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Literature Review of Large Deformation Numerical Modelling of Suction Caisson Installations

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ABSTRACT: Suction caissons have been used successfully in the offshore oil and gas industry since the 1980s and more recently in offshore wind developments. These structures are installed by applying suction inside the caisson, whereby it penetrates the soil. This paper reviews the state-of-the-art for large deformation numerical modelling of suction caisson installation. It is found that the mechanisms governing the coupling between large deformations of the soil and pore water flow is not studied in detail. It is further observed that although suction caissons have been applied for decades, there has been limited utilization of the data collected during the installations. It is believed that further knowledge could be gained by analysing such data and combining them with numerical analyses, leading to improved design methods, more reliable information about soil properties (e.g., permeability and interface wall-soil friction), verification of design, and benefitting post-installation lifetime assessments.

Keywords: suction caissons; suction anchors, large deformation numerical modelling, suction installation

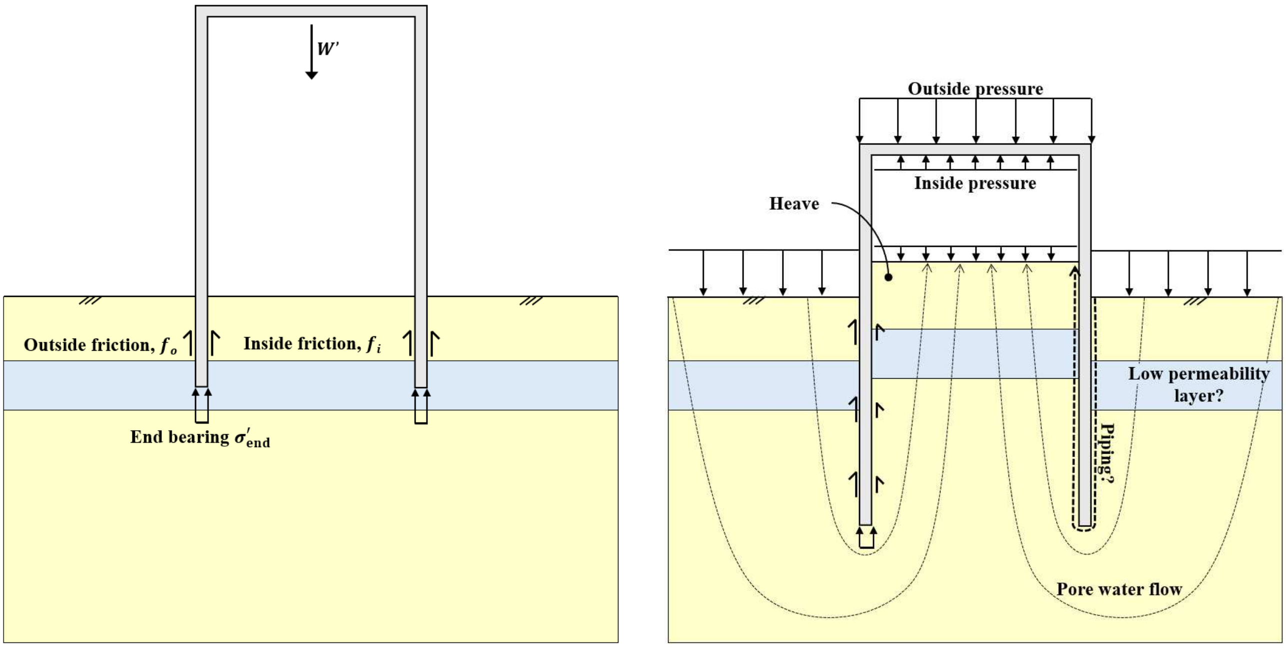
1 INTRODUCTION

Offshore renewable energy plays a crucial role in the global effort to mitigate future climate change. To align with the Paris Agreement, the Global Offshore Wind Energy Compact (GWEC) has set a goal of achieving 2000 GW of installed capacity by 2050. By the end of 2022, the total global offshore wind capacity reached 64 GW. To meet net-zero target, a significant acceleration of offshore wind installations is necessary. However, current technologies are insufficient to support this growth; industry innovation is essential. The required acceleration of offshore wind installations could largely benefit from methods that extract knowledge from current and future installation data.

Suction caissons have been successfully used for offshore oil and gas installations since the 1980s and more recently for offshore wind projects. Recently, suction anchors have also become relevant in relation to mooring systems for floating offshore wind. Suction caissons and suction anchors are installed by generating suction within the caisson/anchor, allowing it to penetrate the seabed driven by the pressure difference between the outside and the inside of the caisson. The penetration resistance, i.e., the wall friction and the skirt tip resistance, depends upon the soil type and soil strength, soil stress changes, pore water flow, and more (Figure 1).

Near the skirt tip, the soil will experience large shear deformation. This may give reduced strength (strain softening) of sensitive clay and increased strength in dilative over-consolidated clays. Sands will approach the stress-dependent critical state void ratio. The shear stresses along the caisson wall depends on the interface strength. In clay, the failure generally takes place as large shear deformations and remoulding in a thin zone along the wall. In sand, failure can take place as slip along the wall-soil interface. In addition, pore water flow will influence the effective stresses in the sand, and there are factors such as piping and soil layering to add further complexity.

Several authors have worked on penetration resistance of suction caissons. The traditional approach is to use bearing capacity equations (e.g., Andersen et al., 2008; Andersen & Jostad, 1999; Houlsby & Byrne, 2005b, 2005a). Another approach is using CPT-based correlations providing a direct relation between CPT tip resistance and penetration resistance (e.g., Senders & Randolph, 2009).



(a) Self-weight penetration *(b) Suction installation*

Figure 1. Schematic drawing of caisson installation. The driving forces are the caisson submerged weight W' and the pressure difference between the outside and the inside. The resisting forces are the friction on the outside f_o and on the inside f_i walls, and the end bearing σ'_{end}, depending on soil properties and effective stresses.

Still there are many aspects of suction installation that need further investigation. When soil conditions get more complex, things like penetration resistance, pore water flow, and piping are suddenly more elusive to predict. In some projects this has even been handled by using micro-siting. This means that the design considers the contingency that the installation will not succeed at the proposed location. In this case the installation will be attempted again at a different micro-site within the micro-siting distance.

Hardly any other foundation concepts operate with such explicit uncertainties. Addressing these uncertainties requires a better understanding about the coupled mechanisms during installation and the behaviour after installation. Such understanding can potentially be gained from looking at installation data from existing installations. One way of understanding these data is by combining them with numerical methods that can replicate and quantify the governing processes and uncertainties.

The next section details how large deformation numerical modelling can be used to explore these uncertainties. Key shortcomings of current practice and methods are highlighted.

2 LARGE DEFORMATION MODELLING

Large deformations, as for example during caisson installation, present a challenge for numerical modelling. Traditional Lagrangian finite element modelling is limited to small strains and thus not able to capture large deformations. Since the 1990s, however, several techniques have been developed that attempt to solve this issue. For the application of suction caissons, studies utilizing such techniques have been published since mid-2000s and have seen a steady increase until today.

2.1 Methods

Four different methods typically used for large deformation analyses of geotechnical problems are:

- The coupled Eulerian-Lagrangian (CEL) method (Benson, 1992; Noh, 1963)
- Arbitrary Lagrangian-Eulerian (ALE) finite element methods (Ghosh & Kikuchi, 1991)
- The remeshing and interpolation technique with small strain (RITSS) (Hu & Randolph, 1998), which falls into the category of ALE methods.
- Particle-based methods, most notably the material point method (Sulsky et al., 1994, 1995)

The CEL technique and the ALE technique have been used for several studies of suction caissons, while particle-based methods have been used only in a couple of studies (Jin et al., 2017, 2019; Stapelfeldt et al., 2021). The reported results indicate, however, that such methods are promising for simulation of large deformation penetration problems. Somewhere between mesh-based and particle-based methods is the

Table 1. Summary of methods used for large deformation numerical analyses of suction caisson installations. For a comprehensive discussion on the characteristics and merits of these methods for geotechnical engineering applications refer, for example, to Augarde et al. (2021).

	CEL	ALE	RITSS	PFEM	MPM
Time-stepping	Primarily explicit	Explicit or implicit	Primarily implicit	Primarily implicit	Primarily explicit
Mesh	Fixed Eulerian mesh for soil, updated Lagrangian mesh for structure	Mesh relocation or remeshing	Frequent remeshing	Dynamic remeshing based on particle positions	Grid with moving material points overlain by (fixed) mesh
Field variable mapping	Mapped on fixed Eulerian grid ("advection")	Mapped between old and new mesh ("convection")	Mapped between old and new mesh	Tracked by particles within mesh	Carried by particles, mapped between particles and mesh
Availability	Commercial software (e.g., Abaqus, LS-DYNA)	Commercial software (e.g., Abaqus, LS-DYNA)	Limited (primarily custom implementations)	Limited, some pre- and post-processing tools available but mainly run by scripts	Open-source software available (e.g., Anura3D)
Advantages	Can accommodate complex boundary value problems Suitable for dynamic problems	Wide range of applications (e.g., 2D and 3D, quasi-static and dynamic) Handles coupled problems Good constitutive model flexibility	Simple and robust for quasi-static problems Straight-forward constitutive model implementation	Good at multiphysics coupling Easy to implement dynamic boundaries	Can solve the equations for different phases with distinct layers of MPs No mesh distortion
Disadvantages	Common implementations have limited multiphysics coupling and are limited to 3D Limited constitutive model flexibility	Limitations related to boundary value problem complexity Limitations in the distortion of boundaries	Complex remapping Not suited for high-speed dynamic applications	High sensitivity to mesh quality Numerical diffusion from remeshing Difficult to implement complex soil models	Numerical diffusion High computational cost Challenging boundary condition implementation

particle finite element method (PFEM) (Idelsohn et al., 2004).

Khoa & Jostad (2016) discussed some differences between the CEL and ALE methods implemented in Abaqus, pointing out that the ALE implementation is more flexible as it can be applied to planar, axisymmetric, and three-dimensional boundary value problems, while the CEL implementation is limited to 3D. Also, ALE is available for both Abaqus/Explicit and Abaqus/Standard, while CEL is only available in Abaqus/Explicit. This limits the applications to which CEL can be applied, as pore fluid flow coupled with soil deformations is not available. This constitutes a problem particularly for the modelling of sand. On the other side, with ALE, the material boundaries in Abaqus are assumed to be Lagrangian, meaning that it cannot handle large deformation of these boundaries. Stapelfeldt et al. (2017) circumvented the problem of coupled pore water flow and deformation in Abaqus/Explicit CEL by using temperature as a proxy for pore pressure, and use the coupled temperature-deformation solver to model suction caisson penetration in sand. D. Wang et al. (2015) compared the capabilities of a CEL, an ALE algorithm, and a RITSS algorithm, and Augarde et al. (2021) presented a more comprehensive review of the different methods. Table 1 summarizes some main characteristics of the methods. Note that some of the advantages and disadvantages listed, mainly for CEL and ALE, relates to the most popular commercial implementations and not strictly the methods themselves.

2.2 Outline of previous studies

Many of the existing studies have looked at installations in clay, using total-stress based linear elastic-perfectly plastic constitutive models with the Tresca failure criterion (Chen et al., 2009; Q. Wang et al., 2020, 2021; Y. Wang et al., 2018; Xiao et al., 2019; Zhao et al., 2018; H. Zhou & Randolph, 2006; M. Zhou et al., 2016, 2022). The clay sensitivity is then only taken into account by the ratio between the interface strength and the soil undrained shear strength which is input to the analytical models.

A few early works focused on the differences between suction installation and jacking. For example, H. Zhou & Randolph (2006) found that the total installation force is similar for the two installation methods. Later studies have made slightly different conclusions. Y. Wang et al. (2018) found that the total resistance for suction installation is smaller, the main contribution being lower internal friction.

In recent years focus has shifted towards using large deformation numerical analysis to establish semi-analytical design tools, for example, for estimating penetration resistance during installation. Caissons without stiffeners (Xiao et al., 2019), with stiffeners (Q. Wang et al., 2020; M. Zhou et al., 2016, 2022), and with just a single pad-eye stiffener (S. Zhou et al., 2022) have been studied, while S. Zhou et al. (2021) investigate the effect of an interbedded sand layer in clay.

Some authors (e.g., Chatterjee et al., 2014; Ghorai & Chatterjee, 2020; Ma et al., 2022; Xiao et al., 2020; S. Zhou et al., 2022) have modified the shear strength to account for strain rate effects and strain softening using the expression presented by Einav & Randolph (2005).

Two studies have used the critical state models for clay (Koh et al., 2018; Vásquez et al., 2010) in effective stress-based models, thus being able to model pore water flow and pore pressure dissipation. Vásquez et al. (2010) looked at the set-up effects, finding, for example, that the entire weight is carried by exterior friction after the setup following suction installation. Koh et al. (2018) proposed equations for calculating dissipation of excess pore pressure.

Only a few studies have modelled suction caisson installations in sand. Stapelfeldt et al. (2017) used a hypoplastic effective stress-based material model with the Matsuoka-Nakai yield surface. H. Wang et al. (2021) used an elastoplastic model with isotropic hardening and a Drucker-Prager yield surface in their attempt to investigate the effect of pore water flow on penetration resistance. Their conclusion was that the penetration resistance was significantly smaller during suction. The reason is the upward pore water flow inside the caisson, leading to a reduction in the effective stresses and thus the inside wall friction as well as the tip resistance. For a jacked installation on the other hand, they found that the effective stress is increased.

Jin et al. (2017) and Stapelfeldt et al. (2021) used a linear elastic, perfectly plastic material model with the Mohr-Coulomb yield criterion in their particle-based numerical models. Finally, Jin et al. (2019) used a particle-based method with a critical state-based model.

3 OUTSTANDING ISSUES

Common to nearly all previous studies is that they use centrifuge data or laboratory tests to validate the models, often followed by parametric studies to investigate a range of geometrical configurations and/or soil properties. An exception is M. Zhou et al. (2016) who used installation data to validate their semi-analytical expression for penetration resistance.

To the authors' knowledge no studies exist that use data from real suction caisson installations in combination with large deformation numerical analyses to investigate the soil response and behaviour during and after installation for more realistic soil profiles. Furthermore, the studied soil conditions are generally simple and there is only a couple of studies that considers sandy soil or layered soil. The following outstanding issues can, thus, be identified from the previous studies employing large deformation numerical analyses to study suction caissons:

- Most consider simplistic soil profiles with homogeneous and isotropic soil.
- There are limited studies on sand and only a couple of studies consider pore water flow.
- Many studies do not include a realistic representation of the suction itself; the penetration being simply displacement-controlled without application of suction.
- There are no studies on piping phenomena in combination with large deformations.
- No identified studies investigate in detail the effect of cycling to reduce penetration resistance.
- No identified studies tap into the data collected from previous suction caisson installations, all use centrifuge or laboratory data.

4 A LOOK AHEAD

Based on these observations and experience showing the obvious uncertainties related to installation of these structures, it is obvious that there are insights to be gained by further research. Also there seems to be no studies of how installation data can be used more directly as a source of data in and by itself after the caisson is in place. The installation data represent information from the actual installation site at the scale of the foundation. Thus, it could provide useful information that can be used to reduce uncertainty in soil parameters and foundation behaviour. It could, for example, be used to validate whether the capacity of the installed caisson is sufficient or be used for lifetime extension evaluations. Combining installation data with machine learning techniques, large deformation numerical analyses, or other analyses methods, could greatly benefit the asset management of offshore wind farms. If methodologies could be established for directly relating suction caisson installation data and in-place soil properties (e.g., permeability and interface wall-soil friction), foundation capacity could be directly verified, and more reliable lifetime assessments could be achieved, thus maximising the benefit from offshore wind developments.

AUTHOR CONTRIBUTION STATEMENT

Eirik Nilsen: Investigation, Writing - Original Draft. **Hans Petter Jostad:** Supervision, Writing - Review and Editing. **Yutao Pan:** Supervision, Project administration, Writing - Review and Editing.

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