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DEM modelling of small-scale plate and pile penetration through scour protections

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ABSTRACT: The offshore wind industry has grown significantly over the past decade with the increasing demand for clean energy, and over 80% of offshore wind turbines have monopile foundations. The installation of these foundations requires monopiles to penetrate several pre-installed scour protection rock layers before reaching the required penetration depth. With the increasing sizes of both monopiles and the extent of scour protection layers, various challenges arise during the monopile's driving and self-weight penetration process, such as misalignment and early pile refusal. Lab scale testing and empirical modelling are time-consuming and normally not general enough to be applied to different scenarios. Within the Optimising Pile Installation through Scour Protection (OPIS) project, the high fidelity discrete element method (DEM) has been deployed to consider both the discrete nature and shapes of the scour protection rocks. A double-layer (armour & filter) scour protection with a sand layer underneath was simulated using the DEM. Detailed rock dynamics and the armour rocks dragging down during penetration are revealed and particle-geometry rolling friction is identified as the dominant parameter. The effects of the sand layer thickness and pile wall thickness on penetration resistance are also addressed.

Keywords: Scour Protection; Plate Penetration; Monopile Installation; DEM;

1 INTRODUCTION

The stability and longevity of marine and offshore structures rely heavily on effective scour protection, particularly in erosion-prone areas (Gerwick Jr, 2007; Mandviwalla and Christensen, 2021; Mayall et al., 2020). Scour, the removal of sediment by water flow, can compromise structures like bridges, pipelines, and offshore platforms (Cao et al., 2015). Engineers commonly use methods such as riprap placing rocks or concrete blocks around a structure's base to prevent erosion and geotextile mattresses, which reinforce soil and can work alongside other protective measures (James, 2020; Wang et al., 2023). New approaches, including real-time scour monitoring and advanced numerical models, are used to assess the impact of scour protection during offshore wind turbine installations and operations (Z. Zhang and Wang, 2015; Ma and Chen, 2021; S. Zhang et al., 2023)

As wind turbine power increases, monopile foundation diameters are expanding from around 8 metres to over 12 metres, which demands thicker armour layers with higher rock gradings for scour protection. (Barbuntoiu and Thijssen, 2024; Whitehouse et al., 2011). Estimating resistance during monopile penetration through the armour rock layers and managing installation risks becomes more challenging. While field tests and validated empirical models are ideal, they are often too costly and time-consuming. A practical alternative is down-scaled experiments, such as centrifuge tests, which apply centrifugal force to simulate field-scale loads (Nietiedt et al., 2023). However, centrifuge modelling has limitations in scour protection cases, as the simulated field stress inside a centrifuge may result in buckling or tip damages on the down-scaled thin-walled monopiles. A good alternative is to perform numerical simulations to model the monopile penetration behaviour during the penetration process. Due to the discrete nature of armour rocks, the discrete element method shows its advantages in simulating pile rock interactions. To date, there are only a few numerical studies focused on this aspect and all of them are only focusing on modelling penetration in sandy soils using spherical particles (Cerfontaine et al., 2021; Miyai et al., 2019).

Within the OPIS project, a high-fidelity DEM model was developed based on results from laboratory scale tests on plate and pile penetration through a double-layer scour protection system (Cengiz et al., 2024).

This paper summarises the key findings during the DEM model development and presents insights beyond what can be achieved in the experiments. The modelling method is introduced in Section 2 while the simulation setup and simulated cases are introduced in Section 0. Section 4 illustrates the main findings of the developed numerical model. Conclusions are drawn in Section 5.

2 MODELLING METHOD

2.1 Discrete element method

The Discrete Element Method (DEM) is a numerical simulation technique used to model the behaviour of systems made up of discrete particles, such as granular materials. It computes particle interactions - such as forces and motions - by treating each particle as an individual entity/element. DEM is particularly useful for simulating granular flow, packing, and compaction, and is widely used in industries like mining and civil engineering. While highly accurate in modelling complex interactions, DEM can be computationally intensive, especially for large systems.

2.2 Materials

During the monopile penetration process, there are two types of materials involved: scour protection rocks (armour and/or filter) and sand (from the seabed). To model the shape more accurately, multi-spheres are utilised to model the irregularly shaped rocks as shown in Figure 1. The simple sphere is chosen to represent the sand particles as they are typically more round or spherical in shape. Two rock gradings are chosen to be modelled here: armour with d_{50} = 25 mm and filter with d_{50} = 6.5 mm. The original sand particle size of d_{50} = 0.28 mm is coarse-grained (scaled up) to 2.8 mm for computational efficiency. The sand material has a d_{90}/d_{10} of 2.09 while the filter and armour materials have narrower distributions compared with sand and have values of 1.75 and 1.85, respectively.

2.3 Contact models and software

For both spherical particles and multi-spheres, our DEM model employs the Hertz-Mindlin (no-slip) (Di Renzo and Di Maio, 2005; Mindlin, 1949, 1964) contact model with Type C rolling friction (Wensrich and Katterfeld, 2012) that has been widely used for non-cohesive bulk materials. In the Hertz-Mindlin contact model, the normal and tangential springs are non-linear following the Hertzian and Mindlin theories. The contact model input parameters are separated into two categories: the calibrated and verified material parameters and intrinsic material properties. The actual deployed values for all different materials used in this study are summarised in Table 1 and Table 2, respectively.

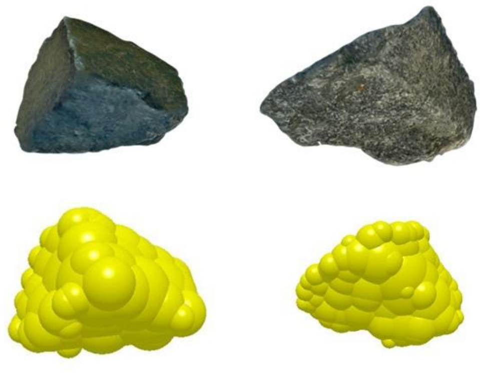

Figure 1. Two different scanned armour rock shapes and their corresponding multispheres representation.

Table 1. Sliding, rolling frictions and restitution coefficients used for different interactions.

Interactions	Parameter	Value
Sand-Sand	$\mu_{s,p-p}$	0.64
	$\mu_{r,p-p}$	0.1
	e_{p-p}	0.75
Sand-Geometry	$\mu_{s,p-g}$	0.5
	$\mu_{r,p-g}$	0.05
	e_{p-g}	0.6
Sand-Filter & Sand-Armour	$\mu_{s,p-p}$	0.64
	$\mu_{r,p-p}$	0.1
	e_{p-p}	0.75
Armour-Armour	$\mu_{s,p-p}$	0.58
	$\mu_{r,p-p}$	0.5
	e_{p-p}	0.5
Armour-Filter	$\mu_{s,p-p}$	0.64
	$\mu_{r,p-p}$	0.1
	e_{p-p}	0.75
Armour-Geometry	$\mu_{s,p-g}$	0.95
	$\mu_{r,p-g}$	0.5
	e_{p-g}	0.5
Filter-Filter	$\mu_{s,p-p}$	0.72
	$\mu_{r,p-p}$	0.5
	e_{p-p}	0.5
Filter-Geometry	$\mu_{s,p-g}$	0.88
	$\mu_{r,p-g}$	0.5
	e_{p-g}	0.5

Table 2. Intrinsic material properties for all the materials used in this study.

DEM Parameter	Unit	Sand	Filter Rock	Armour Rock	Geometry
Density (ρ_s)	[kg/m^3]	2664	2680	2680	7850
Shear modulus (G)	[GPa]	0.1	0.1	0.1	78
Poisson's ratio (υ)	[-]	0.25	0.3	0.3	0.28

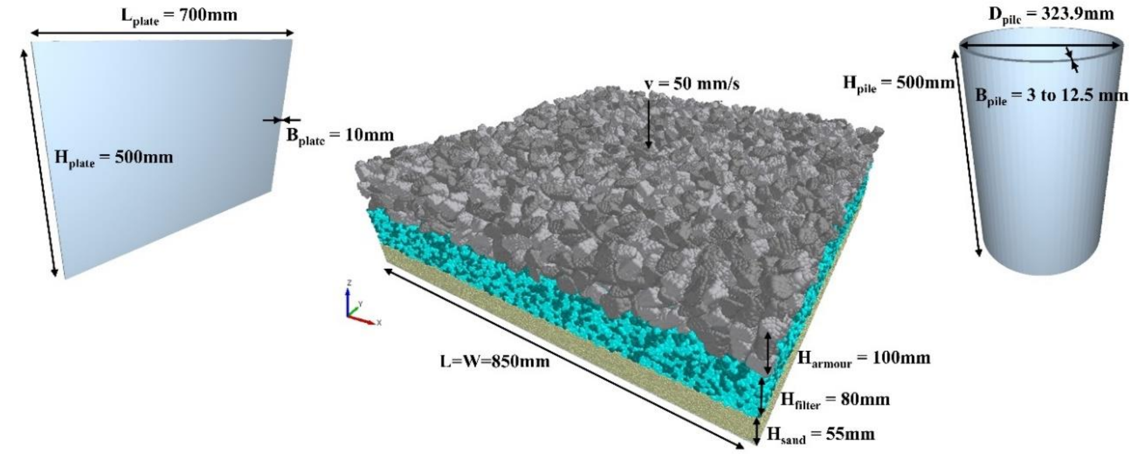

Figure 2 – The simulation setup of the plate and pile penetrations in a double-layer scour protection system. Left to right: plate, a cut of armour-filter-sand material domain and pile.

These material parameters are determined with the help of small-scale penetration experiments (Cengiz et al., 2024) and the procedure for calibration, verification and validation is explained in detail in (Shi et al., 2025). The actual particle size distributions of sand, filter and armour rocks are modelled as user-defined mass distribution (10 discrete bins) during the generation of the materials.

Altair EDEM (version 2022.3) and Altair HyperStudy (version 2022.3) software packages are employed in this work and all the simulations were conducted on a dedicated workstation using an NVIDIA RTX A6000 (48 GB) GPU card.

3 SIMULATION SETUP

The simulation setup involves the penetration of a plate or pile into a double-layer scour protection system, as illustrated in Figure 2. The domain is 850 mm in both length (x-direction) and width (y-direction), with three layers in height (z-direction): a 55 mm sand layer at the bottom, an 80 mm filter layer in the middle, and a 100 mm armour layer on top. Two geometries are used for the penetration process: a steel plate measuring 700 mm x 500 mm x 10 mm and an open-ended steel pile with an outer diameter of 323.9 mm and height of 500 mm. Unlike the plate, the pile has two wall thickness options—3 mm and 12.5 mm. The penetration velocity remains constant at 50 mm/s, stopping at a penetration depth of 200 mm, where the geometry penetrates slightly (approximately one armour rock size) into the bottom sand layer. The process parameters here are chosen to match as closely as possible to the small-scale experiments (Shi et al., 2025).

4 RESULTS

4.1 Drag-down of the armour particles

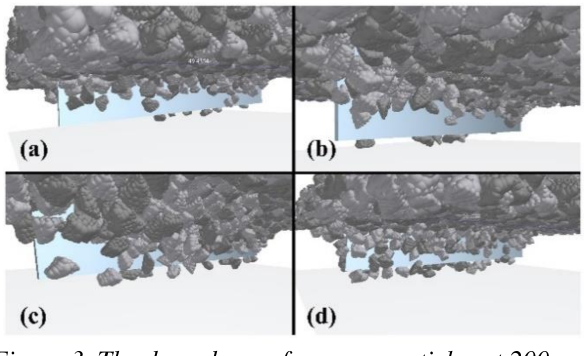

Figure 3. The drag-down of armour particles at 200 mm penetration depth with different particle-geometry rolling frictions: (a) 0.01, (b) 0.1, (c) 0.5 and (d) 1.0.

To investigate the armour particles being dragged/pushed along with the geometry during the plate penetrations, various simulations were performed which cover from very low (0.01) to very high (1.0) particle-geometry rolling frictions and the results are given in Figure 3, where the snapshots at 200mm penetration depth are revealed by removing both sand and filter materials. It is observed that with very low particle-geometry rolling friction (0.01), there are almost no armour rocks pushed/dragged down under the bottom tip of the plate. However, when the particle-geometry rolling frictions are changed to higher values (0.1, 0.5 & 1.0), a substantial amount of armour rocks are dragged down by the bottom tip of the plate to a depth deeper than 200 mm. Note that the rolling friction of 0.5 & 1.0 used here are for the exploration of its effect within the scope of the TypeC contact model for perfect spheres. The actual rolling friction values that represent the armour/filter rocks are expected to be much lower and need to be carefully determined by experiments, which is still a great challenge.

4.2 Effect of sand layer thickness and pile wall thickness

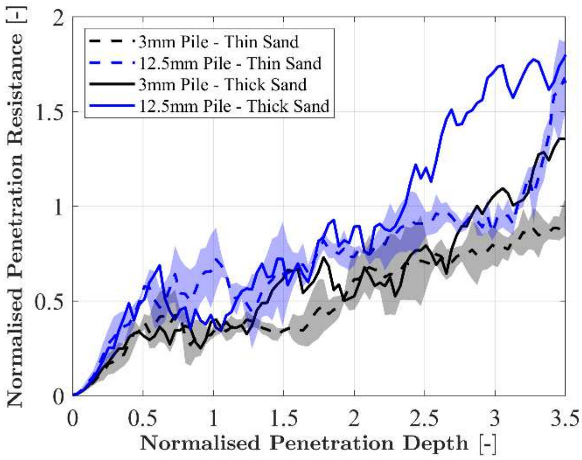

Figure 4. The effect of sand layer thickness and pile wall thickness on the penetration resistance. The shading areas are deviations obtained from simulations with different initial packings.

To further evaluate how the thickness of the sand layer and the wall thickness of the pile influence the penetration behaviour, extra simulations are performed with a thick sand layer (3x thickness of the thin sand layer) using both 3 mm and 12.5 mm pile wall thicknesses and the results are shown in Figure 4. Here, the penetration resistance is normalised by the characteristic resistance measured in the small-scale experiments and the depth is normalised based on the effective disturbed sand height at the maximum penetration depth. For the first 2.5 penetration depth, there is no significant effect of increasing the sand layer thickness, the penetration resistances from the thick sand layer are consistent with those from the thin sand layer. Interestingly, it is observed for piles with both 3 mm and 12.5 mm wall thicknesses, increasing the sand layer thickness results in an increase of penetration resistance after 2.5 penetration depth, which is inside the filter layer. This indicates that the thick sand layer gives a stiffer response than the thin sand layer. Furthermore, increasing the pile wall thickness from 3 mm to 12.5 mm leads to increases in the penetration resistance during the whole penetration process and this increase trend is consistent for both thin and thick sand layers.

5 CONCLUSIONS

This paper presents the important findings during the development of a novel Discrete Element Method simulation model on the small-scale plate and pile penetration through double-layer scour protections. The drag-down effect of armour rocks during the plate penetration process is depicted and the particle-geometry rolling friction is identified as the dominant parameter by associating the drag-down effect with the high penetration resistances. During the pile penetration process, a thicker sand layer under the scour rocks gives higher penetration resistance only at the penetration depth around halfway through the filter layer and a thicker pile wall results in consistently higher penetration resistance. The DEM model enables effective modelling in areas where traditional continuum-based numerical methods offer less accurate predictions, providing valuable insights that are challenging or nearly impossible to achieve through experimental approaches.

AUTHOR CONTRIBUTION STATEMENT

Hao Shi: Writing - review & editing, Writing - original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cihan Cengiz**: Writing - review & editing, Writing - original draft, Validation, Investigation, Data curation. **Giulia Macaro**: Writing - review & editing. **Mario Martinelli**: Writing - review & editing, Supervision. **Jovana Jovanova**: Writing - review & editing, Supervision. **Buket Yenigul**: Writing - review & editing. **Dingena Schott**: Writing - review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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