Small Strain, Hu and Randolph 1998) approach is classified under the 'arbitrary Lagrangian-Eulerian' (ALE) methods, which are particularly effective for handling large-deformation problems. This approach decomposes a complex large-deformation analysis into a sequence of small-deformation increments, each followed by a remeshing process and interpolation of field variables from the old mesh to the new one. Four core modules: pre-processing, updated Lagrangian calculation, post-processing, and interpolation, are required for each increment to progress accurately.

A key advantage of the RITSS approach is its flexibility: it can be implemented using a combination of commercial and non-commercial software, with each module managed by a package best suited to that task (Zhang et al. 2015). In this study, pre-processing tasks, such as setting parameters and meshing deformed sections, as well as the updated Lagrangian calculations, were managed using Abaqus, a commercial finite element software. These tasks required only minimal custom automation code. Field quantity interpolation between meshes was accomplished through a built-in algorithm in Matlab, while Python scripts were used for post-processing tasks, including the extraction of field variables, nodal coordinates, and model boundaries from the prior mesh. In each increment, finite strain theory was applied, with the equivalent plastic shear strain constrained to values less than unity to preserve accuracy. This modular approach enables the RITSS method to address complex deformation scenarios effectively, balancing automation with precision by leveraging specialized software for each component.

The fluid diffusion and stress analysis are coupled within the Lagrangian framework to accurately model the interaction between pore fluid pressures and the soil skeleton's response under stress (Dong et al. 2021). The analysis assumes a porous medium governed by the Modified Cam Clay (MCC) model, which is widely used for simulating the behaviour of clayey soils under varying stress conditions. Pore water flow within this medium adheres to Darcy's law, ensuring that the movement of water through the soil matrix aligns with classical principles of hydraulic conductivity.

An implicit iterative method is employed to solve for both the excess pore fluid pressures and the effective stresses within the soil matrix, allowing for a stable and accurate integration of these coupled variables over time. To control the accuracy of each consolidation step, the maximum permissible change in pore pressure per time increment was carefully monitored. This value was optimized to be as high as possible to maximize computational efficiency without compromising the convergence of the solution. By fine-tuning this parameter, the analysis achieves a balance between precision and computational speed, ensuring that pore pressure changes are accurately reflected at each time step and that effective stresses are reliably calculated throughout the consolidation process.

For each increment, the mesh is regenerated with refined elements concentrated around the annulus of the bucket foundation. Figure 1 shows the mesh configuration for the initial penetration increment. Accuracy is ensured by using over eight elements directly beneath the foundation tip. Four-node axisymmetric element (CAX4) was used with the minimum mesh size being 0.006 m. The bottom boundary is fully fixed and only vertical movement is allowed at the outer boundary.

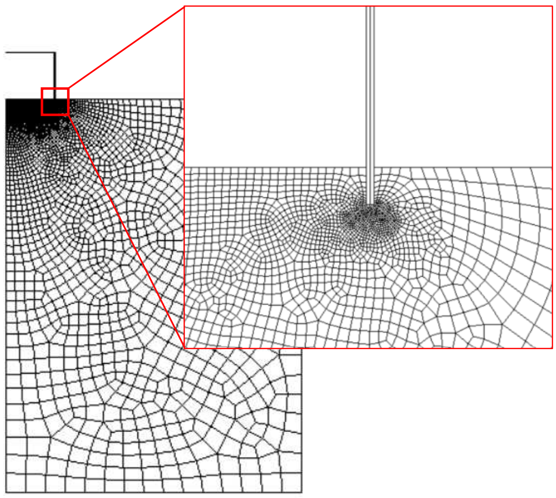

Figure 1 – Mesh details used in the numerical modelling

2.1 Procedure and parameters

The numerical modelling follows these key procedures:

- **Initial state**: An 40 m × 50 m soil ground is generated, with a gravitational acceleration of 9.8 m/s² applied. The initial geostatic stress is set with an earth pressure coefficient of unity, and the soil is assumed to be normally consolidated. The initial void ratio is calculated based on isotropic consolidation conditions and is applied at the beginning of the analysis. No excess pore pressure is present in the initial soil state.

- **Self-weight installation**: The bucket foundation is lowered by gravity at a controlled penetration rate of 2 m/hour. Only vertical movement is allowed, ensuring no tilt during installation. A free drainage hydraulic condition is set at the seabed, while no drainage occurs at the interfaces between the bucket and the soil.
- **Suction-aided installation**: Self-weight penetration stops once the resistance equals the foundation's weight. Suction is then applied to the soil inside the bucket through pore water boundary condition, with an equivalent force at the bucket lid to promote further penetration. Suction force is updated at the beginning of every step. The suction rate is controlled at 0.1 kPa/s, following best practices communicated by industry practitioners. The numerical modelling concludes once the target penetration depth is achieved.

The jacked installation of bucket foundation is simulated for comparison, following the same procedure as the self-weight penetration until the target penetration depth is reached. The study employs a Modified Cam Clay (MCC) model characterized by an elliptical yield surface. Table 1 lists the main soil properties and hydraulic parameters used in the numerical modelling. The material properties are not specific to a particular site but are considered representative of typical marine clays. The chosen material properties are expected to have minimal impact on the overall findings.

Table 1. Material properties used in the numerical modelling

Properties	Value	Unit
Specific weight of pore fluid, γ_w	10	kN/m^3
Effective unit soil weight, γ'	10	kN/m^3
Bucket diameter, *D*	12	m
Bucket depth, *l*	6	m
Wall thickness, *t*	0.06	m
Slope of the unloading-reloading line, κ	0.02	
Slope of the virgin consolidation line, λ	0.1	
Specific volume at 1kPa, v_0	1.2	
Slope of the critical state line, *M*	1.33	
Poisson's ratio, ν	0.25	
Soil permeability coefficient, *k*	10^{-3}~10^{-7}	m/s
Friction coefficient of interface between wall and soil	0.5	

3 RESULTS AND ANALYSIS

3.1 Jacked installation

In the first scenario, the bucket foundation is installed to a target depth of 6 meters using a jacked installation approach at a penetration speed of 5 mm/s (equivalent to 0.3 m/min). This relatively high installation rate, combined with a low soil permeability coefficient of 10^{-7} m/s, ensures undrained conditions during installation with the dimensionless velocity being $\frac{vt}{c_v} = 67$ (> 30; House et al. 2001).

Figure 2 shows the installation resistance against penetration depth, allowing for a clear analysis of resistance behaviour over the installation process. For comparison, an analytical solution based on the API method (API 2011) is also plotted in the figure, providing a benchmark for evaluating the resistance profile.

The undrained shear strength is computed based on the MCC model as follows (Wroth 1984)

$$\frac{s_u}{p'} = \frac{M}{2}\left(\frac{OCR}{2}\right)^{\Lambda} \quad (1)$$

where $p^{'}$ is the effective mean stress, OCR the overconsolidated ratio, and $\Lambda = \frac{\lambda-\kappa}{\lambda}$. In the study, $OCR = 1$. The installation resistance under undrained condition is given by

$$R = (9s_u + \sigma'_{v0})A_{an} + \alpha s_u\left(A_{sh,in} + A_{sh,out}\right) \quad (2)$$

where $\sigma_{v0}^{'}$ is the effective overburden pressure, and A_{an}, $A_{sh,in}$ and $A_{sh,out}$ are annular area, inner shaft area and outer shaft area, respectively.

It can be observed from the figure that the installation resistance increases with the penetration depth as expected. The penetration resistance is about 3000 kN at the final depth of 6 m. The numerical results from the large deformation modelling match the analytical results well.

For the case of high permeability (10^{-3} m/s), the drained condition is warrantted. Coulomb friction is activatited at the interface between the shaft and soils. So the installation resistance is given by

$$R = qA_{an} + \beta K\sigma'_{v0}\left(A_{sh,in} + A_{sh,out}\right) \quad (3)$$

where parameter β is relevant to friction coeefcient, and q is the stress acting on the annular of the bucket and given by

$$q = N_q \sigma'_{v0} + N_\gamma \frac{t}{2} \gamma \qquad (4)$$

where N_q and N_γ are bearing capacity factors relevant to the internal friction anagle of soil. The internal friction angle of MCC type soils can be given by (Wroth 1984)

$$\varphi \approx \frac{9}{8} \sin^{-1} \frac{3M}{6+M} \qquad (5)$$

Figure 3 illustrates the relationship between installation resistance and penetration depth. Under drained conditions, the installation resistance is significantly higher than in undrained conditions, with the final depth reaching a resistance of 16,000 kN. Overall, the numerical results align closely with the analytical predictions.

Additionally, Figure 4 presents deviatoric stress contours, offering a detailed view of the stress distribution mechanisms during the penetration process, which cannot be directly observed in experimental or field tests. Initially, deviatoric stress is minimal at shallow penetration depths. As the foundation penetrates deeper, the stress intensifies and concentrates beneath the bucket foundation's wall tip. When the penetration depth reaches 4 m, the maximum deviatoric stress exceeds 20 kPa. The disturbed zone extends from the wall tip to the surfaces both inside and outside the bucket, highlighting the localized stress impact around the foundation.

3.2 Suction aided installation

In the second scenario, the suction-aided installation of the caisson is simulated following its penetration under self-weight. The caisson is assumed to weigh approximately 400 tons, resulting in a self-weight penetration depth of about 2 m under drained conditions, as predicted by the jacked installation resistance discussed earlier.

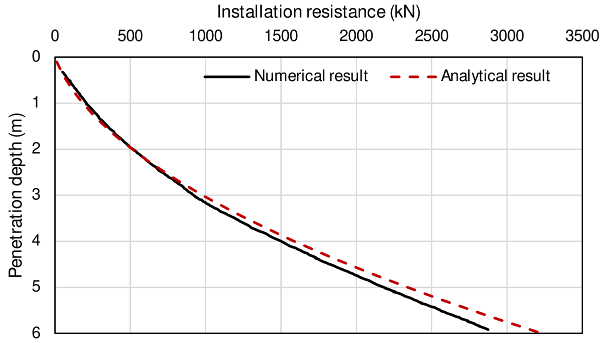

Figure 2 – bucket foundation installation resistance against penetration depth under undrained condition using the jacked installation approach

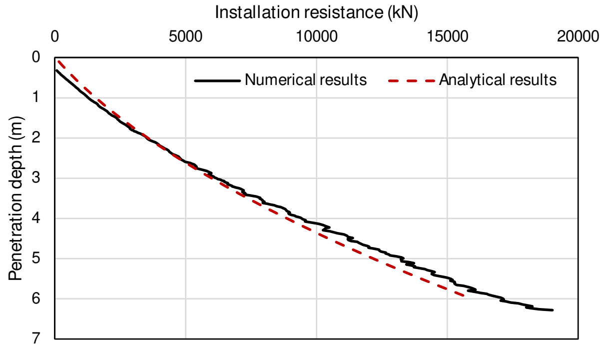

Figure 3 – bucket foundation installation resistance against penetration depth under drained condition using the jacked installation approach

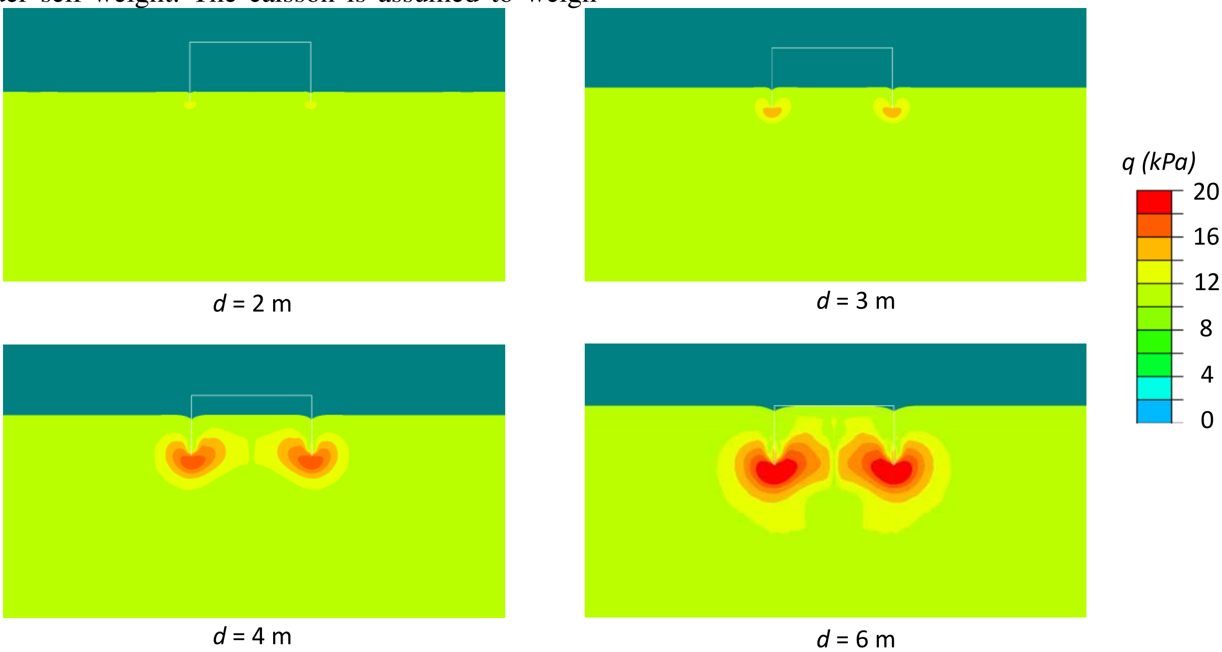

Figure 4 – Evolution of deviatoric stress contours during jacked installation process (d is penetration depth)

Figure 5 illustrates the applied suction pressure against the penetration depth. The suction pressure steadily increases as the caisson penetrates deeper into the soil. A suction pressure of 48 kPa is required to reach a penetration depth of 5.5 m. However, the target depth of 6 m could not be achieved due to significant soil heave inside the caisson, which hindered further penetration.

Figure 6 also presents the equivalent installation resistance versus penetration depth. This resistance is determined as the sum of the caisson's self-weight and the suction force applied to the caisson lid. It is evident that the installation resistance during suction-aided installation is significantly lower than that observed during jacked installation (analytical – drained). This reduction is attributed to the influence of upward hydraulic seepage flow inside the caisson, which decreases the effective stress acting on the soil. The reduction in effective stress causes a marked decrease in inner skin friction and tip resistance.

The primary advantage of numerical modelling is its ability to visualize the mechanisms underlying the mechanical and hydraulic behaviours during caisson installation. Figure 7 illustrates the pore water pressure contours at different stages of installation (penetration depths of 2 m, 3 m, 4 m, and 5 m, respectively).

During the self-weight penetration stage (2 m depth), excess pore pressure is observed, with a concentration at the caisson tip. In the suction-aided installation stage, positive excess pore pressure persists around the caisson's annular region, particularly near the outer walls. However, a significant negative excess pore pressure develops inside the caisson, especially near the soil surface. This observation aligns with the applied suction at the caisson lid. The suction effect also induces soil heave, as the upward suction force causes slight upward movement of the soil adjacent to the caisson wall.

Horizontal equipotential lines are visible inside the caisson, indicating upward seepage flow driven by the suction pressure. The maximum excess pore water pressure remains concentrated at the caisson tip, extending beyond the caisson boundaries. This suggests that seepage flow outside the caisson also moves upward, which differs from traditional theoretical assumptions that suction increases skin friction along the outer caisson wall. This finding highlights an important deviation: suction-aided installation may not significantly enhance skin friction on the outer wall surface, contrary to common theoretical models. This phenomenon warrants further investigation under varying soil and hydraulic conditions to refine our understanding of suction caisson installation mechanics.

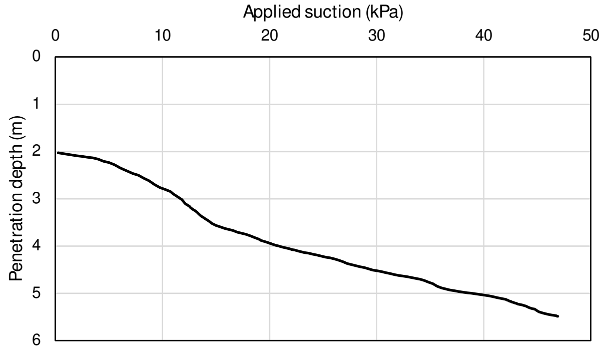

Figure 5 – applied suction against penetration depth

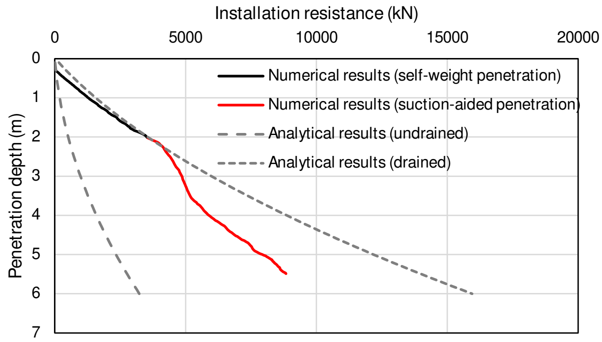

Figure 6 – equivalent penetration resistance against penetration depth during suction aided installation

4 CONCLUSIONS

This study investigates the performance of suction-aided installation for suction caissons using a newly developed large-deformation, mechanical-hydraulic coupled finite element method. The approach builds upon an existing Arbitrary Lagrangian-Eulerian (ALE) finite element framework, enhanced with remeshing and interpolation techniques, and is extended to address:

- Continuous large-deformation penetration during installation.
- Solid-fluid coupling that governs the suction-aided installation process.
- The implementation of a realistic suction interface.

This computational tool provides detailed insights into the mechanisms underlying prediction methods based on theoretical assumptions.

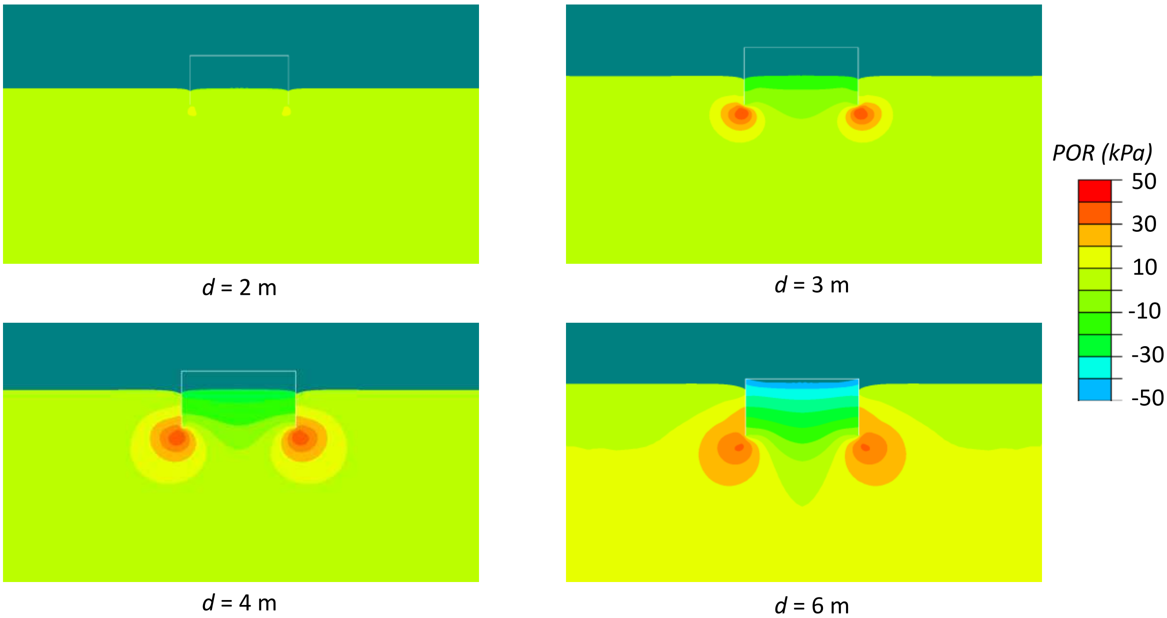

Figure 7 – Evolution of deviatoric stress contours during suction aided installation process

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