Parametric Study of Pile Installation Using a Numerical Approach with Material Point Method

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Abstract. In engineering, problems involving rigid structures penetrating the ground are common. This work aims to conduct a parametric study of pile installation by impact driving using a prototype numerical model to analyze the behavior of these structures when penetrating the soil. Through Anura3D, an open-source simulator based on the Material Point Method (MPM), it was possible to model the soil using the Mohr-Coulomb criterion and treat the pile as a rigid body. The parametric study included the analysis of different impact velocities and varying levels of soil cohesion and adhesion. The results indicated that higher velocities result in greater penetration depth due to the higher energy transferred. The importance of soil cohesion becomes evident even during the self-weight phase, where it is observed that lower cohesion is associated with greater pile penetration depth. The insights obtained are valuable for optimizing engineering projects, such as driving conductor casings in oil wells and installing monopiles in wind turbines. A detailed understanding of the factors influencing pile driving allows for the construction of more accurate numerical models, improving the planning and execution of pile driving projects and making them more effective and efficient.

Keywords: Impact driving; MPM; Soil.

Introduction

In the field of engineering, the study of pile driving is fundamental as it provides solutions to more complex problems, such as the installation of conductor casings in oil wells. Problems related to the penetration of rigid structures into the ground are common, and a detailed understanding of this process can be obtained through numerical studies. For example, the literature includes studies on the free-fall penetrometer (FFP) method, which has become popular for characterizing shallow sediments due to its speed, low cost, and versatility [1]. Another example is impact driving, a particularly relevant technique employed in both the penetration of monopiles for wind turbine construction [2] and the installation of conductor casings in oil wells.

The installation of offshore monopiles causes significant soil disturbances, affecting their axial and lateral bearing capacity. However, numerical simulation is challenging due to the non-linear behavior of soils, large deformations around the pile, and large displacements. Traditional methods, such as the Finite Element Method (FEM), have limitations due to severe mesh distortions.

Recent advances with the Material Point Method (MPM) offer an effective alternative, handling large deformations through a cloud of material points moving through a background mesh, avoiding the distortion issues of FEM[1]. This work aims to conduct a parametric study of pile installation by impact driving, using Anura3D[3], an open-source simulator based on MPM. The analysis focuses on the variation of impact velocity and the variation of soil cohesion and adhesion, crucial factors to optimize the installation of piles in oil wells and improve the efficiency of engineering projects.

Methodology

The problem is simulated using the Material Point Method (MPM), an advanced numerical technique that integrates Lagrangian and Eulerian approaches to address large deformations and complex interactions in solids and fluids. In MPM, the problem domain is discretized into material points that carry physical properties such as mass, velocity, and stress, and move through a fixed background mesh. These material points represent the material and interact with the fixed mesh to solve the equations of motion and physical laws. The background mesh is used to compute forces and material behavior, while the material points record deformation and movement, as shown in Fig. 1. This approach enables accurate simulation of material dynamics, overcoming the limitations associated with mesh distortion typical of traditional methods like the Finite Element Method (FEM). MPM is particularly effective for simulating phenomena involving large deformations and topological changes, providing a more accurate representation of complex material behaviors [3].

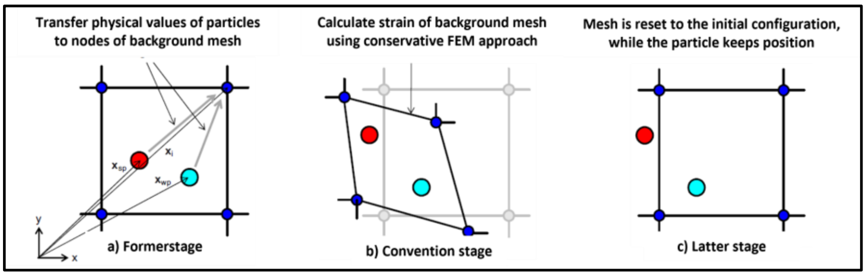

Figure 1 : Schematic figure of typical computational mesh and particles [4]

This will be using an axisymmetric simulation in order to optimize the computational cost, as shown in Fig. 2. The impacting body is treated as a rigid body, while the soil is modeled using the Mohr-Coulomb model. The properties of the materials involved are presented in Tab. 1.

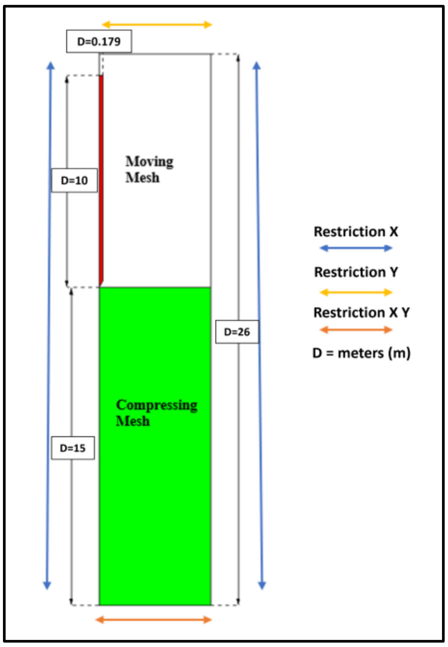

Figure 2 : Geometry of the impact problem

Table 1. Material parameters of the impacting body and the soil [3].

Material	Impacting Body	Soil
Material type	Dry material	Dry material
Initial porosity	0.0	0.5
Density soil[kg/m3]	3500	2650
K0-value	0.5	0.6
Material model solid	Rigid Body	Mohr-Coulomb
Young modulus[KPa]	-	5000
Poisson	-	0.33
Cohesion[KPa]	-	0.5
Friction angle[degrees]	-	40
Dilatancy angle[degrees]	-	0.0
Tensile strength[KPa]	-	0.0

This study analyzes soil behavior in response to variations in impact velocity and soil cohesion. Impact velocities of 3, 4, 5, 6, and 7 m/s will be evaluated [2], while soil cohesion will be analyzed at levels of 0.011, 0.162, and 0.5 [5]. However, we cannot consider only cohesion as a parameter to analyze the soil; we must also analyze adhesion, as they are interdependent properties. We will use the adhesion relation ($A = C/2$)[6].

For this analysis, we use one material point in the rigid body and three material points for the soil. The initial impact velocity is assigned to the material points of the impacting body, with the tip of the impacting body positioned in contact with the soil. Specifically, an initial velocity of 5 m/s is applied to the falling body. In this problem, an unstructured triangular mesh will be used, consisting of 9,103 elements, 15,819 material points and 4,725 nodes. In this model, a gravitational acceleration of 9.81 m/s² is considered [7, 8].

Results

In the graph below (Fig. 3) show that the gain in depth tends to stabilize over time when only self-weight is applied. This occurs due to the resistance of the soil, which increases with greater depth. The data reveal a correlation between the applied impact velocity and the achieved penetration, demonstrating the dynamics of the pile installation process under the specified conditions. After 1 second, hammering started with an impact velocity based on the intervals used for each test, applied at the top of the pile as shown in Fig. 3.

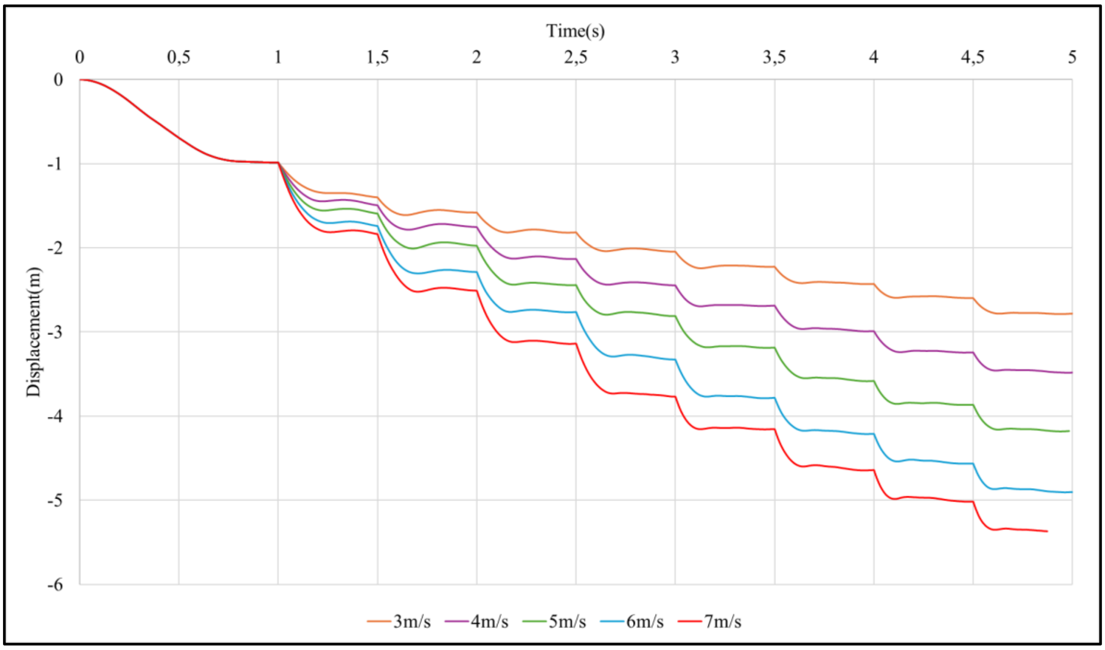

Figure 3: Geometry of the impact problem

As the impact velocity increases, deeper penetration of the pile into the soil is observed. This phenomenon becomes particularly noticeable from a depth of approximately 1 meters. At this depth, more blows are needed for the structure to be driven deeper. For high velocities, such as 6 and 7 m/s, the upper layer of the soil, starting from a depth of 2.5 meters, offers less resistance due to low compaction from its own weight. As the depth increases, the soil density stabilizes due to greater compaction, resulting in less soil deformation.

Lower impact velocities have more difficulty penetrating the soil as depth increases. For example, a velocity of 3 m/s could not reach a depth of 3 meters even after 8 blows, while a velocity of 4 m/s reached this depth after 6 blows. With an increase in impact velocity, the number of blows needed to reach a depth of 3 meters decreases. This behavior also applies to greater depths, such as 4 and 5 meters, where only the highest velocities could drive deeper than 4 meters. Specifically, only the impact velocity of 7 m/s could reach a depth of 5 meters. This behavior indicates that higher impact velocities are more effective for driving piles at greater depths, due to the higher energy transferred to the soil and the subsequent compaction and soil resistance.

Analyzing the scenarios with varying cohesion along with adhesion, it is observed that soil penetration becomes more difficult as cohesion increases. Comparing the data on cohesion and adhesion used earlier, we find a significant difference when using the correlation from [6], as shown in Fig. 4. Note that the curves for cohesion 0.5 original and cohesion 0.5 with adhesion 0.25 behave similarly up to approximately 2.5 meters of depth. Beyond this point, soil compaction increases and cohesion becomes a decisive factor, causing the curves to progressively diverge with increasing depth.

The curves for cohesion 0.011 and 0.162 exhibit similar behavior to the previous curves, diverging only from a depth of 3.5 meters, despite a difference in cohesion of approximately 10 times. The influence of cohesion becomes more pronounced at greater depths, where soil density is high due to increased compaction.

This phenomenon suggests that, although the initial cohesion of the soil does not significantly affect the surface layers, its impact increases considerably in deeper layers due to the increased resistance of the soil to penetration. It is observed that, predominantly, the greater the soil cohesion, the shallower the depth achieved. This trend can be initially identified during the self-weight phase, where, unlike the velocity graph, the curves start to clearly differentiate.

When the impact phase begins, this relationship persists until approximately 4.5 seconds, at which point the curve with cohesion $c = 0.5$ and adhesion $A = 0.25$ starts to reach a greater depth than the curve with cohesion $c = 0.162$. This behavior reflects the complexity of interactions between soil properties and depth.

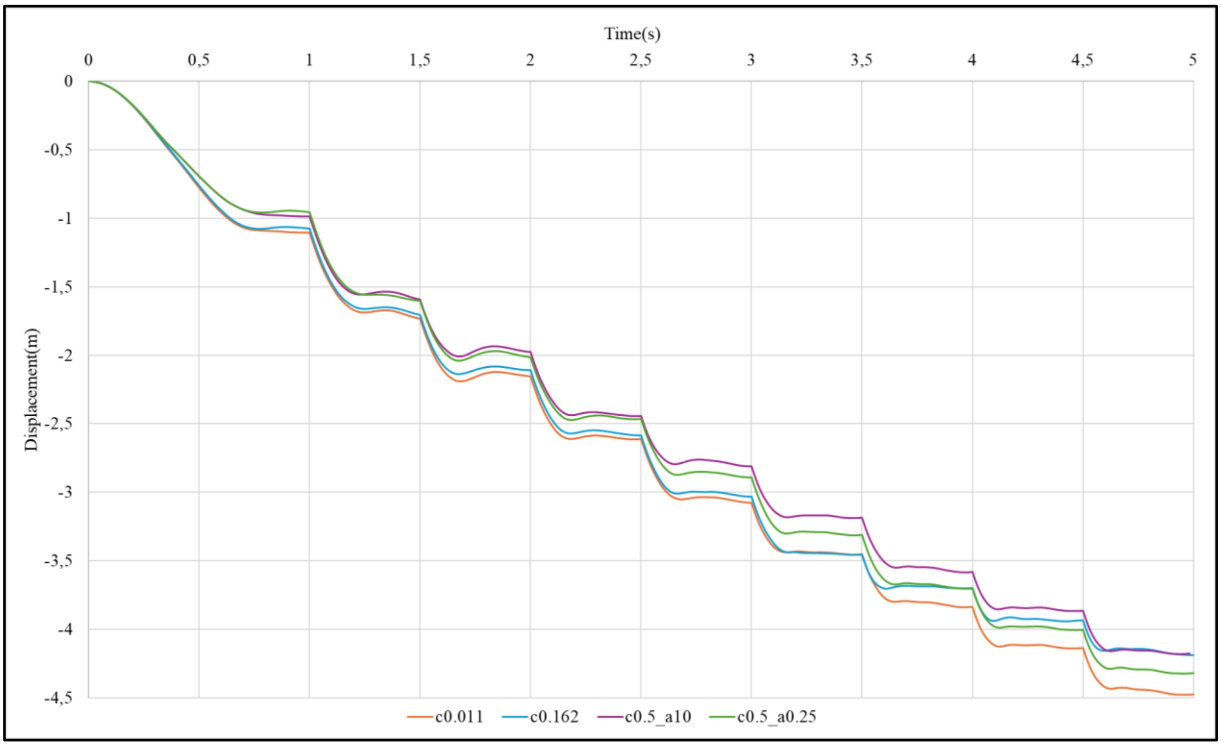

Figure 4: Cohesion variation of impact problem

Conclusions

This study investigated pile installation by impact driving using a numerical model based on the Material Point Method (MPM), with a focus on analyzing the influence of impact velocity and soil properties, such as cohesion and adhesion, on the efficiency of pile driving. The experiments were conducted using the Anura3D simulator, which highlighted the crucial importance of impact velocity on pile penetration.

The data revealed that only the velocity of 7 m/s was able to achieve a depth of 5 meters, demonstrating that high velocities are more effective for driving piles at greater depths due to the higher energy transferred to the soil. This behavior underscores the growing importance of cohesion at greater depths, where soil density increases. The analysis showed that soil cohesion plays a fundamental role in resistance to penetration in deeper layers, indicating that variations in cohesion should be carefully considered in the design and analysis of pile driving.

The relationship between cohesion and depth proved significant, with more cohesive soils showing greater resistance to penetration in deeper layers. These findings offer valuable insights for optimizing driving processes, contributing to the effectiveness and efficiency of engineering projects under various geotechnical conditions. A detailed understanding of these factors allows for the development of more accurate numerical models, which can enhance the planning and execution of pile driving projects.

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References

[1] L. Zambrano-Cruzatty and A. Yerro, "Numerical simulation of a free fall penetrometer deployment using the material point method". International Journal of Geomechanics, vol. 20, no. 5, pp. 1–20, 2020.

[2] V. Galavi, M. Martinelli, A. Elkadi, P. Ghasemi, and R. Thijssen, "Numerical simulation of impact driven offshore monopiles using the material point method". *Proceedings of the XVII ECSMGE-2019*, vol. 1, n. 1, pp. 1–8, 2019.

[3] A. Yerro, A. Rohe, J. Fern, F. Ceccato, and V. Girardi, "Anura3D MPM Software Tutorial Manual," Anura3D MPM Research Community, versão 2023, junho 2023

[4]Abe, K., Soga, K., & Bandara, S. (2014). Material Point Method for Coupled Hydromechanical Problems. *Journal of Geotechnical and Geoenvironmental Engineering*. **Accepted for publication on July 22, 2013**. DOI: 10.1061/(ASCE)GT.1943-5606.0001011.

[5] BRAGA, F. de V. A., "Estimativa dos parâmetros da resistência do solo ao cisalhamento através de pedotransferência". *Tese de Doutorado*, Universidade Federal de Santa Maria, 2014

[6]Sega, Karla Rafaela. "Determinação do Ângulo de Atrito e Adesão entre Solo e Materiais de Construção." Orientador: Pérsio Leister de Almeida Barros. Departamento de Geotecnia e Transporte - DGT - Faculdade de Engenharia Civil, Arquitetura e Urbanismo - FEC - UNICAMP, PIBIC/CNPq.

[7] C Detournay and E Dzik. Nodal mixed discretization for tetrahedral elements. In 4th international FLAC symposium, numerical modeling in geomechanics. Minnesota Itasca Consulting Group, Inc. Paper, number 07-02, 2006.

[8] I.K.J. Al-Kafaji. Formulation of a dynamic material point method (MPM) for geomechanical problems. PhD Thesis, Institut für Geotechnik der Universität Stuttgart, Germany, 2013.