Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Pile penetration through scour protection: integrating physical, field and numerical approaches into a predictive tool

G. Macaro
Deltares, Delft, The Netherlands, giulia.macaro@deltares.nl

M. Martinelli
SPERI SpA Rome, Italy, formerly Deltares, Delft, The Netherlands, mmartinelli@sperispa.com

C. Cengiz
Deltares, *Delft, The Netherlands, cihan.cengiz@deltares.nl*

H. Shi, J. Jovanova, D. L. Schott
Delft University of Technology, Delft, The Netherlands
h.shi-3@tudelft.nl, j.jovanova@tudelft.nl, d.l.schott@tudelft.nl

E. Alderlieste
Equinor, Fornebu, Norway, eald@equinor.com

T. Van der Linden
Heerema Engineering Solutions, Delft, The Netherlands, tvanderlinden@hes-heerema.com

A. Kherief
Jan De Nul Group, Aalst, Belgium, aimen.kherief@jandenul.com

S. Brinkman, G. Chortis
Van Oord, Gorinchem, The Netherlands, sanne.brinkman@vanoord.com, george.chortis@vanoord.com

ABSTRACT: The installation of monopile foundations through pre-installed scour protection layers presents challenges for offshore wind projects. This paper presents the development of a semi-empirical modelling framework to predict the maximum penetration resistance in such conditions. The work was carried out within a research joint industry project on optimisation of pile installation through scour protection. The model integrates data from physical experiments, field measurements, and numerical simulations. Governing variables such as sand density, intruder thickness, rock size, and the thicknesses of the armour and filter layers were identified and included in the formulation. A weighted regression approach was applied to develop a predictive surface, with separate fits for loose and dense sand conditions. The results show that empirical data, when combined with physical interpretation, field observations, and numerical simulations, can be used to develop a predictive tool with high accuracy. The work contributes to the development of methods for offshore foundation installations and demonstrates the value of integrating physics, field, and numerical approaches into a predictive model.

1 INTRODUCTION

Offshore monopile foundations subject to scour erosion are installed with scour protection systems, typically comprising a coarse armour layer overlying a filter layer above the seabed. Installation through pre-installed filter and armour layers imposes risks associated with pile run or piles becoming stuck in the rock layers. While traditional geotechnical methods can predict penetration resistance in homogeneous sands and clays, they are not directly applicable to coarse, discrete armour layers because of particle-scale effects, layer heterogeneity, and scale-dependent behaviour (Andersen et al., 2008; Miyai et al., 2019; Varela et al., 2022). Consequently, predicting monopile penetration resistance through complex scour protection systems remains a significant challenge in offshore foundation and installation engineering.

Experimental studies have been instrumental in advancing understanding of penetration through granular layers (Houlsby and Byrne, 2005; Andersen et al. 2008; Varela et al. 2022; Nietiedt et al. 2023).

Complementary numerical studies provide additional insight into penetration mechanisms that are difficult to isolate experimentally (Li et al. 2018; Miyai et al., 2019).

Current offshore guidance, including DNV-RP-0618 (DNV, 2022) and DNV-RP-C212 (DNV, 2019) provide general principles for scour protection design and offshore soil behaviour but offers limited guidance for predicting monopile penetration resistance through pre-installed coarse granular layers during installation.

The OPIS research project (Cengiz et al., 2024) directly addresses this gap by integrating experimental, numerical, and field approaches to develop a robust predictive framework. Preliminary results from OPIS (Cengiz et al., 2025; Shi et al, 2025), present findings from the experimental testing and numerical modelling programmes, respectively, and demonstrate the importance of understanding pile–scour protection interactions and identifying the key controlling parameters. The research is conducted by a consortium of 12 partners, including research institutions, offshore developers and operators, contractors, engineering firms and suppliers. The collaborative nature of the project provides access to dedicated testing facilities, field data, and high-fidelity numerical modelling capabilities.

The present study builds on the preliminary findings from the OPIS project to outline a semi-empirical framework for estimating monopile penetration resistance through pre-installed scour protection layers. The framework combines empirical evidences from laboratory experiments and field measurements, with insights from numerical simulations and physical interpretation. Regression analysis is used to identify and quantify the influence of key governing variables, such as pile geometry, rock size, armour and filter thicknesses, and sand density. The objective of this contribution is to present the structure and governing trends of the proposed framework rather than a fully deployable model. Detailed model formulation, its coefficients and applicability domain are intentionally omitted.

This paper is organised with an overview of the database, comprising experimental, field and numerical sources (Section 2); details of the semi-empirical modelling framework (Section 3); presentation of representative predictive behaviour and model performance (Section 4); and discussion and conclusions (Sections 5 and 6).

2 DATABASE

The semi-empirical model uses a combination of data collected through: (i) experimental test campaigns at both small and medium scales, (ii) offshore field measurements and (iii) results from numerical simulation at large scale. Table 1 provides an overview of the database. In the table and throughout this paper, the term 'tests' refers collectively to experimental tests, numerical simulation results, and field measurements; while 'data points' refers to unique test conditions and configurations, as further explained in Section 3.1.

Table 1. Summary of tests and unique test conditions (data points) for each data source and scale.

Source	Scale	Tests	Data points
Experiments	Small	220	74
Experiments	Medium	4	3
DEM	Large	33	22
Field	Large	15	15
All	-	272	114

Each of these three sources has a specific contribution to the overall model development. The experimental test results are used to identify critical parameters governing the penetration of an intruder (i.e. a plate or a pile) into granular media. The study is based on scaled configurations that preserve representative dimensionless ratios, such as pile wall thickness to armour size and relative layer thickness. These tests also provide the inputs for calibrating and validating the numerical model. The numerical simulation predictions provide inputs at larger scales, which are not covered by the experimental programme. The field measurements provide real data to both verify the numerical model and provide real-scale inputs to the semi-empirical predictive model.

2.1 Physical experiments

Experimental results consist of tests carried out at Deltares' Soil and Water Flume facility where an intruder (plate or pile) is being moved vertically into the soil with various levels of complexity (Figure 1). Hereafter, the term 'intruder' is used to refer generically to both plates and piles.

As part of the wider OPIS project, 678 penetration tests were conducted, on both a plate and pile, at small- and medium-scale, under both displacement and force control, varying a wide range of parameters, such as the intruder thickness (t), the armour rock size ($D_{50,A}$), the armour and filter thicknesses (t_A and t_F), and the density of the underlying sand layer (loose and dense). The effects of disturbance, a surcharge, sand accumulation, cyclic loading conditions and bevelled intruder edge were also considered. First, 357 small-scale penetration tests were performed on a 700 mm-thick plate under displacement control to understand the evolution of penetration resistance in granular media. Then, 311 small-scale tests were performed on a 323.9 mm outer diameter pile under both displacement and load control, to increase the realism associated with the tests. Next, 10 tests included medium-scale 1.5 m-diameter pile penetration tests, to assess how the small-scale tests can be related to medium-scale experiment and fit the field data into perspective. Further details of the experimental programme can be found in Cengiz et al. (2025).

A number of 224 tests results is selected over the 678 tests to structure the experimental database in preparation for the semi-empirical model development and refined it according to the following criteria: undisturbed tests with significant scour protection thickness, under displacement-controlled conditions.

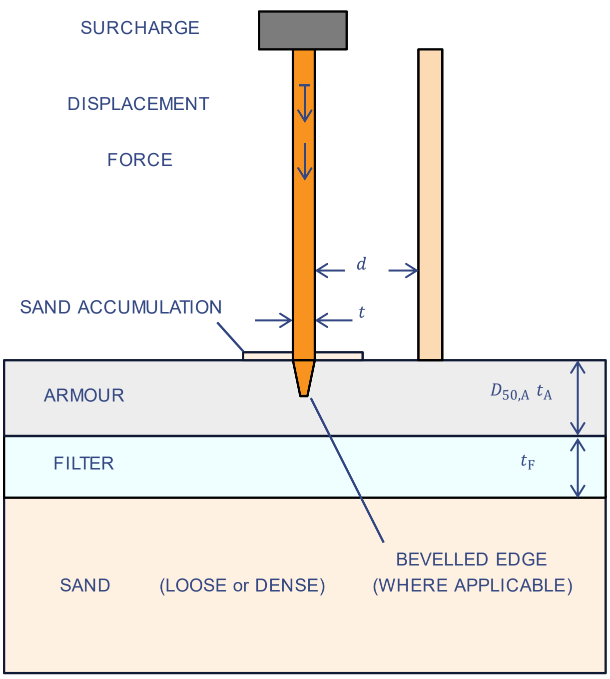


Figure 1. Sketch of experimental tests (not on scale).

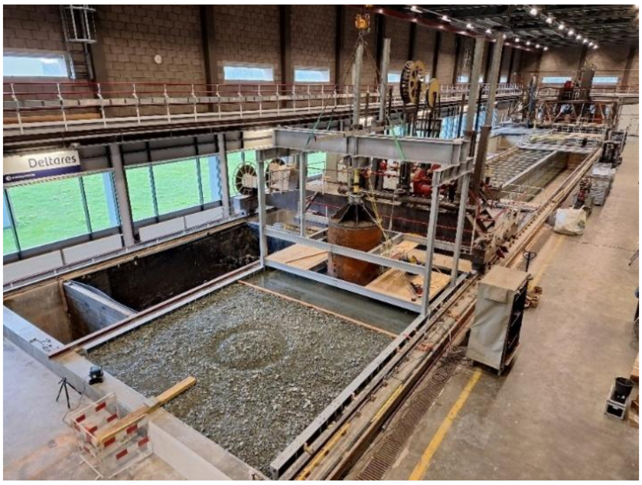


Figure 2. Completed experimental test setup for medium-scale pile penetration tests.

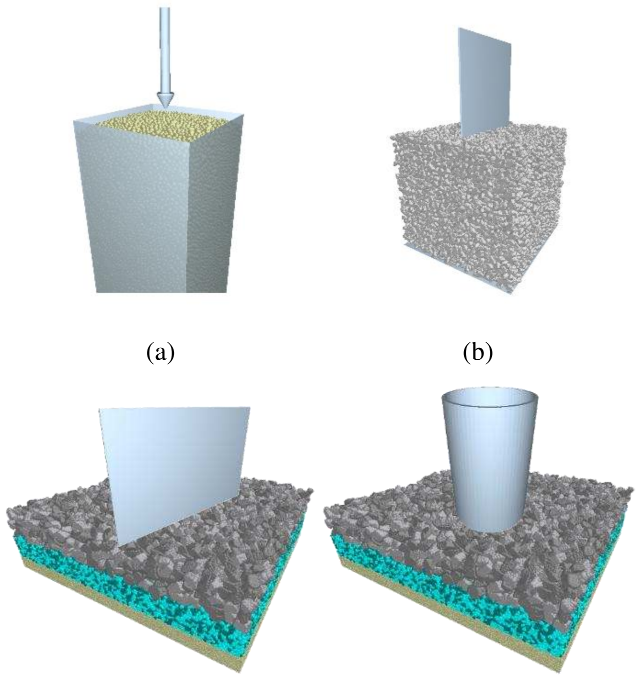
An exception is made for the medium-scale tests, for which only force-controlled conditions are available, hence monotonic force-controlled tests are also included in the final database. Figure 2 provides an overview of a completed medium-scale experimental test, with the pile footprint clearly visible on the rock surface.

2.2 Field measurements

Field measurements were provided by OPIS consortium partners and used for further development (refinement) of the semi-empirical model. This data consisted of 15 measurements during offshore pile installations and covered monopile and scour protection dimensions larger than those used in the medium-scale experimental tests. Therefore they were of valuable use for refining the model to larger scales. To maintain anonymity, only qualitatively results are shown in this paper.

2.3 Numerical simulations

Numerical simulations were performed by means of a discrete element method (DEM) in the commercial software Altair EDEM (version 2022.3). Following an extensive set of numerical analyses dedicated to model development, calibration, verification and validation, a second set of numerical analyses was carried out purely in a predictive mode to contribute to the semi-empirical framework development.



(a) (b)

(c) (d)

Figure 3. DEM simulation setups: (a) penetrometer, (b) plate penetration on rock, (c) plate penetration on scour protection and (d) pile penetration on scour protection.

The development of the DEM model follows the framework described in Shi et al. (2025), which is only summarised here for clarity; the corresponding DEM simulation setups are shown in Figure 3.

Calibration and verification were performed by means of comparison against experimental results described in Section 2.1. Sand behaviour was calibrated using penetrometer simulations (Figure 3a). Plate penetration simulations into rock assemblies (Figure 3b) were used to generate initial packings and identify the sensitivity of the model parameters on distinct packings of armour and filter materials. Calibration of the armour and filter rock materials was made through plate penetration simulations into layered armour and filter rock layers (Figure 3c). Additional verification was carried out by comparing plate penetration simulations with corresponding physical tests.

The DEM model was then validated with pile penetration simulations through scour protection layers (Figure 3d), with numerical predictions compared against both experimental results and field measurements. Validation against experimental data is presented in Figure 4 for one of the test cases, showing good agreement between experimental results and numerical predictions. This step demonstrates that the calibrated DEM model is capable of reproducing observed penetration behaviour across different scales and boundary conditions.

Once calibrated, verified and validated, the DEM model is used in a predictive capacity to generate an additional set of 33 numerical simulations, which are used for the development of the semi-empirical model. The simulated pile geometries span outer diameters from 323.9 mm to 12,000 mm and thicknesses between 9 mm and 120 mm, extending beyond the practical limits of physical laboratory testing.

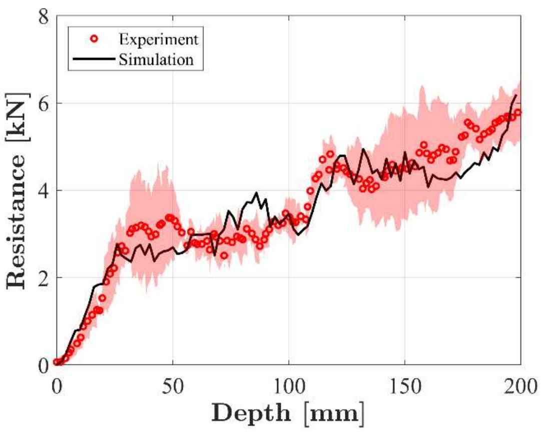


Figure 4. Validation of DEM model against experimental data (Shi et al., 2025). The red shaded area represents the experimental variation; the red dots represent the mean across the experiments.

3 SEMI-EMPIRICAL MODELLING FRAMEWORK

The semi-empirical model is developed to predict the maximum resistance during pile penetration through pre-installed scour protection layers. The approach is termed semi-empirical because it combines empirical data from laboratory experiments and field measurements, with insights from numerical simulations and physical interpretation, to identify the key variables governing penetration behaviour. The model development consists of two main streams of work: (i) the integration and processing of the various data available, and (ii) the weighted regression analysis.

3.1 Data preparation

The results from the 224 selected experimental tests are systematically processed to ensure consistency in data smoothing, extraction, and sampling while reducing the potential for manual errors. The standardised process supports robust comparisons across different test conditions.

The overall dataset of selected 272 tests, combining 224 experiments, 15 field data and 33 numerical simulations, are then further analysed to identify recurring conditions, that are, tests with identical setup and slightly different results. Only unique configurations (with results averaged) are retained for the model development to avoid bias from repeated or overlapping test cases. Such unique configurations are referred to as ‘data points’ in Table 1 and throughout this paper.

3.2 Weighted regression approach

A regression approach is adopted to formulate the model, identifying key governing variables such as sand density, intruder thickness, rock size, and the thicknesses of the armour and filter layers. The entire process, as illustrated below, is implemented in Python, ensuring consistency and reproducibility.

The linear regression approach, using the least squares method (LSM) estimates a regression surface by minimising the squared vertical distances between the predicted surface and the observed data points. The method involves fitting a hyperplane to the data in four-dimensional space. In this context, a hyperplane is a generalisation of a plane to higher dimensions. Here, it represents a regression surface defined by a linear combination of three independent variables:

$$\hat{z} = \hat{a}\,x + \hat{b}\,y + \hat{c}\,w + \hat{d} \qquad (1)$$

with $\hat{z}$ representing the natural logarithm of the expected dependent variable, x, y, and w the natural logarithm of the expected independent variables, and $\hat{a}$, $\hat{b}$ and $\hat{c}$ the estimated regression coefficients, determined by minimising the residual. The analysis incorporates dataset weights to account for the varying number of tests across different configurations, particularly within the experimental programme where repeated tests (up to five times) under identical conditions were performed. Field measurements correspond to unique site and installation conditions and therefore do not involve repeated configuration. Numerical simulations include limited repetitions (up to two cases) associated with sensitivity checks.

The dataset is then divided into training and testing subsets using a 70/30 train/test split, that is, 70% of the data used for training the model and 30% for testing.

The study assesses model performance using, amongst other metrics, residuals, standard deviation of the residuals (σ_{res}) and the coefficient of determination (R^2).

3.3 Model formulation

The model predicts the maximum resistance ($q_{\max}$) during penetration into the scour protection rocks, expressed as it follows:

$$\ln\left(\widehat{\frac{q_{\max}}{p_a}}\right) = f(\text{intruder thickess, rock size, armour, filter}) \quad (2)$$

where f is a linear combination of three independent dimensionless variables and regression coefficients, which differ for scour protection layers placed on loose and dense sand beds, resulting in two separate models.

The three independent variables, expressed in dimensionless form, capture key aspects of (i) intruder thickness to rock size ratio, (ii) armour thickness, and (iii) filter thickness. The maximum pressure within the rock layer ($q_{\max}$) is normalised by the atmospheric pressure (p_a), providing a scale-independent measure of the response.

A standard deviation (σ), accounting for contributions from both the dataset and the regression residuals, is included in the prediction of the penetration resistance to capture model uncertainty.

4 MODEL BEHAVIOUR

Figure 5 presents the model response for the loose and dense sand datasets, illustrating parameter sensitivity and trend consistency. Each subplot shows the relationship between an independent variable (x, y and w) and the penetration resistance ratio ($z \sim q_{\max}$), along with the corresponding best-fit trend. Data points correspond to test results, while the lines represent model predictions.

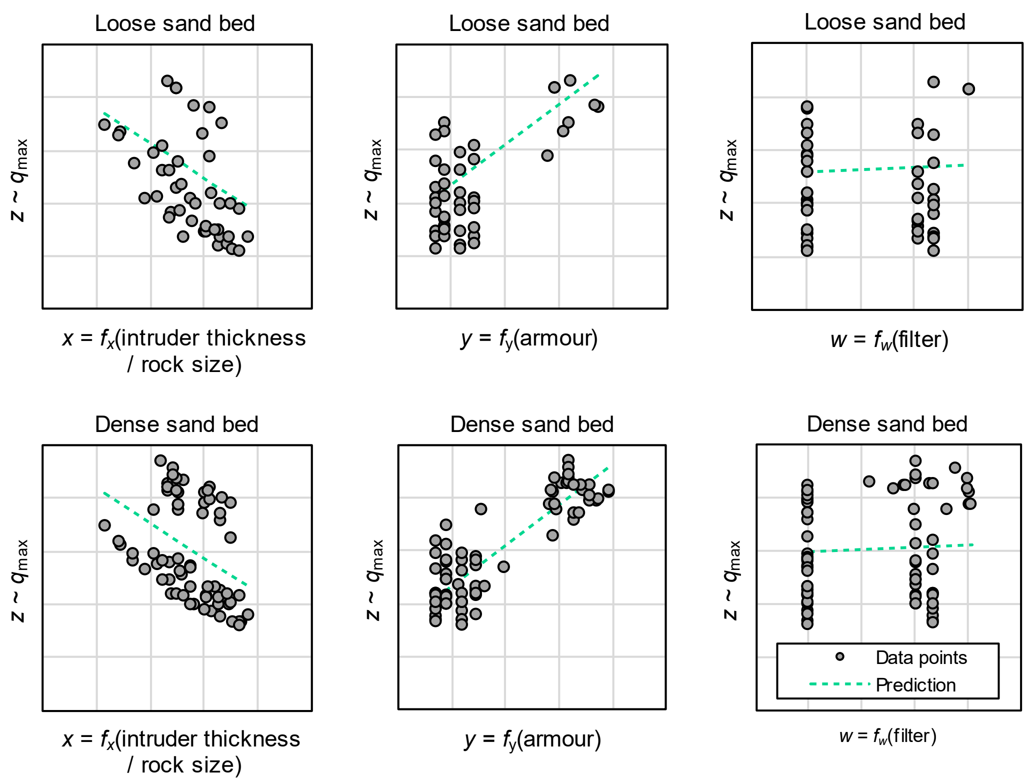


Figure 5. Two-dimensional representation of data points and model predictions for (top) loose and (bottom) dense sand beds (axis values omitted).

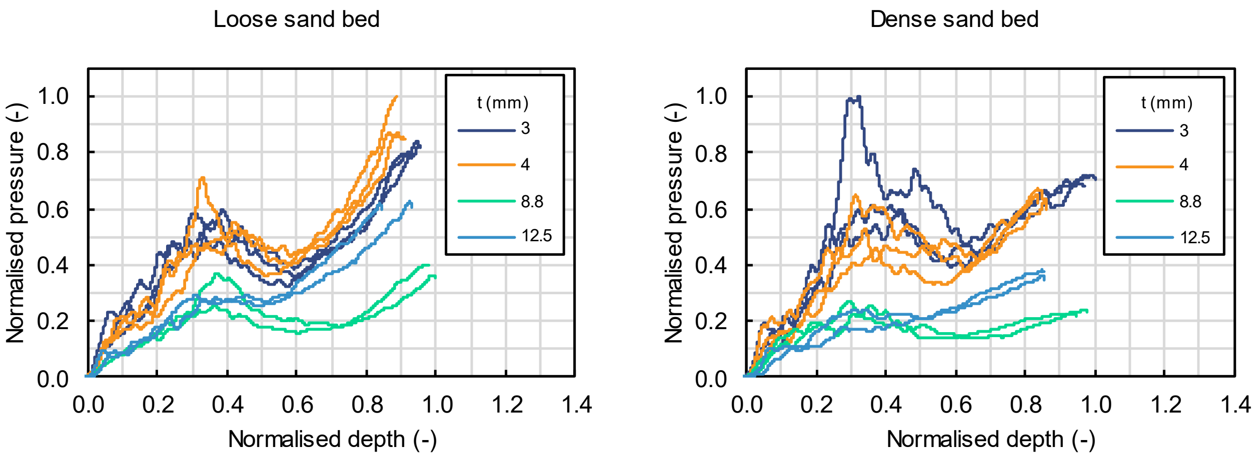


Figure 6. Effect of intruder thickness (t) on experimental pile tests: (left) loose and (right) dense sand. Depth is normalised by maximum depth across the presented test set; pressure is normalised by maximum pressure across the presented test set.

Figure 5 shows that, for both sand conditions, penetration resistance exhibits a negative correlation with intruder thickness to rock size ratio, indicating that resistance decreases as the ratio increases. In contrast, the armour layer parameter exhibits a clear positive correlation with penetration resistance. The filter layer parameter shows a comparatively weak influence, with near-horizontal trends and vertically clustered data points, suggesting limited sensitivity within the investigated range. Scatter around the trends reflects the inherent variability of granular materials and the combined influence of secondary factors not explicitly represented in the two-dimensional projections.

The overall standard deviation, σ, is higher for loose sand bed (0.43) than for the dense sand (0.24), reflecting the increased model uncertainty. Coefficients of determination, $R^2 = 0.84$ and $R^2 = 0.96$ for loose and dense sand, respectively, indicates good to excellent predictive capability, with particular strong agreement for dense sand conditions.

Figure 6 illustrates the influence of intruder thickness on penetration resistance, based on experimental tests with fixed armour size (11 mm) and armour and filter layer thicknesses. For large intruder thickness, resistance curves are smooth and calculated pressures are lower, reflecting stable load transfer over a larger contact area engaging multiple armour particles. This reduces sensitivity to individual grain positions and results in a more uniform response, for which resistance pressure (force divided by the intruder area) provides a reliable measure. In contrast, small intruder thicknesses lead to pronounced pressure fluctuations due to highly localised interactions, where resistance depends strongly on whether individual rock particles happens to lie directly beneath the intruder. The observed reduction in maximum penetration resistance with increasing intruder thickness is consistent with findings from Figure 5.

5 DISCUSSION

The proposed framework provides a practical approach for predicting penetration resistance through scour protection layers on loose and dense sand beds. Given characteristics such as intruder thickness, rock size, and armour and filter thicknesses, the model predicts the expected penetration resistance during monopile installation through pre-installed scour protection systems. Although the precise ranges of these variables are confidential, the study explores representative values covering typical variations encountered in offshore fields, including relative pile wall thickness to armour size, armour layer thickness, filter layer thickness, and sand density. In this way, the framework provides predictions that are directly relevant for engineering assessment and can help reduce installation-related uncertainty.

The experimental programme uses scaled absolute dimensions, but the study focuses on dimensionless ratios that govern pile–scour protection interaction mechanisms, such as pile wall thickness to armour size and relative layer thickness. These ratios are representative of current offshore monopile installations. Numerical simulations complement the experimental work by enabling exploration of configurations closer to field-scale geometries, allowing trends and parameter sensitivities to be interpreted beyond what is directly observable in the laboratory. Together, these approaches provide a robust basis for understanding how different variables interact to influence penetration resistance.

The strength of the proposed framework lies in the integration of physical experiments, field observations, and numerical simulations. Physical testing provides controlled insight into governing mechanisms, field data capture scale effects and site conditions, and numerical modelling enables exploration of parameter interactions not directly observable in experiments. Their combined use is therefore essential for developing physically grounded predictive models for offshore applications.

Future work should focus on expanding the available database, particularly with inclusion of additional field data, thereby improving reliability and extending the applicability range. Additional development could include broader material characteristics, including a wider range of rock gradations, sand densities, presence of a clay below scour protection, and scour protection configurations, particularly to increase variability in filter layer thickness. Such developments would further strengthen the predictive capability of the framework and its relevance to offshore foundation installations.

6 CONCLUSIONS

This paper has presented a semi-empirical framework for predicting penetration resistance of monopiles through pre-installed scour protection layers, developed by combining empirical data, physical interpretation, and numerical modelling. The framework captures the influence of key geometrical and material parameters, and is formulated as a regression surface with coefficients fitted separately for loose and dense sand beds, achieving high predictive accuracy, particularly for dense sand conditions. Penetration resistance is shown to decrease with increasing intruder thickness relative to rock size, with armour layer thickness also exerting a dominant influence on the response.

This study demonstrates the value of integrating physical experiments, field observations, and numerical simulations to develop predictive models that are both scientifically robust and practically relevant. While detailed model formulation and exhaustive validation are beyond the scope of this contribution, the presented framework provides a sound basis for estimating penetration behaviour during monopile foundation installation and supports future development more comprehensive predictive tools for offshore applications.

ACKOWLEDGMENTS

The authors acknowledge the support of the OPIS project, funded by the Rijksdienst voor Ondernemend Nederland (RVO) under grant number HER+22-01-03317702. The financial and technical contributions of the GROW consortium partners are gratefully acknowledged: Deltares, CAPE Holland, DEME, Equinor, HES, HMC, Jan de Nul, Seaway7, TenneT, TU Delft, Van Oord and Vattenfall. The authors also thank the GROW consortium partners for granting permission to publish the results presented in this work.

REFERENCES

Andersen, K. H., Jostad, H. P. and Dyvik, R. (2008). Penetration resistance of offshore skirted foundations and anchors in dense sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 134: 106–116.

Cengiz, C., Macaro, G., Martinelli, M., Peters, T., Elkadi, A. S. K., Shi, H., Jovanova, J., Schott, D., Yenigul, B., Alderlieste, E., van der Linden, T., Karnebeek, T., Gharsallaoui, H., Raymackers, S., de Roo, C., Falke, E. and Wisotzki, E. (2024). Optimising pile installation through scour protection (OPIS) project and preliminary findings. *Proceedings of the 5th European Conference on Physical Modelling in Geotechnics (ECPMG 2024)*. EDP Sciences, Delft, The Netherlands, pp.1–8.

Cengiz, C., Martinelli, M., Macaro, G., Luger, D., Elkadi, A. S. K, Shi, H.,. Jovanova, J., Schott, D., Yenigul, B., Alderlieste, E., van der Linden, T. (2025). 1-g physical tests on monopile penetration through scour protection material. *Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025)*, Nantes, France, International Society for Soil Mechanics and Geotechnical Engineering, pp. 425.

DNV (2019). *DNV-RP-C212: Offshore soil mechanics and geotechnical engineering*. Recommended Practice, First edition (with amendments to 2021). Det Norske Veritas (DNV).

DNV (2022). *DNV-RP-0618: Rock scour protection for monopiles*. Recommended Practice, Edition September 2022. Det Norske Veritas (DNV).

Houlsby, G. T. and Byrne, B. W. (2005). Design procedures for installation of suction caissons in sand. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 158: 135–144.

Li, H., Ong, M. C., Leira, B. J. and Myrhaug, D. (2018). Effects of soil profile variation and scour on structural response of an offshore monopile wind turbine. *Journal of Offshore Mechanics and Arctic Engineering*, 140: 1–10.

Mayall, A., Whitehouse, R. J. S. and Sutherland, J. (2018). Physical modelling of monopile response to scour and scour protection. *Ocean Engineering*, 160: 230–247.

Miyai, S., Kobayakawa, M., Tsuji, T. and Tanaka, T. (2019). Influence of particle size on vertical plate penetration into dense cohesionless granular materials (large-scale DEM simulation using real particle size). *Granular Matter*, 21(4): 105.

Nietiedt, J. A., Randolph, M. F., Gaudin, C. and Doherty, J. P. (2023). Centrifuge model tests investigating initiation and propagation of pile tip damage during driving. *Journal of Geotechnical and Geoenvironmental Engineering*, 149: 04023024.

Shi, H., Cengiz, C., Macaro, G., Martinelli, M., Jovanova, J. and Schott, D. (2025). A validated DEM modelling framework on plate and pile penetrations in a double-layer scour protection. *Ocean Engineering* 319 (2025) 120222.

Varela, E., Miranda, M., Castro, J., Sarmiento, J. and Guanche, R. (2022). Full-scale tests of skirt penetration resistance in gravel for offshore wind structures. *Journal of Geotechnical and Geoenvironmental Engineering*, 148: 04022084.

Whitehouse, R. J. S., Harris, J. M., Sutherland, J. and Rees, J. (2011). The nature of scour development and scour protection at offshore windfarm foundations. *Marine Pollution Bulletin*, 62(1): 73–88.