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Investigating Punch-Through Modelling in Monopile Installation to Reduce Risks in Wind Farm Development

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ABSTRACT: The global urgency to address climate change has accelerated the shift to renewable energy sources, with wind energy emerging as a sustainable alternative to fossil fuels. Offshore wind farms, supported by monopile foundations, are essential to meeting carbon reduction targets. However, as monopiles scale up to support larger turbines, they present engineering challenges, particularly in ensuring foundation stability during installation. A critical risk is "punch-through" failure, where soil bearing capacity is compromised at stratigraphic boundaries, potentially causing rapid monopile acceleration and structural damage. This paper first outlines the centrifuge testing campaign conducted as part of the GEOLAB "Punch-Through Modelling in Monopile Installation" (PTM2I) project at the Deltares Geo-Centrifuge, designed to evaluate soil-pile interaction under artificial gravity. Following this, a blind prediction of a selected case was performed using the Material Point Method (MPM), that was used to provide initial estimates of load and pressure responses prior to experimental testing. Comparisons between MPM simulations and centrifuge test data reveal a strong agreement, validating MPM's predictive accuracy. These findings underscore the potential for advanced numerical modelling (e.g., MPM) in advancing safe monopile design and mitigating punch-through risks, enhancing the resilience of offshore wind infrastructure.

Keywords: Punch-Through Failure, MPM, Centrifuge, Offshore-Wind, Pile-Run

1 INTRODUCTION

The increasing urgency to contrast climate change effects has accelerated the global shift toward renewable energy sources, particularly wind energy, which offers a sustainable alternative to fossil fuels. Wind farms play a crucial role in achieving carbon reduction targets, contributing directly to the global efforts to reduce greenhouse gas emissions. Consequently, the construction of wind farms has seen a significant rise, with offshore wind farms at the forefront due to their potential to generate high levels of clean energy with minimal environmental footprint. Central to the construction of these offshore wind farms is the use of monopiles — large, cylindrical steel foundations driven deep into the seabed to support turbine structures. Monopiles remain the predominant foundation type for offshore wind turbines, due in part to their structural simplicity and ability to support large loads.

As the offshore wind industry seeks to increase efficiency and energy production, monopiles have been steadily growing in size and weight to support larger and more powerful turbines. However, these advancements introduce new engineering challenges, particularly regarding the stability and safety of the monopile foundation system during installation and over the lifespan of the structure. Ensuring safe installation of these larger monopiles is essential, as they constitute critical infrastructures in the renewable energy sector, bearing the immense loads exerted by both the wind action on the turbine and other environmental forces due to sea waves and currents.

One of the primary engineering challenges in monopile installation is evaluating the soil resistance to driving of the soil to avoid structural failure during the early phases of pile driving. In layered soils, where a dense upper layer lies atop a softer substrate, the sudden transition in soil stiffness and strength can result in an abrupt loss of bearing capacity as the monopile penetrates through the stratigraphic contact. This phenomenon, known as “punch-through,” poses significant risks, including rapid and uncontrolled pile acceleration, structural damage, and harm to the supporting vessels. Such risks have become particularly relevant as monopile sizes continue to increase, making them more susceptible to bearing capacity issues during installation.

This paper presents some preliminary simulations of one specific small scale physical model test performed within the experimental testing campaign carried out for the GEOLAB “Punch-Through Modelling in Monopile Installation” (PTM2I) project, performed at the Deltares Geo-Centrifuge shown in Figure 1, under artificial gravity. The primary objective of these simulations was to obtain quantitative data on the anticipated loads for the load cells and the pressure levels for both pore pressure and total pressure sensors intended for installation in the physical model. These simulations were conducted well in advance of the actual testing. Therefore, they can be considered as “blind predictions” of the actual outcome of the centrifuge test.

The simulations were performed using the Material Point Method (MPM), modelling the soils as isotropic hardening critical state elastoplastic materials. The comparison between the results of the numerical simulations and the actual test results provides a quantitative assessment of the predictive capabilities of the advanced numerical platform adopted for the simulations and its ability to capture the key critical factors in soil-pile interaction during monopile installation, ultimately enhancing our understanding of pile-run risks and contributing to safer, more resilient designs in offshore wind farm infrastructure.

Figure 1: Geo-Centrifuge at Deltares

2 SUMMARY OF THE EXPERIMENTAL CAMPAIGN

The experimental campaign of the PTM2I project leverages Deltares’ state-of-the-art centrifuge facility in Delft, a high-capacity testing environment capable of replicating real-world conditions in small-scale physical models by applying an artificially increased “gravity” acceleration (15 g in the tests at hand).

The campaign is designed to observe the behaviour of monopile-like structures during installation in layered soils. The centrifuge simulates soil-pile interactions under realistic conditions, allowing researchers to examine monopile response in soil profiles characterized by the presence of a dense sand layer overlaying a soft clay substrate — commonly encountered in offshore wind farm installations. A steel plate is used as a substitute for a monopile cross-section to simplify and control the experiment while accurately reflecting the low curvature of large monopiles. The experimental approach enables a systematic investigation into the effects of parameters such as clay undrained shear strength, penetration rate, and the effect of different loading control methods.

The soils used in the experiments were Baskarp B15 sand and Vingerling K147 clay. The sand is uniform and fine, with its index properties determined by De Lange (2018). The clay is an artificial lean clay produced by Sibelco. These materials have been used in a series of calibration chamber tests, detailed in De Lange (2018), and the tests have been simulated with the MPM by Yost et al. (2023).

The full testing program includes both displacement-control and force-control insertion methods, to assess the differences in pile response under different installation scenarios. Displacement-control experiments are performed by imposing a constant penetration rate to the plate, observing the overall response of the plate-soil system to the imposed penetration speed. Force-control experiments mimic the effect of the monopile penetration under the combined action of an increasing load and the pile self-weight. In this case, the penetration rate varies with time, reflecting the pile-soil response to the applied external and gravitational forces. Test controllability may be lost if, by reaching a weak layer, the pile bearing capacity reduces below the currently applied load level. By performing monotonic and cyclic loading tests, the experimental campaign examines whether the pile-soil responses, and hence pile stability, vary with the loading pattern, giving a holistic view of soil-pile interaction in layered conditions.

To capture detailed data on pile-soil interactions, the centrifuge model is outfitted with a comprehensive array of different sensors. Pore pressure transducers, displacement transducers, and total stress sensors are embedded at key points within the layered soil and along the soil-plate interface. The container's transparent front wall allows for real-time observations of soil displacement, while Particle Image Velocimetry (PIV) and high-speed cameras, with resolutions up to 1920 x 1800 pixels at 2500 frames per second, record detailed movement of soil particles around the plate. This allows high precision tracking of the soil deformation, which is crucial for understanding pile-run initiation.

The experimental setup also incorporates a Cone Penetration Test (CPTu) with a miniature piezocone, performed before the plate installation to obtain quantitative information on the soils shear strength. The pore pressure transducer at the cone tip remains active during the plate insertion, allowing to record the excess pore water pressures induced by the plate penetration. During each CPTu test, the cone tip resistance (qc), sleeve friction (fs), and pore pressure are continuously measured, providing a comprehensive profile of the soil response.

Pore pressure and total pressure sensors mounted on the steel plates simulating a small angular section of the pile allow measurement of the total stresses and pore pressures around the plate tip, offering insights into how changes in soil strength affect pile penetration and stability.

The test layout adopted for most of the centrifuge tests is illustrated in Figure 2, with the dimensions provided in Table 1.

Each test is run in two stages. In the first stage, the model is accelerated with a rate of 10 g per minute, up to the final centrifuge acceleration of 15 g, and then maintained at this spin rate for 2 hours, to let the pore pressures in the soils to equalize up to hydrostatic conditions. In the second stage, the in-flight execution of the CPTu test and the insertion of two different plates are carried out in sequence.

The black full circle on the right of the strongbox in the top view of Figure 2b shows the position of the CPTu test. The smallest distance of this vertical to the lateral rigid walls is 100 mm. At the end of the CPTu penetration, a pore pressure equalization stage with a duration of about 45' (at model scale) is performed before inserting the plates.

Each test is designed to insert two plates, possibly using different insertion methods. The first plate to be installed (Plate 1) is located at the centre of the strongbox, to maximize the distance between the plate and the lateral walls. At the end of the first plate installation, after a resting period of 10', the second plate (Plate 2) is installed at a point located at the same distance from Plate 1 and the left lateral wall of the strongbox. At the end of Plate 2 installation, after a 10' resting period, the centrifuge spinning is gradually slowed down up to the complete stop of the rotation.

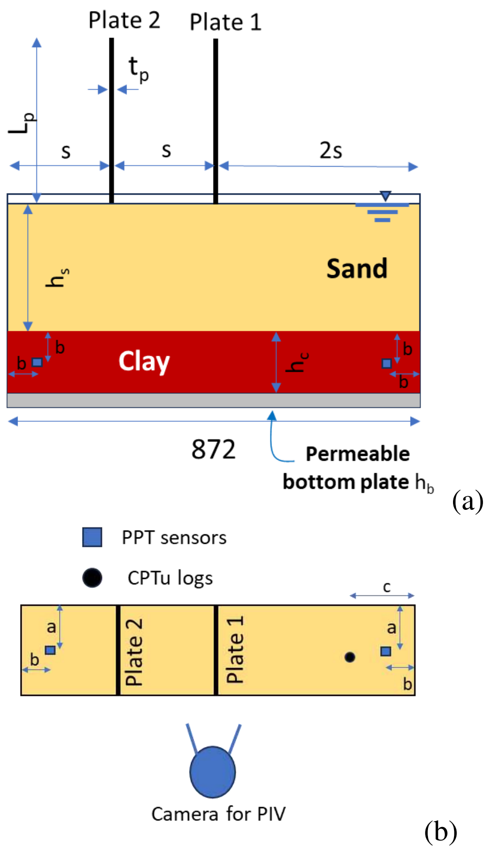

Figure 2: (a) front-view and (b) top-view of the model.

Table 1. Dimensions of the model.

	Model scale [mm]	Prot. Scale [m]		Model scale [mm]	Prot. Scale [m]
t_p	10	0.15	c	145	2.175
L_p	350	5.25	s	218	3.27
b_p	100	1.5	h_s	250	3.75
a	100	1.5	h_c	130	2.0
b	66	1.0	h_b	30	0.45

The PTM2I project includes a large experimental campaign of centrifuge tests, whose details and main results will be presented in a subsequent publication. Here we focus on some of the results obtained in Test 01, performed considering a soft clay layer (preconsolidated at 40 kPa) at the bottom of the soil profile, with the two plates inserted under displacement control at 1 mm/s penetration rate.

3 NUMERICAL SIMULATIONS

The NorSand model (Jefferies and Been, 2015) is adopted to simulate the behavior of the sand layer which, given its high permeability and stiffness, is assumed to deform in drained conditions. A total stress approach with the Tresca constitutive model is adopted for the clay layer in undrained conditions. The penetration rate in the test is chosen to ensure that the response of the clay is fully undrained. Since clay behavior is modeled with a total stress approach, the numerical model is rate-independent. Calibration of these two constitutive models has been performed by Yost et al. (2023). In this paper, the NorSand model has been recalibrated using the same experimental dataset adopted by Yost et al. (2023), reducing the linear elastic stiffness, and adjusting the hardening parameter to match the experimental results from laboratory tests. The set of the NorSand parameters adopted in the MPM simulations is given in Table 2.

Table 2. NorSand parameters of Baskarp B15 Sand

Parameter	Value
$\boldsymbol{e_{cs,0}}$	0.90
λ	0.012
m	0.7
G_{ref}	185
b	0.57
e^*_{min}	0.051
φ_{cs}	30
N	0.1
χ	2.7
ν	0.2
$\boldsymbol{H_0}$	74.5
$\boldsymbol{H_{\psi_i}}$	113.5

The total stress characterization for the clay layer is consistent with the one provided by Yost et al. (2023): the undrained shear strength (s_u) is set to 27.9 kPa, the shear modulus (G) to 552 kPa, and the undrained Poisson's ratio to 0.495.

3.1 Simulation of the CPTu test

The CPTu test is simulated with the spatial discretization shown in Figure 3. Given the presence of the lateral rigid walls on 3 sides of the CPTu vertical, the cone penetration has been simulated assuming axisymmetric conditions, with an external radius of the domain set to 100 mm.

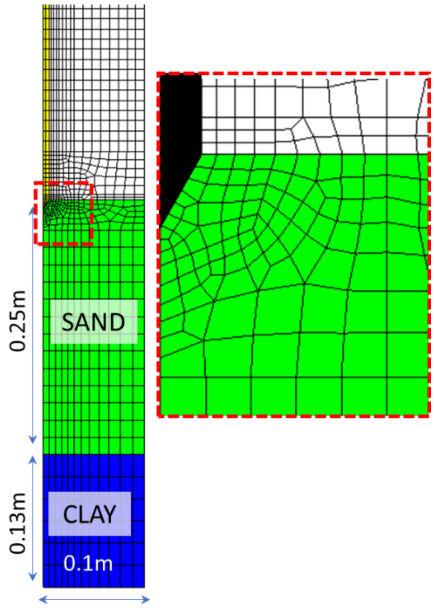

Figure 3: Domain discretization adopted in the MPM simulation of the CPTu test, showing the initial position of the cone tip.

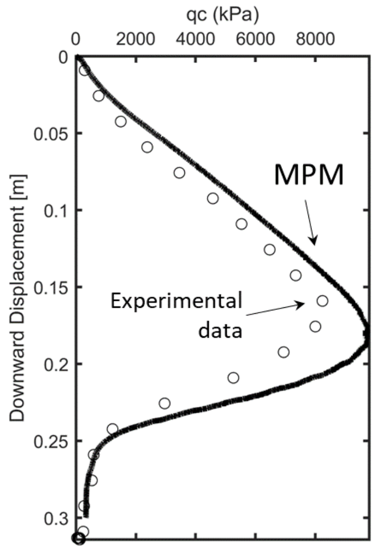

Figure 4: Predicted vs. measured cone tip resistance profile in the CPTu test.

Figure 4 presents a comparison between the cone tip resistance profile predicted by the MPM simulation conducted prior to the test and the experimental results obtained from the miniaturized CPTu test performed in-flight. As expected, while the cone is penetrating the sand layer, q_c increases with depth up to a penetration depth of about 180 mm, i.e, at about 70 mm distance from the stratigraphic contact, where q_c reaches it maximum and then decreases as soon as the cone approaches the soft clay layer. The cone tip resistance corresponding to the undrained strength of the soft clay is achieved at about 300 mm penetration depth. It corresponds to a cone factor $N_c = 10$, which is in line with the values suggested in the literature and validates the s_u value adopted in the simulations.

The cone tip resistance profile measured in centrifuge Test 01 is shown in Figure 4 with open circles. The match with the q_c profile provided by the MPM simulation of the same test is very good, from both the qualitative and quantitative points of view. In particular, the simulation is able to capture the observed peak in q_c, followed by a significant decrease as the stratigraphic contact is approached. The error in the predicted depth of the maximum of q_c is about 13%, while the error in the predicted $q_{c,\max}$ value is approximately 7%.

3.2 Simulation of Plate 1 insertion

The simulation of the first plate penetration test (Plate 1 of Figure 2) is performed with MPM under plane strain conditions, with the initial spatial discretization shown in Figure 5. The mesh exploits the symmetry of the problem with respect to the vertical axis of the plate, so only half of the domain is discretized.

A set of fixed material points is used to impose a fixed displacement boundary condition at the base of the domain. The computational mesh moves along with the plate, while a separate set of material points remains stationary to simulate the effect of a rigid container. This approach has been successfully used by Talmon et al. (2019) to simulate an underwater sand cutting process and by Zwanenburg et al. (2024) to simulate a plate penetration process in clay.

The interaction at the soil-pile interface is critical for accurate punch-through predictions. In this study, frictional contact is assumed for sand, with a contact friction angle of 20 degrees, and adhesive contact is used for clay. The description of the contact formulation is provided in Martinelli and Galavi (2022).

The actual profile of the plunger force with depth actually measured in the centrifuge Test 1 is also shown in Figure 6. As for the simulation of the cone tip resistance profile of the CPTu test, the comparison between the blind MPM prediction and the measurements of F_y is very good, from both the qualitative and quantitative points of view. In particular, the simulation is able to capture the trend in the evolution of the plate resistance with the penetration depth. The predicted depth at which F_y reaches its maximum is captured quite well by the MPM simulation, while the error on the maximum predicted value of F_y is approximately 8%.

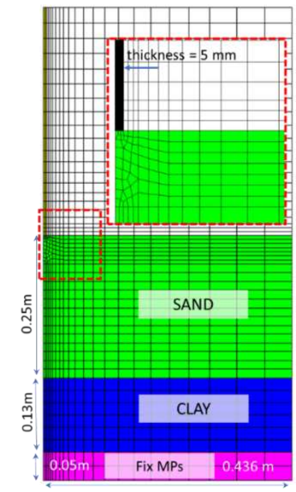

Figure 5: Domain discretization adopted in the MPM simulation of the Plate 1 installation, showing the initial position of the plate tip.

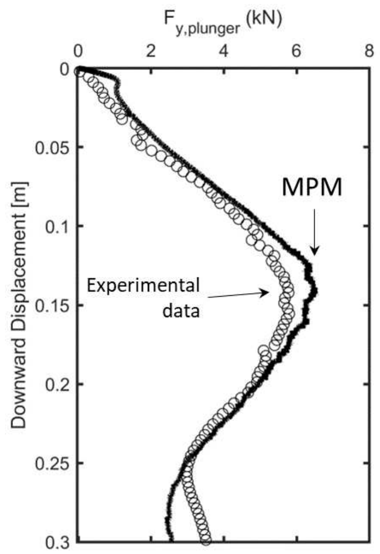

Figure 6: Comparison of plate force during penetration: experimental data versus MPM simulation.

The main difference between the prediction and the observed behavior in the Plate 1 penetration is in a rightward shift of the bottom part of the measured F_y profile with respect to the computed one, which starts to occur when the plate tip reaches the sand/clay interface to stabilize to approximately 1 kN at 300 mm penetration.

The discrepancy between the predictions and experimental observations is most likely due to the flat shape of the plate tip, which causes a significant amount of sand to be dragged along with the plate bottom as it enters the clay layer. This phenomenon was visually confirmed through high-speed camera images taken through the transparent front wall of the strong box.

4 CONCLUDING REMARKS

Some selected experimental results taken from a single centrifuge test – performed as a part of the GEOLAB "Punch-Through Modelling in Monopile Installation" (PTM2I) project – was used to assess the predictive capabilities of the MPM computational platform in reproducing the loss of penetration resistance experienced by large diameter, open-ended driven steel piles. This assessment was conducted by comparing experimental data with MPM predictions generated prior to the experiment, qualifying the simulations as "Class A" (blind) predictions according to Lambe (1973).

The strong agreement between experimental results and numerical predictions—both for the cone tip resistance profile in the CPTu test and for the plunger force—demonstrates the MPM method's ability to capture key aspects of soil-pile interaction during large monopile installations in soil profiles susceptible to pile-run phenomena.

While the MPM tool was successfully applied by Thijssen et al. (2024) to assess punch-through risks in XXL monopile installations, the findings of this study further confirm its robustness. Moreover, the numerical model provides a valuable tool for investigating aspects of soil-pile system response during installation that are challenging to capture experimentally. These insights contribute to a deeper understanding of pile-run mechanics and ultimately support the development of safer, more resilient offshore wind farm infrastructure.

Despite the strong validation results, further research is needed to assess the influence of parameter variability and model sensitivities. Conducting sensitivity analyses will enhance confidence in the model's robustness and provide insight into the uncertainties associated with soil properties, constitutive parameters, and interface behaviors. Due to space limitations, this aspect is not explored in the present study but will be addressed in a forthcoming journal publication.

AUTHOR CONTRIBUTION STATEMENT

Mario Martinelli: Data curation, Formal Analysis, Writing- Original draft. **Claudio Tamagnini**: Data curation, Supervision, Writing- Reviewing and Editing. **Cihan Cengiz, Astha Sharma**: Conceptualization, Methodology, Supervision. **Kateryna Oliynyk:** Data curation, Reviewing and Editing**. Patrick Staubach**: Writing- Reviewing and Editing. **Merita Tafili, Christoph Schallück, Roosmarijn Ceelen, Toby Powell:** Reviewing and Editing.

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