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NUMERICAL INVESTIGATON OF THE INSTALLATION OF SUCTION CAISSON IN SAND USING MATERIAL POINT METHOD

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Abstract. *Suction caisson has gained interest in recent years as an alternative foundation for offshore wind turbines due to its cost-effectiveness and easy installation compared to conventional foundations such as monopile. After initial penetration due to its self-weight, suction is applied until the caisson reaches the desired depth. Applying suction provides additional driving force due to the pressure difference between inside and outside the caisson and induces seepage that degrades friction and tip resistance, which further facilitates the installation. The seepage plays a vital role in installing suction caisson in sand; however, it might change the soil state which affects the ultimate bearing capacity of the caisson. Several research works have been conducted to study the suction caisson installation in sand. However, the complexities of the problem including large deformation, solid-fluid and soil-structure interaction, inhibited these studies from fully understanding the installation mechanism. This paper proposes a large deformation modeling framework by using the material point method (MPM). MPM is a hybrid Lagrangian-Eulerian particle-based method that uses material points over a fixed computational mesh where governing equations are solved. During the convection of the particles, the background mesh is kept fixed, making it suitable for large deformation problems. The model considers soil-structure interaction by adopting a Coulomb contact algorithm between the caisson and surrounding soil. In this paper, the stability of the contact algorithm is ensured by correcting material point velocities in the vicinity of the caisson interface using a limiting velocity based on the element size and time step. The framework is validated by comparing a simulation of caisson installation under constant velocity with results published in the literature. Our proposed framework's results agree with previous published results, demonstrating that the simplified stabilization procedure does not affect the simulation results. This is a promising result that will enable the incorporation of fully coupled analysis to better understand the effects of induced seepage on the installation mechanism of suction caissons.*

Keywords: Offshore, Suction Caisson, Sand, MPM, Soil-Structure Interaction

1 INTRODUCTION

Suction caisson is an open-ended cylindrical steel structure equipped with a lid. It has recently been considered an alternative foundation for offshore wind turbines due to its easy installation and cost-effectiveness. It can reduce the cost of material and installation by up to 20% compared with conventional foundations like monopile [1]. The installation process consists of two phases: self-weight penetration and suction-assisted penetration. In the first phase, the caisson penetrates the soil due to its self-weight, then when no further penetration is noticed, suction is applied on top of the caisson until it reaches the desired depth. The suction process creates pressure difference between the inside and outside of the caisson, providing additional driving force. Additionally, it creates seepage that degrades the tip resistance and wall friction, further facilitating the installation in sand.

Many numerical studies have been conducted to study the installation of suction caisson in sand; however, the complexity of the problem including large deformation, soil-structure, and solid-fluid interaction inhibited these studies from fully understanding the installation mechanism. The penetration resistance and required suction was studied by [2] using finite difference model. MPM model was developed by [3] to study the soil deformation mechanism during self-weight and suction-assisted penetration of suction caisson in sand. Finite element model was used by [4] to investigate the installation feasibility considering water depth and pumping rate as main parameters to control in order to ensure a safe installation against piping. Arbitrary Lagrangian-Eulerian (ALE) large deformation solid-fluid coupled finite element method was used by [5] to examine the change of seepage field during the installation.

This study uses the material point method (MPM) to study the installation of a suction caisson as an offshore wind turbine foundation in sand. This paper abords numerical instabilities encountered and proposes a simplified correction to stabilize the contact algorithm. To validate the proposed framework, a model where the caisson is pushed into the ground under constant velocity (jack installation) was developed. The soil is modelled as saturated drained behaviour, and the results are compared with those reported in [6].

2 THE MATERIAL POINT METHOD (MPM)

The material point method (MPM) [7,8] is an extension from the particle-in-cell (PIC) method [9] largely used in soil-water-structure interaction problems such as [10,11,12]. MPM is ideal for suction installation simulation because it can handle large deformation simulations without problems associated with mesh entangling, and it also handles accurate tracking of state variables. MPM also allows the simulation of soil-structure interaction problems using contact algorithm that allows relative displacement between soils and structures [13].

The media in the MPM is discretized in two different frames: first, a set of material points (MPs) represents the continuum body and carries all the updated kinetic, kinematic, and history-dependent state information. Second, the problem domain is covered with a fixed computational mesh where the governing equations are solved [14].

The computation cycle of MPM can be seen in figure 2. Data such as position, mass, velocity are projected from MPs to the nodes of the computational mesh by mapping function at every time step. After solving the governing equations at the nodes, all the updated data are mapping back to the MPs. Finally, the MPs data are updated, and the mesh is redefined to its original shape [15].

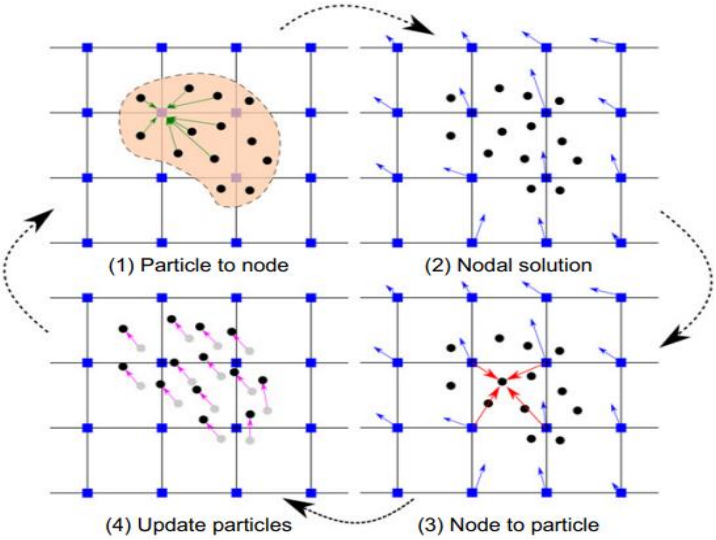


Figure 1: MPM Computational Cycle [15].

3 ENCOUNTERED INSTABILITIES

3.1 Contact instability

The main issue that has been encountered trying to develop the model is the flying of one soil MP which caused an installation instability and the simulation stopped. It is always one of the MPs in the adjacent elements that share contact nodes with the rigid body (the caisson). The source of the error is the poor registration of mass on the contact nodes which produce a very large (unrealistic) velocity. The issue was not solved despite using different mesh sizes, number of MPs/element, geometry, materials, etc. until some justification to the code was made. The proposed intuitive solution is the following:

1. For each element in the caisson (the rigid body), search for adjacent elements in the deformable material (the soil).
2. Search for MPs inside these adjacent elements.
3. Determine if these MPs have a very large velocity (Vmp > $k\frac{\mathrm{Hel}}{\Delta \mathrm{t}}$)

Where: Vmp: MP velocity, k: empirical factor ranging between (0.7-0.8), Hel: the minimum length of the triangular element, Δt: single time step.

4. If the condition in 3 is correct, then the MP is unstable.
5. Correct the velocity of unstable MP to be (Vmp = $k\frac{\mathrm{Hel}}{\Delta \mathrm{t}}$)

The solution was inspired by [13] with the difference that the correction in here is applied during the convictive phase not the contact. The idea is to make sure that the velocity of a single MP in the adjacent elements is not large enough to make the MP leave the element in a single time step. This can help to avoid the empty elements as well.

3.2 Interpenetration

The other issue that caused numerical instability is the interpenetration of the soil MPs into the rigid body. The issue here is when the soil MPs intepenetrate with a high stress to a zero stress field in the rigid body and then leave the rigid body to the high strees field of the soil again, an explosion happened affecting the calculation of the reaction forcess of the caisson tip and walls. The solution to prevent the interpenetration is using a triangular tip insted of regular tip with changing the normal direction of the nodes as can be seen in figure 5.

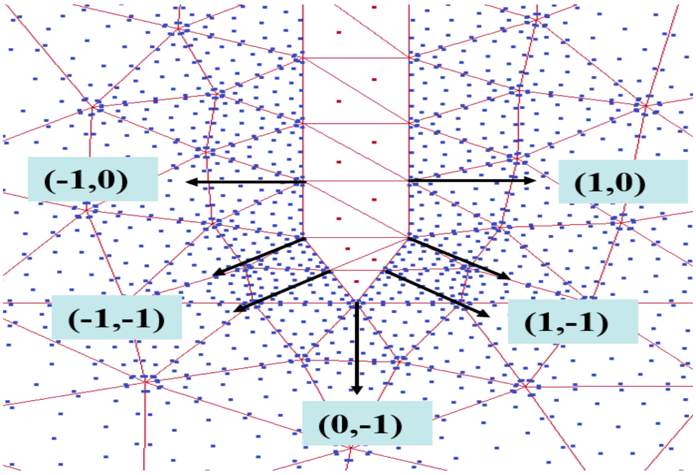


Figure 2: triangular tip and normal direction of the nodes.

3 THE NUMERICAL MODEL

The model geometry in figure 3 and soil properties in table 1 were taken from a model developed by [6]. The model was developed as a 2D axisymmetric to take advantage of the axisymmetric nature of the problem and to reduce its computational cost. The soil is sand in saturated drained condition and modelled as elastic-plastic material using Mohr-Coulomb constitutive model. The sand has the following properties:

Table 1: Soil properties

Parameter	Unit	Value
Initial porosity	-	0.4
Density solid	Kg/m3	2500
Density liquid	Kg/m3	1000
Young modulus	KPa	5000
Soil friction angle	degree	30
Contact friction angle	degree	20

Finer mesh and more material points (46 MPs/element) were used in the penetration path, and the caisson (6m diameter, 7m length) was modeled as a rigid body with one MP/element. The use of the rigid body can significantly reduce the critical time step in comparison with a high-stiffness steel model while maintaining a reasonable representation of the material. Additionally, it will reduce the computational cost because the stress is not calculated for the rigid body [12]. The caisson was pre-embedded in the soil (0.5m) and pushed into the ground (jack installation) by assigning a prescribed velocity (0.1m/s).

The frictional contact algorithm proposed by [13] is used to consider the soil-structure interaction for this problem. The contact algorithm allows sliding, rolling and separation between bodies by automatically detecting the contact nodes [16], and it is already implemented in the MPM.

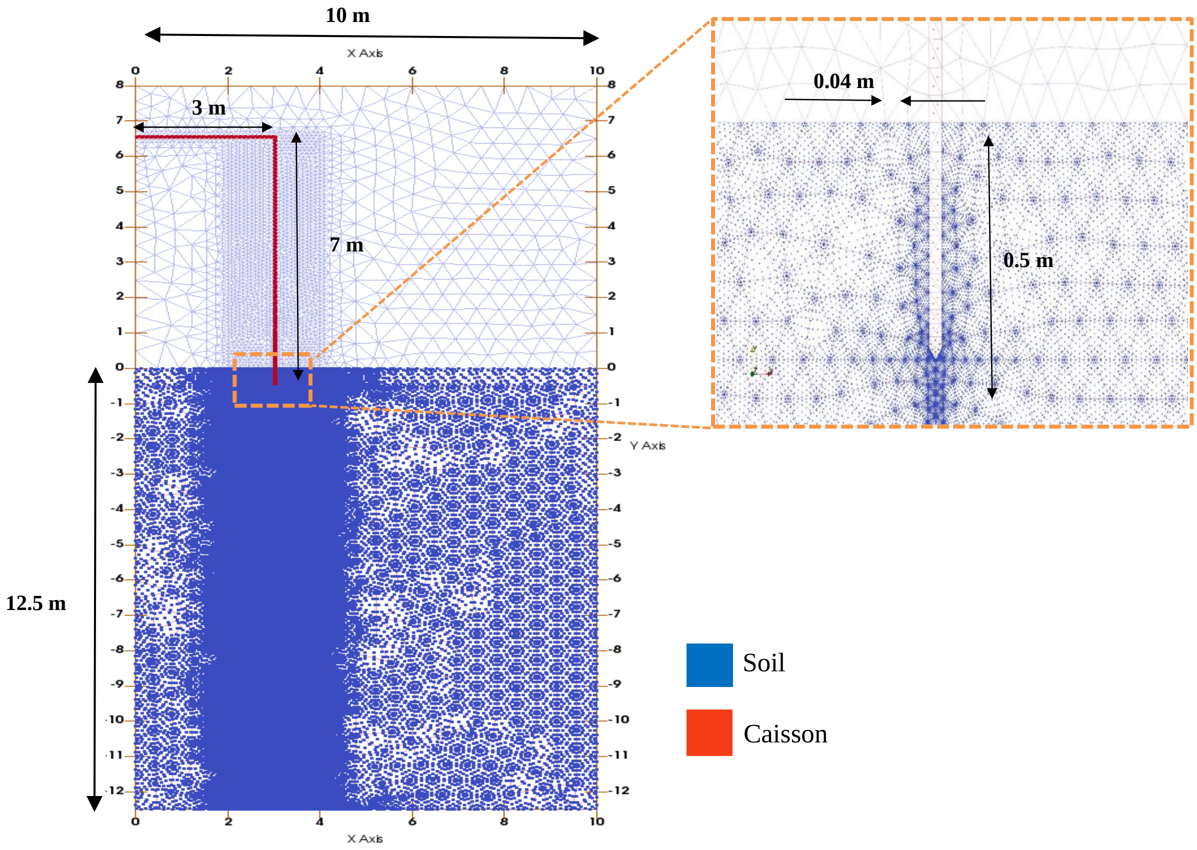


Figure3: Model geometry

The moving mesh technique is applied in this model. It moves according to the movement of a reference material which is the rigid body (the caisson) in this model. The moving mesh is recommended in soil penetrating problems because it preserves the penetrating body geometry throughout the simulation and keeps a well-defined contact surface which allows a smooth use of the contact algorithm and more precise calculation of the reaction forces [12].

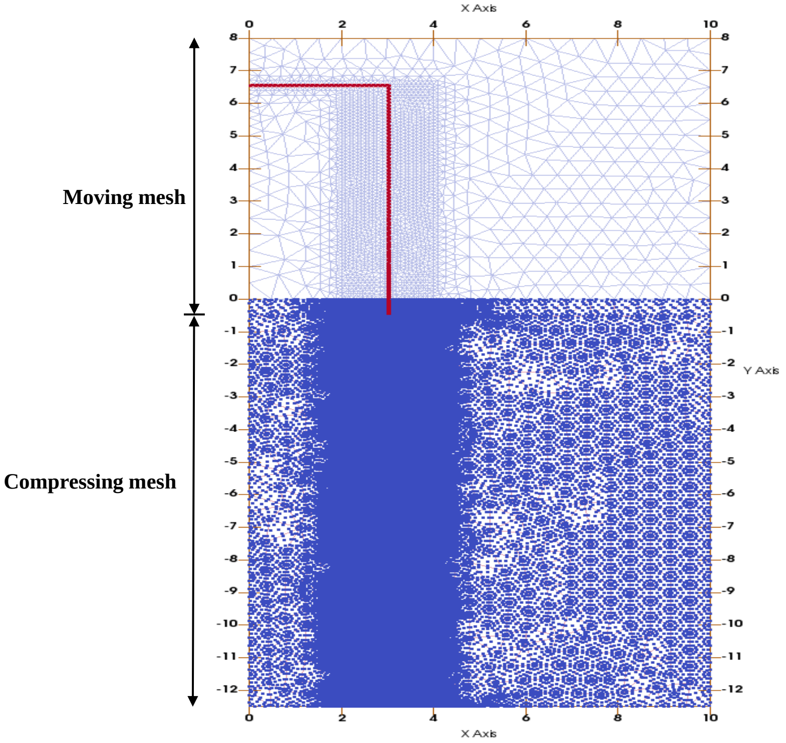
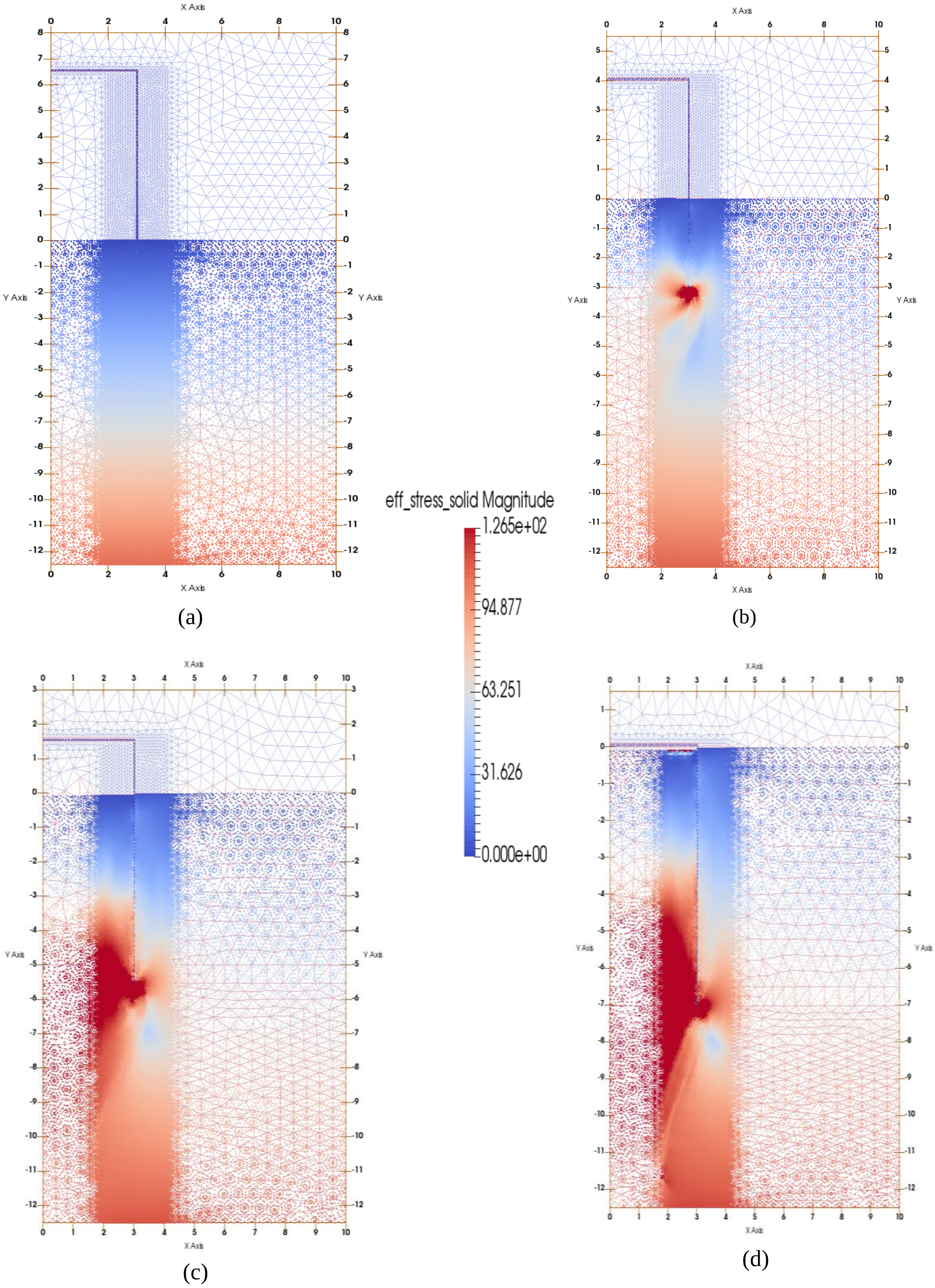


Figure 4: moving and compressing mesh

6 MODEL RESULTS

After applying the proposed solutions, the contact instability and interpenetration was eliminated. A full installation model can be seen in figure 6. The effective stress is increasing under the tip and this increase is extended to the soil inside the caisson with the increase in the penetration depth. Figure 7 shows a good agreement between the developed saturated drained model with the previous published result [6], demonstrating that the simplified stabilization procedure does not affect the simulation results.



(a) (b) (c) (d)

Figure 6: Effective stress in (KPa) with different penetration depth: (a) First time step, (b) 2.5m penetration, (c) 5m penetration, (d) Full penetration 6.5m

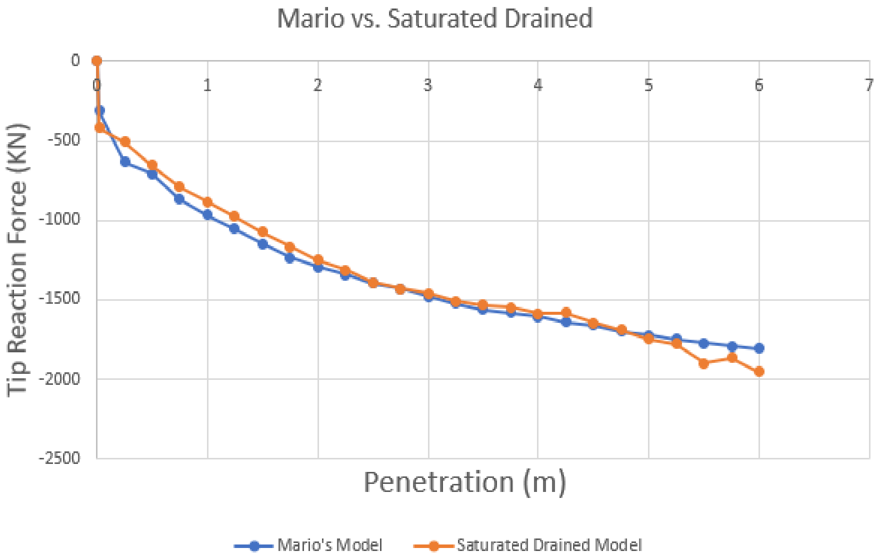


Figure 7: Comparison between tip reaction force

8 CONCLUSION

Simulation instabilities caused by the contact algorithm and the interpenetration of soil MPs inside the rigid body were encountered. A simplified stabilization procedure is proposed in this paper to overcome the contact instability by controlling the velocity of the MPs in the adjacent elements that share contact nodes with the rigid body. Moreover, the change of the tip shape and nodes normal direction eliminate the interpenetration of the soil MPs. A good agreement between the developed model and previously published data in the literature, suggesting that the proposed solution has no effect on the simulation results. This is a promising result that will enable the incorporation of fully coupled analysis to better understand the effects of induced seepage on the installation mechanism of suction caissons.

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