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Numerical analysis of a suction bucket penetrating in sand with a combined Lagrangian – SPH approach

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Abstract

The penetration of a suction bucket in the soil redistributes the soil stress state and influences the interactions between the foundation and the surrounding environment. However, few finite element studies on suction buckets consider the influence of the installation phase. In this paper, a combined Lagrangian – Smoothed Particle Hydrodynamics method (SPH) under large deformations is adopted to simulate the installation phase and the behavior of the foundation submitted later on to static loadings. The numerical model is validated using laboratory experimental results that prove the ability of the combined Lagrangian – SPH method to reproduce the suction bucket installation, the soil stress state redistribution and the various interactions.

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Keywords: smoothed particle hydrodynamics (SPH); suction bucket; foundation; sand; large deformations.

1. Introduction

A suction bucket is a closed-top steel tube, which is first lowered to the seafloor allowing to penetrate under its own weight, and then push to full depth with suction force producing by pumping water out of its interior. The main advantages of suction buckets are the convenient installation method, their repeatedly use and the fact that they may mobilize a significant amount of passive suction during uplift. Recently, suction buckets have been widely used for

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different types of constructions, such as gravity platform jackets, jack-ups, offshore wind turbines, subsea systems and seabed protection structures. For an optimum design, a better understanding of the performance of suction bucket foundations is therefore necessary.

In recent years, a number of 2D and 3D numerical studies have been performed to research the suction bucket bearing capacity under different loading combinations and drainage conditions [1-4]. In all these studies, elasto-plastic constitutive models were used for the soil but the influence of the installation process was ignored.

In this article, numerical simulations are presented of a suction bucket penetrating in sand. To deal with large deformations during the installation phase, a combined Lagrangian - Smoothed Particle Hydrodynamics method (SPH) is adopted and the Mohr-Coulomb elasto-plastic law is used for the soil. The numerical results are compared with laboratory experiments and the ability of the combined Lagrangian-SPH method to reproduce the suction bucket installation, the soil stress state redistribution and the various interactions influence of the penetration phase is discussed.

2. Numerical modeling of a suction bucket foundation

2.1. Experimental campaign

In order to validate the numerical model, a laboratory test of a suction bucket foundation in sand including the installation phase and the application of monotonic and cyclic static loadings is chosen [5]. The experimental set-up in [5] consists of a sand box (1600mm × 1600mm × 1150mm), a loading frame and a hinged beam. A system of steel cables and pulleys induces a static (monotonic and sinusoidal) loading to the foundation through an electric motor drive placed on the hinged beam. The load, set by means of three weight hangers, is transferred to the foundation through a vertical beam bolted on the bucket lid. The foundation is instrumented with three LVDTs (Linear Variable Differential Transformer) and two load cells [6]. The testing set up follows the features of a similar testing apparatus [7]. Cone Penetration Tests (CPT) are carried out to assess the soil parameters. The suction bucket foundation is made of steel, has an outer diameter of 300 mm, a lid thickness of 11.5 mm, a skirt length of 300 mm and a skirt thickness of 1.5 mm.

2.2. Numerical model

2.2.1. Lagrangian and combined Lagrangian - SPH model

In this article, the ABAQUS Finite Element (FE) code is adopted for the simulations. The FE soil domain has side lengths of 1600mm and a depth of 1200mm. On the outer and bottom faces, the translational degrees of freedom are constrained. The plate thickness used for the skirt and lid of the bucket is 2mm and 10mm respectively. The diameter (D) of the bucket foundation and the skirt length (d) are equal to 300mm. Following Foglia et al. 2015[5], the density of the bucket is taken equal to 7800kg/m³, the Young modulus 200GPa and the Poisson ratio 0.3. For the soil, the density is 1100kg/m³, the Young modulus 26MPa, the Poisson ratio 0.25, the frictional angle 40.8, the dilation angle 17.5, the friction coefficient of the interface 0.35 and the cohesion 6kPa.

One disadvantage of the meshless methods (e.g. SPH) over the Lagrangian models is their computational demand. The SPH method is also less accurate under small deformations. For this reason, only a part of the soil domain is modeled with the SPH method. Lagrangian model is adopted for the rest (combined Lagrangian - SPH model). The "Tie Constraint" ABAQUS command is adopted. This command "ties" two separate surfaces so that no relative motion exists; it allows fusing two domains even though their meshes are not identical. By using the "Tie Constraint" command, the SPH particles are thus "tied to" the Lagrangian domain.

In the combined Lagrangian - SPH model, only the portion of the soil experiencing the largest deformations is modeled with SPH particles (see Fig. 1). The SPH domain is 800mm at each side and 1200mm deep (for the CPT simulation presented however, each side of the SPH domain is reduced to 400mm and the depth to 600mm in order to decrease the calculation time, see Fig. 2(a)). For a model with densely packed SPH particles, it is recommended that the initial particle distance in each direction stays approximately constant. Finally and for numerical stability reasons, at least four SPH particles per face of the Lagrangian element in contact with the SPH domain are considered.

As shown in Fig. 2(b), a classical Lagrangian finite element model is also adopted. For this model, the penetration phase is ignored and the bucket foundation is initially considered into the soil. The finite element domain has the same dimensions as the combined Lagrangian - SPH model. The purpose of the Lagrangian model is to study the influence of the penetration phase on the final results, comparing with the combined Lagrangian - SPH model.

2.2.2. Simulation sequences

One CPT, one penetration test under pure vertical load and five displacement controlled monotonic tests under different dimensionally homogenous moment to horizontal load ratios (M/DH) at constant vertical load (V_{const}) are simulated. The applied load is V_{const} is 241 N and includes the buoyant self-weight of the bucket and the weight of the measuring system mounted on the foundation. All monotonic loading paths are followed until the vertical bearing capacity (VM) or the horizontal capacity and moment capacity (MR) are reached.

The combined Lagrangian - SPH model of Fig. 2(a) is used to simulate the CPT test, the combined Lagrangian - SPH model of Fig. 1 for the penetration test and the five displacement controlled monotonic tests (named as Simulation-Y) and the Lagrangian finite element model of Fig. 2(b) for the five displacement controlled monotonic tests (neglecting the penetration phase - Simulation-N). These last calculations are done in order to check the influence of the penetration phase on the final results. For all simulations, the dynamic explicit method is adopted. The spatial discretization parameters of the numerical models are given in Table 1.

Table 1. Spatial discretization parameters.

Simulation	L (mm)	W (mm)	D (mm)	N° of SPH particles	N° of FE elements
CPT	400	400	600	23814 (Lagrangian - SPH)	78304
Simulation-Y (with penetration)	1600	1600	1200	53361 (Lagrangian - SPH)	147456
Simulation-N (without penetration)	1600	1600	1200	0 (Lagrangian)	67982

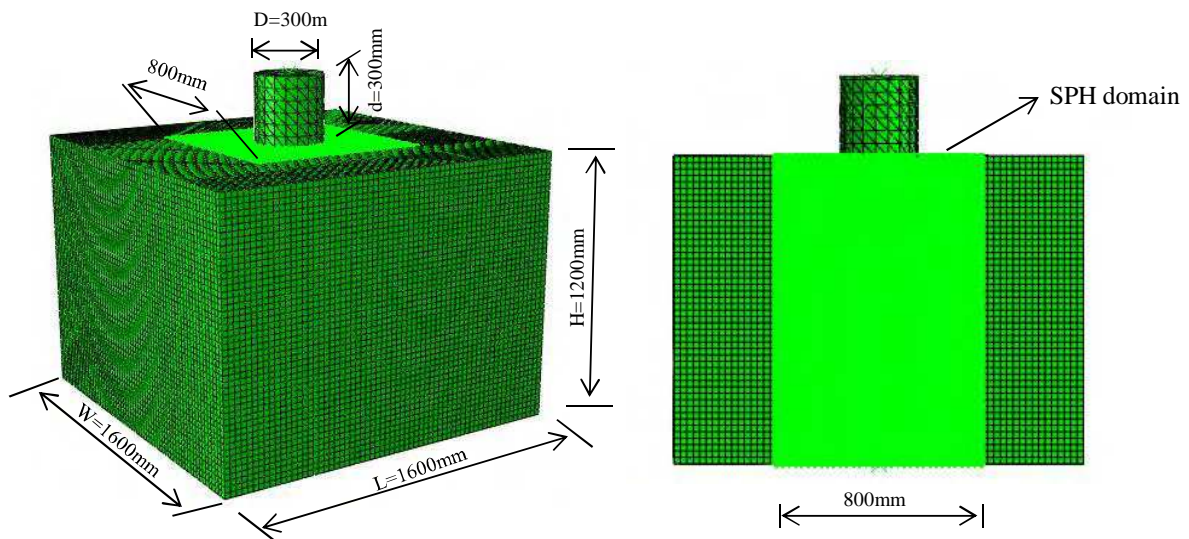


Fig. 1. Schematic plot of the combined Lagrangian - SPH model.

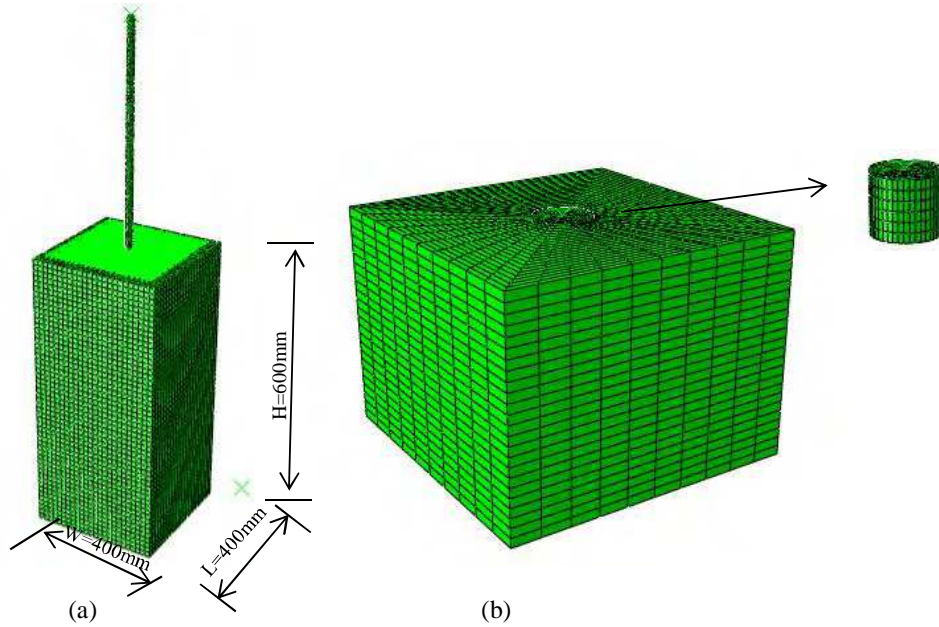


Fig. 2. Schematic plot of (a) the combined Lagrangian - SPH model used for the CPT simulation (b) the Lagrangian model.

3. Numerical simulations

3.1. CPT

In order to validate the chosen material parameters, a CPT simulation is presented hereafter using the combined Lagrangian - SPH model of Fig. 2(a) and the material parameters presented in the previous section. During the simulation, the cone velocity was kept constant and equal to 5mm/s [8]. The comparison between the experimental and the numerical results is shown in Fig. 3, where the four CPT experimental results are taken from [5]. The chosen material parameters are therefore acceptable, as the numerical simulation curve is situated within the four experimental CPT results.

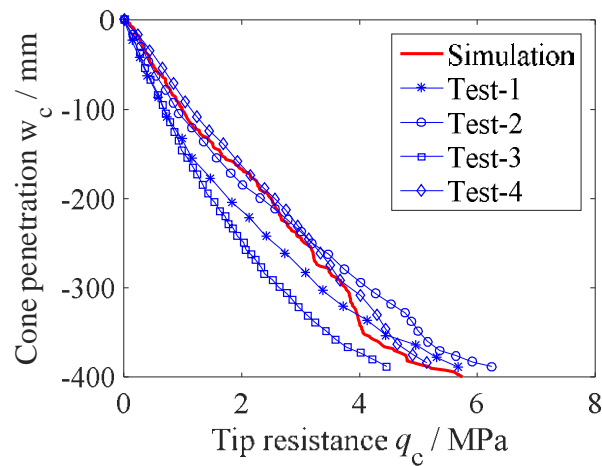


Fig. 3. CPT. Experimental vs. numerical results.

3.2. Simulation-Y and Simulation-N

The combined Lagrangian - SPH model of Fig. 1 is used to simulate the penetration test and the five displacement controlled monotonic tests (Simulation-Y), while the Lagrangian finite element model of Fig. 2(b) is adopted for the five displacement controlled monotonic tests (neglecting the penetration phase - Simulation-N).

During the first phase of Simulation-Y, the first 300mm of the bucket suction foundation penetration into the soil are numerically reproduced. The suction bucket is forced into the soil at a constant velocity of 30mm/s. Fig. 4 shows the normalized vertical displacement vs. vertical force and Fig. 5 the vertical stresses at 300mm of penetration. It shows that The comparison of the experimental and the numerical results clearly show the ability of the combined Lagrangian - SPH model to capture extremely large deformations.

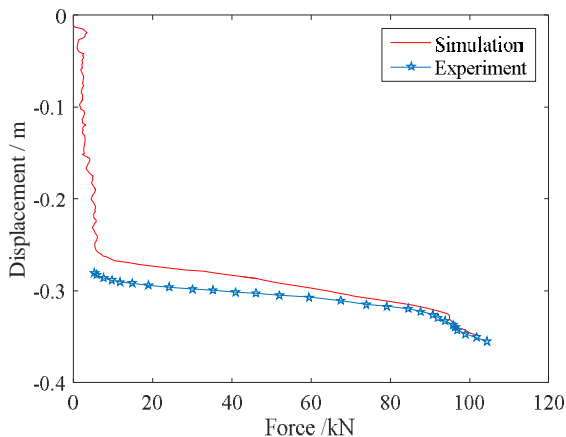


Fig. 4. Penetration phase. Experiment vs. numerical results (combined Lagrangian - SPH model, Simulation-Y).

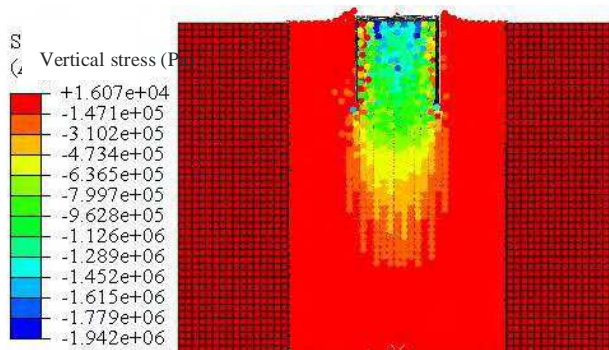
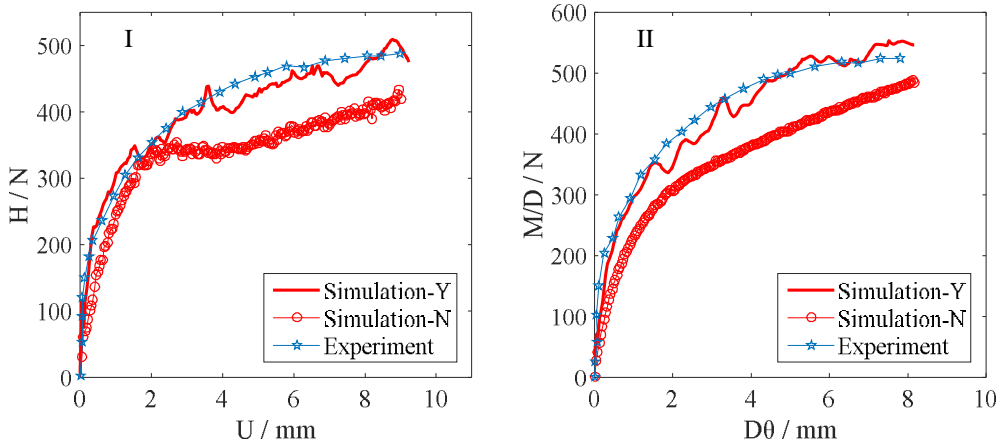
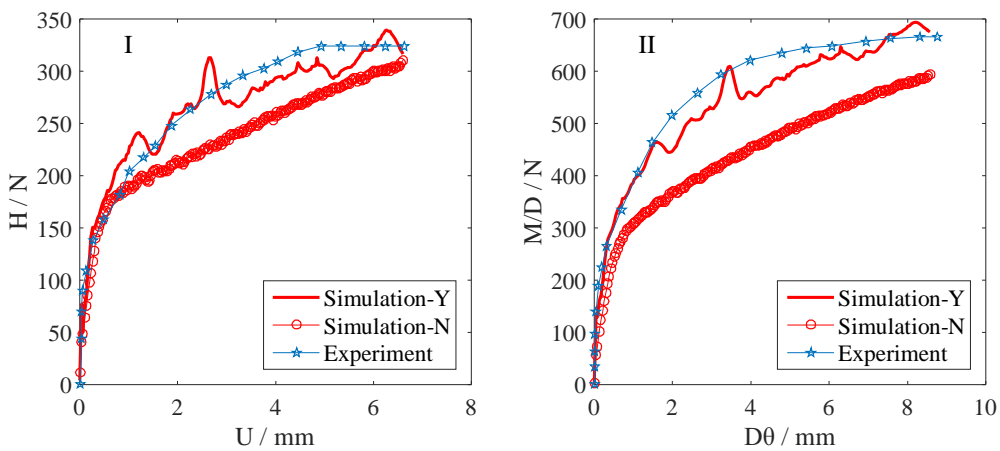


Fig. 5. Penetration phase. Numerical predicted vertical stresses at 300mm of penetration (combined Lagrangian - SPH model, Simulation-Y).

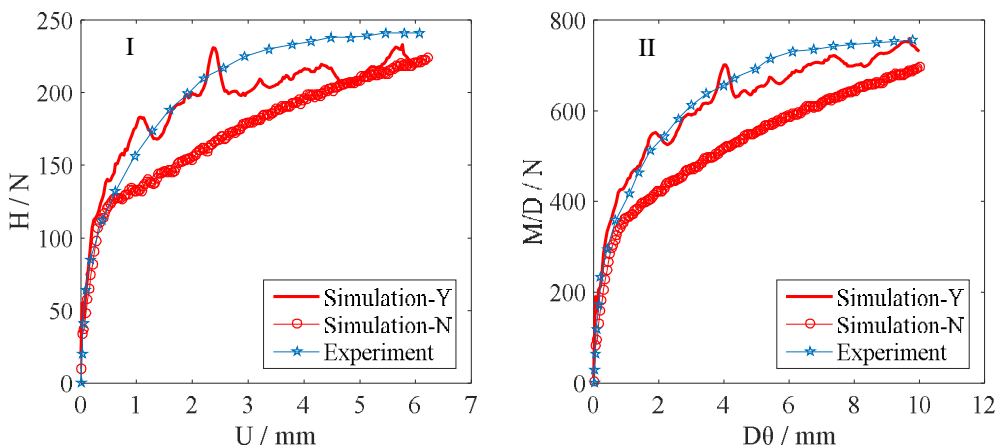
Fig. 6 presents the results of Simulation-Y and Simulation-N (for five typical M/DH values (1.100, 1.987, 3.010, 5.820 and 8.748)). For all five cases, the horizontal displacement (U) vs. the horizontal load (H) curves and the rotational displacement ($D\theta$) vs. the dimensionally homogeneous moment (M/D) curves are provided respectively in sections I (left) and II (right) of the figure. Numerical results are compared with the experimental ones.



(a) $M/DH=1.100$



(b) $M/DH=1.987$



(c) $M/DH=3.010$

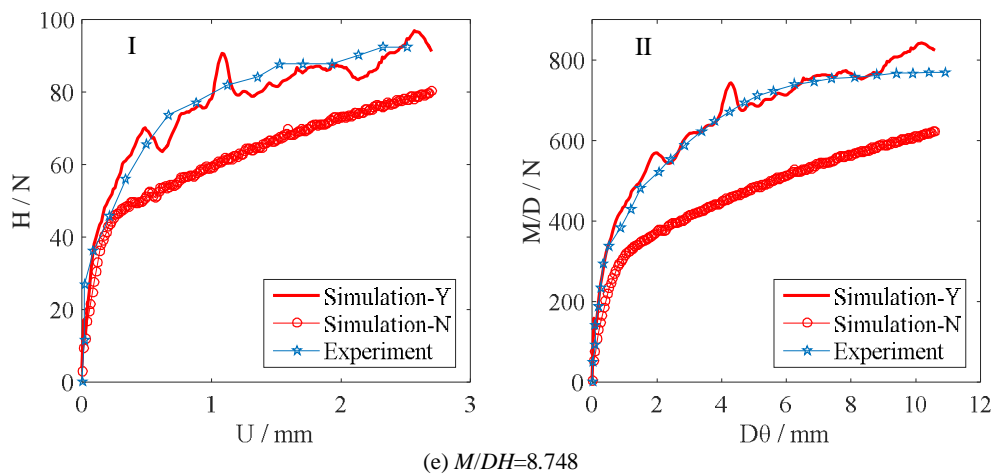
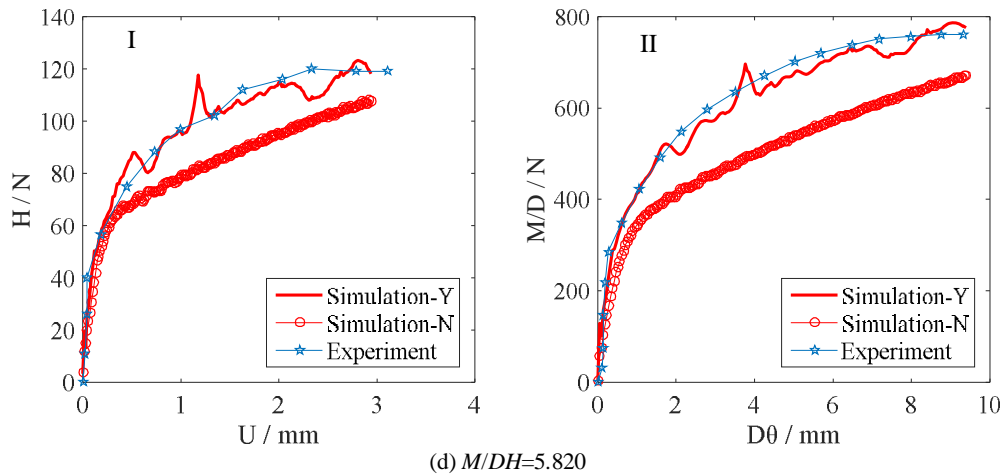


Fig. 6. Monotonic multidirectional loading paths: experimental vs. numerical results.

4. Conclusions

The combined Lagrangian–SPH model is proven able to reproduce the penetration of a suction bucket foundation in sand and its behavior under complex multidirectional loading paths. Results deteriorate significantly if the penetration phase is ignored; the numerical calculated yield point occurs earlier and the horizontal and moment capacities are underestimated.

Acknowledgements

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