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Optimising pile installation through scour protection (OPIS) project and preliminary findings

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ABSTRACT: Scour protection is commonly installed around monopile foundations of offshore wind farms to prevent loss of soil support due to scour erosion. The conventional practice involves a three-step scour protection installation process: (i) placing a filter layer composed of smaller rocks, (ii) installing the monopile through the filter layer, and (iii) positioning the armour layer of larger rocks on top. This workflow requires multiple visits of the rock dumping vessel to the site which increases costs, time spent offshore by the vessels, and consequently carbon emissions. A 3-year joint industry project, Optimizing Pile Installation through Scour Protection (OPIS), has been established in 2023 to streamline the pile and scour protection installations, reducing costs and carbon emissions associated with offshore wind developments and, overall, helping to reach the target of energy transition. The project investigates the technical feasibility of pile installation through coarse rock to enhance the feasibility of the operation. This paper provides an overview of the ongoing OPIS research project, describes its experimental approach, and presents preliminary results. The workflow consists of four branches, namely, three laboratory testing campaigns, and a numerical modelling study. The experimental tests include 357 plate penetration tests, and 313 and 8 pile penetration tests at small and medium scale respectively, and consider different scour protection designs, such as single- and double-layer systems, and different rock densities (high and normal density rocks). The numerical analyses describe the mechanisms at the rock particle level. Preliminary results and challenges encountered during the experiments and numerical analyses are discussed, and innovative solutions devised to overcome specific testing needs are highlighted.

1 INTRODUCTION

Offshore wind turbine foundations are often subject to scour erosion processes originated by the fluid–structure interaction, i.e. sea current downflow and vortex shedding along the monopile. The vortex shedding results in a three-dimensional pressure field around the monopile and near the soil, causing sediment transportation to different areas and generating a scour hole around the structure. The scour dimension is dependent on local hydrodynamics aspects and soil properties. Scour leads to a reduction of the pile embedment, with a significant effect on its lateral response (Qi et al., 2016). In severe cases, scour can expose a considerable part of the foundation and, consequently, change the structural natural frequency (Li et al., 2018; Mayall et al., 2018), reduce fatigue life (Rezai et al., 2018) and lead to structural collapse (Matutano et al., 2013). If the risk of scour is significant, pre-installed scour protection systems may be incorporated during the installation of the foundation.

Scour protection systems may be installed following two distinct approaches. The double layer scour protection consists of a filter layer of small size rocks serving as a preparatory layer at the bottom and an armour layer made of larger rocks on top of the preparatory filter layer. The single layer scour protection, instead, consists of only one, wide-graded, rock layer. Scour protection methods are extensively illustrated in the findings of the joint industry project HaSPro (Deltares, 2023). In common practice, the installation is carried out by a rock dumping vessel, visiting twice each turbine location (once for each scour protection layer). The so-called three-step scour protection installation consists of: (i) placing the filter layer; (ii) installing the monopile, allowing it to penetrate through the filter layer under its own weight (i.e. self-weight penetration); and (iii) placing the armour layer. Drawback of this current practice include two visits of the rock dumping vessel for placing the two scour protection layers, and the complexity of placement of the armour layer around the pile rather than in a clear field.

A two-step installation is sometimes preferred and consists of: (i) placing the scour protection on the seabed during one visit of the rock dumping vessel; and (ii) installing the monopile. This approach may result in reduction of installation time and project duration, and consequent significant cost savings and reduction of overall carbon footprint. According to DHI (2021), utilising a one-layer system can reduce 30% construction cost of an offshore wind scour protection system.

Risks associated with monopile installation through scour protection concerns the uncertainty on the pile behaviour and the pile integrity during penetration. There is uncertainty in whether the pile will successfully penetrate a pre-installed scour protection layer. In other words, the influence of rock materials on the pile penetration resistance lacks full understanding. Another concern regards the pile tip integrity, as the penetration through a thicker rock layer can cause local buckling or localised fracture. The joint industry project Optimising Pile Installation through Scour protection (OPIS) was developed to gain understanding of the pile penetration through scour protection and streamline the installation process.

This paper provides a summary of the ongoing activities and preliminary results out for the OPIS project. The OPIS framework and the desk study are introduced in Sections 2 and 3. Sections 4 to 6 illustrate the experimental testing program and present some preliminary results. Section 7 describes the numerical modelling approach. Conclusions and implications for the industry are drawn in Section 8.

2 THE OPIS PROJECT

The joint industry project Optimising Pile Installation through Scour protection (OPIS), established in 2023, aims at investigating the technical feasibility of monopile installation through scour protection to enhance the feasibility of the operation. The project is led by Deltares, collaborating with 10 partners from the GROW consortium, including universities, windfarm developers and operators, contractors, suppliers of equipment and suppliers of materials. Project success will also contribute to reducing carbon footprint of the monopile installation process, accelerating the energy transition towards a carbon-neutral environment.

The project is divided into six strands of work, the so-called work packages (WP). WP1 covers the desk study and experimental design. The laboratory experimental campaign is divided between plate penetration tests (WP2), small-scale pile penetration tests (WP3) and mediums-scale pile penetration tests (WP4). The numerical modelling and development of prediction tool, based on discrete element method (DEM) and finite element method (FEM), is carried out in WP5. WP6 is reserved for analysis, synthesis and conclusions.

3 DESK STUDY

Penetration of monopile through scour protection requires a sound understanding of its penetration resistance, and its dependency on factors such as the thickness of the pile (or the penetrating tool), and the size of the rocks of the armour and filter layers.

While currently available standards and recommended best practices such as the International Organization for Standardization ISO 19901-4:2016 (ISO, 2016) and Det Norske Veritas DNV-RP-C212 (DNV, 2019) provide guidance on penetration resistance estimates by analytical formulas or empirical correlations, the utility of these expressions is limited for estimating the magnitude of penetration resistance in most cases. Moreover, there are notable studies investigating the penetration of skirted foundations in sands (Andersen et al., 2008; Houlsby and Byrne, 2005) and more recently, Varela et al. (2022) reported the results of full-scale tests on skirt penetration resistance in gravels. Despite the relevancy of the topic, there are no studies addressing the penetration of monopiles through scour protection layers which necessitated the experimental and numerical work undertaken in OPIS.

Current practice of pile installation through scour protection was gathered from various sources. Details of double layer scour protection systems, including their geometries and rock gradings, are collected by Whitehouse et al. (2011). Their paper illustrates as-built information on scour protection systems, and their scour developments, at offshore wind locations in the North Sea. However, that collection is limited to monopiles up to 6 m of diameter, which is not representative of the growing size of turbines and its monopile foundation. With the regards to single layer scour protection systems, available information is limited to their performance in small- and large- scale laboratory experiments (Petersen et al., 2018; Schendel et al., 2014). It should be noted that the characteristics of the rock material used for scour protection are set out in the European standard EN13383-1:2002 (DNV, 2022) and in the Rock Manual (CIRIA, 2007).

In OPIS project, field data and best practices were gathered through interviews with each consortium partner. The interviews shed light on field experience related to penetration through scour protection of up to 12 m diameter piles, including installation methods, risks for pile run, pile arrest and pile integrity, potential failures and other practical concerns. Field data were collected anonymously and consisted of pile information, subsoil characteristics and scour protection designs.

Figure 1 summarises the range of dimensionless scour protection geometries (such as te scour layer thickness and corresponding pile wall thicknesses) gathered from the project partners. The corresponding values used in the OPIS experimental tests are also presented in the same figure. The experimental programme aimed at testing realistic geometries, as combinations of plate thickness, rock layer thickness and rock size, whilst also carrying out a comprehensive sensitivity analysis on the effect of these parameters.

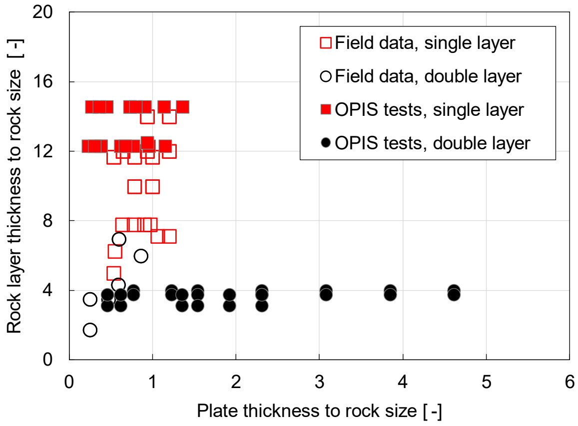

Figure 1. Dimensionless scour protection geometries: collected from project partners and tested in OPIS

4 PLATE PENETRATION TESTS

OPIS project involved 357 individual plate penetration tests on model-scale scour protection layers. The rationale behind these tests was to develop a sound physical understanding of the phenomena where the intruder thickness is substantially smaller than the mean particle diameter. By making use of the information gathered during the desk study, the prototype scale scour protection layer types and geometries were determined. Following this step, the model-scale scour protection layers were scaled with a geometric scaling ratio of 10.

The study considered two 160-mm-thick single layer systems with normal and high-density rock (eclogite sourced from Norway) which were designated as Zone-A and Zone-B. Additionally, two double layer systems were also built over an 80-mm-thick filter layer. These were designated as Zone-C and Zone-D and their thicknesses were 100 and 120 mm, respectively. The mean particle diameter (d_{50}) for these zones were 11, 13, 25, and 32 mm, for Zones A, B, C, and D. Finally, filter material had a d_{50} of 6.5 mm. The zones described above were constructed in a 2.4 m wide flume section with a total length of 31 m. Two sets of tests were performed over loose and dense sand beds of 1 m deep with relative densities of 40 and 80%.

In each set, the flume was subdivided to host different scour protection zones described above. The plates used in the tests had a length of 700 mm and variable thickness (5, 8, 10, 15, 20, 25, and 30 mm). Figure 2 illustrates a sketch of the instrumentation details and photograph of the plate penetrating the rock material in Zone-C. The penetration was displacement-controlled at a rate of 11 mm/s.

Figure 3 illustrates the relative effects of loose and dense sand beds supporting the rock material where the effects of seabed stiffness on the penetration resistance can be seen. The normalized penetration resistances are significantly larger when the rock is supported by dense subsoil.

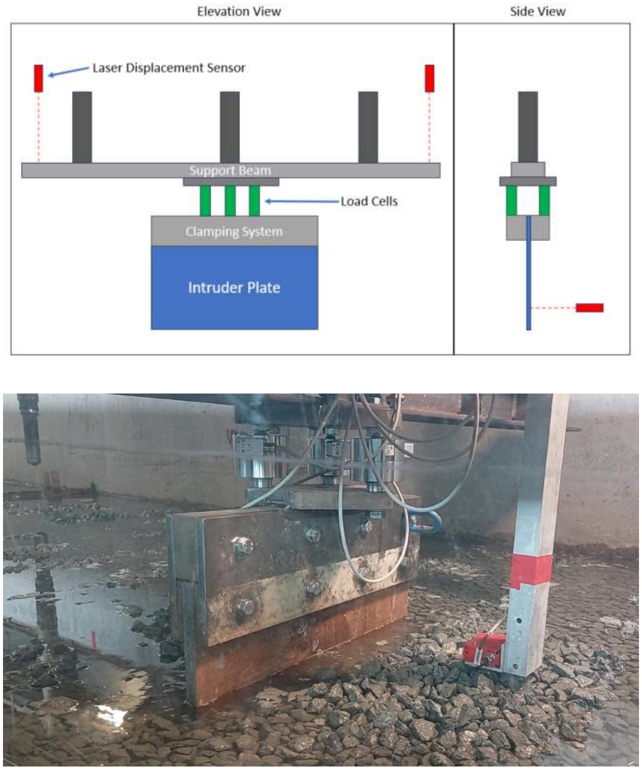

Figure 2. A sketch of the instrumentation and a photograph of the plate midway in the rock

Additionally, in plate penetration tests, different testing variations are also included. These include tests where effects of sand ingress into the rock is simulated. Furthermore, the additional surcharge resulting from the placement of a piling template and repeated penetrations over the same footprint are also studied.

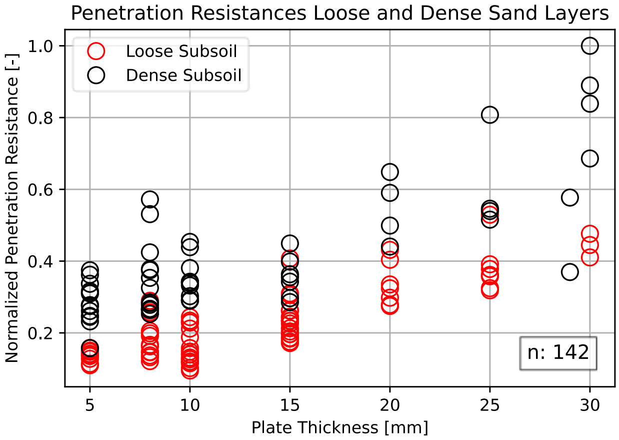

Figure 3. Normalised plate penetration resistance for loose and dense sand beds, normalisation entails equating the largest penetration resistance to unity

5 SMALL-SCALE PILE PENETRATION

Building on the fundamental physical understanding developed from the plate penetration tests, the experimental program proceeded on to the study of penetration behavior of cylindrical intruders which resemble the shape of the piles. In the experiments, constant pile outside diameter of 323.9 mm was used and piles of varying wall thicknesses were penetrated through model-scale rock material under displacement and force-control.

Figure 4 illustrates the normalised penetration resistance for displacement-controlled tests. The penetration resistance regimes in dense and loose sand-supported rock layers are significantly different. In dense sand, a local maximum of penetration resistance is reached for most piles at the rock–filter boundary with the exception of the 12.5 mm thick pile. The rock material supported by loose material exhibits a different behavior whereby the maximum is reached within the filter layer. In both cases, upon entry in sand, the resistance generally drops before picking up again due to the increased effective stresses at larger depths.

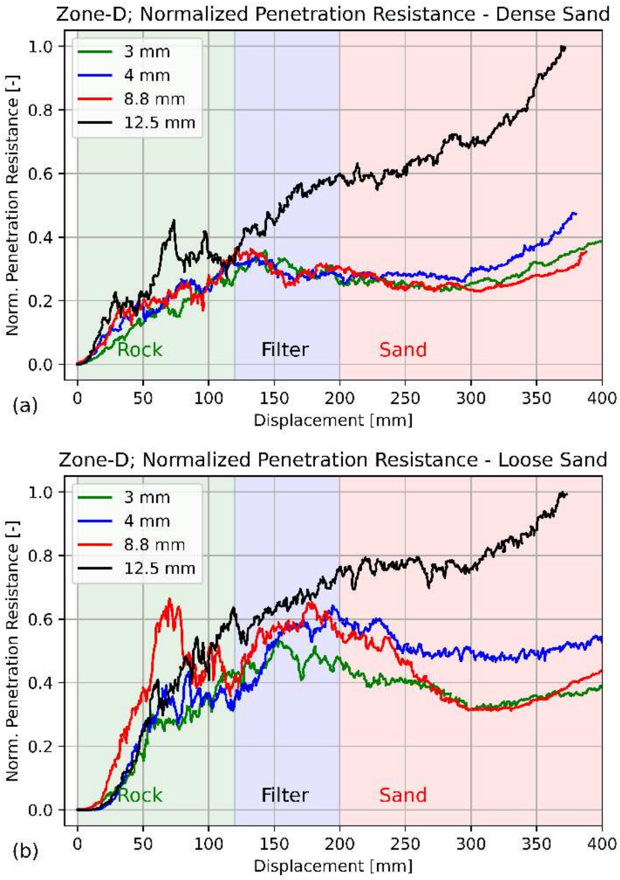

Figure 4. Normalised penetration resistance plots for rock material supported by (a) dense and (b) loose sands (normalisation entails equating the largest penetration resistance to unity in each plot)

In force-controlled tests, the pile was allowed to penetrate through the scour protection layer either under its own self-weight or by the acceleration provided by a scaled vibro-hammer. Figure 5 illustrates the pile-vibro-hammer assembly suspended in the outrigger system. A typical recording of the pile penetration under the action of a vibro-hammer is provided in Figure 5. In the test series, different pile driving scenarios are also simulated. This includes partial penetration of the pile into the rock and re-penetration and re-location of the pile in the close proximity of the initial penetration zone.

Figure 6 illustrates a time-history of pile displacement during vibro-hammer installation. At point 1, the pile is in the air and as the pile is lowered into the rock, initial contact with the rock is made. Following initial contact, the pile-hammer assembly penetrates into the rock under its own self-weight (until point 2). As the self-weight is calibrated so as not to cause complete punch-through, the remainder of the penetration is made possible by the activation of the vibro-hammer at point 3. At point 4, the pile extraction is commenced while the hammer is still operational. The hammer is switched off at point 5 and extraction is completed at point 6.

Figure 5. A photograph of the model-pile installation

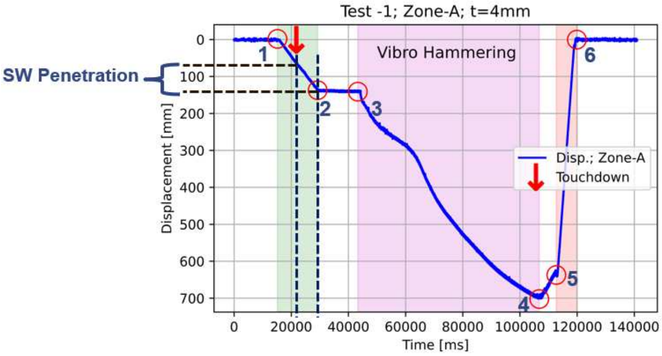

Figure 6. A plot of the pile penetration time-history

6 MEDIUM-SCALE PILE PENETRATION

Expanding upon the findings of the small-scale pile penetration tests, the next level of testing will include medium-scale tests with a 1.52 m outside diameter pile (wall thickness will be 15 mm so as to keep the common pile diameter to wall thickness ratio of 100). The aim for these series of tests is to observe the punch through behavior of piles at a much larger scale to bear more resemblance to the prototype. A sketch of the foreseen experimental assembly is illustrated in Figure 7.

The research ambition in this work package is to study the penetration of reasonably large piles into different rock types. The pile integrity will also be a part of the studies. In order to study local damage (bucking and fracture) mechanisms, a model pile with an outside diameter of 1.52 m and a wall thickness of only 2 mm will also be used in the tests.

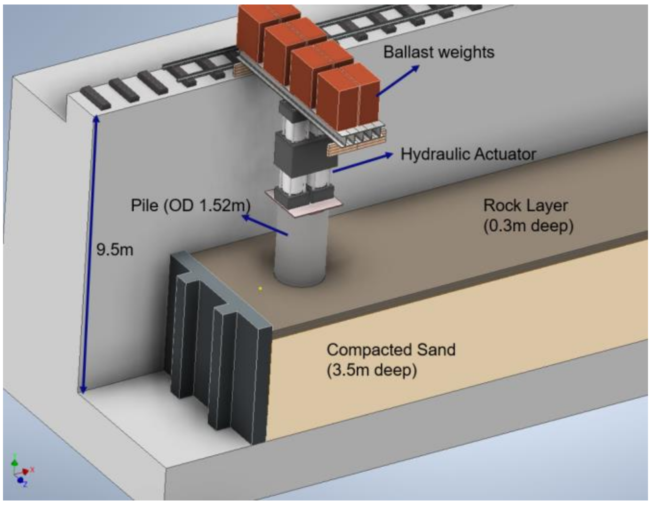

Figure 7. A sketch of the foreseen experimental assembly

7 NUMERICAL MODELLING

In parallel to the experimental testing, a numerical modelling framework is developed to represent the plate and pile penetration through scour rock layers.

To capture the discrete nature of rocks and the continuum nature of steel plate and pile, Discrete Element Method (DEM) is deployed with Altair® EDEM^{TM} (EDEM, 2022). A state-of-the-art modelling framework is developed for the rocks interacting with the plate and pile using DEM and validated against small to medium scale experiments in this project. In this framework, the sand and rock particles are modelled using spheres and multi-spheres (clumps), respectively. The Hertz–Mindlin no-slip contact model with Type C rolling friction is chosen because of the non-cohesive nature of the rock interactions. The material interaction parameters are calibrated using a multi-stage design of experiments optimisation approach combined with the Global Response Search Method (GRSM) and Genetic Algorithm (GA). An example of the pile penetration DEM model is shown in Figure 8.

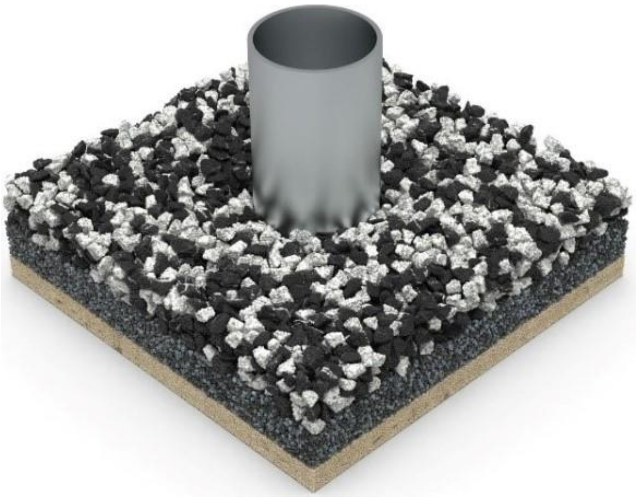

Figure 8. DEM simulation of pile penetration through a double-layer scour protection.

Similarly to the experimental test preparation, the sand layer is first generated using a random volume packing method followed by the generation of the two rock layers after the settlement of the sand layer. The penetration process is simulated after the full settlement of both rock and sand layers with a constant penetration velocity. These simulations are repeated at least 3 times to collect the variability at different penetration locations and the outcomes are validated against the experiments on penetration resistances. The validated numerical model will be upscaled towards a real field scale to facilitate or even replace (partly) the experimental testing. Furthermore, the scour protection designs as well as the risks during the monopile penetration process can also be evaluated by coupling FEM to the trustworthy DEM model, which can help determine the feasibility of future scour protection deployments

8 CONCLUSIONS

This contribution summarised the research endeavour undertaken within the OPIS project. At the time of writing this conference proceeding, the project is still underway. By the time the project will be completed, following outcomes will be reached:

- The laboratory results of plate and pile penetration will be compiled into a high quality experimental database.
- The project will also deliver a empirical/analytical model predicting the penetrability of rock layers with specific use for monopile installations. The utility of the model can be expanded to other pile types, as well. This model will be trained with experimental data and numerical modelling.

- The project also aims to prescribe effective remedial actions when penetration fails, for instance, pile driving with limited applied energy when a pile gets stuck in the scour layer.

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