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# 1-g Physical Tests on Monopile Penetration through Scour Protection Material

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**ABSTRACT:** Conventional scour protection installation around monopiles for offshore wind farms involves placement of smaller filter layer rocks and larger armour layer rocks in two separate operations, requiring multiple visits of the rock dumping vessel to the site which increases costs, time spent offshore by the vessels, and consequently carbon emissions. The joint industry project Optimizing Pile Installation through Scour Protection (OPIS), helps reaching the target of energy transition by streamlining the pile and scour protection installations, reducing costs and carbon emissions associated with offshore wind developments. The project investigates the technical feasibility of pile installation through coarse rock to enhance the practicality and efficiency of the operation. A series of small and medium scale laboratory experiments has been conducted, considering different scour protection designs such as single- and double-layer systems, and different rock densities. Furthermore, this contribution elaborates on the design and intricacies of the scaled laboratory tests, providing insights into the design and implementation of laboratory setups. Moreover, preliminary results and challenges encountered during the experiments are discussed. Specific testing outcomes such as sub-soil stiffness, repeated penetration effects, proximity of neighbouring tests, effects of sand ingress into the rock material, and effects or bevelled edge geometry are discussed.

**Keywords:** Scour protection layer; monopiles; 1-g physical tests; punch-through; installation

## 1 INTRODUCTION

Wind energy is becoming increasingly important in responding to global energy demand and it is now an integral part of the energy mix. According to some estimates, the global offshore wind installed capacity is predicted grow exponentially in the next decades (Dingle et al., 2023). Based on the 2023 projections of the International Energy Agency, by 2030, the offshore wind energy will constitute 18% of the global renewable energy and it is projected to make up for 40% by year 2050 (Renewables 2023 Global Status Report, 2023; World Energy Outlook 2023, 2023). Despite the promising growth trends and projections, installation and upkeep of offshore wind assets faces technical challenges presented by the harsh marine environments. Given the relevance of offshore renewable energy, 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 contribution elaborates on the testing results acquired in the Water-Soil Flume at Deltares.

The offshore environment has unique hydrodynamic conditions with erosive currents which prove to be detrimental to the stability of offshore installations. When a pile is installed to support an offshore wind turbine, the presence of the pile causes disruptions in the velocity profile within the seawater which leads to localized scour around the base of the monopile. For example, the local scour depth around the monopiles in the Scroby Sands offshore wind farm, one of the first commercial offshore wind farms in the UK, has reached 1.4D, where D represents the outside diameter of the monopile (Whitehouse et al., 2008). Similar findings were reported by Zhang et al. (2022) for an offshore wind farm in East China Sea where the scour depths varied between 0.43 to 1.4D. Given the large diameters and rather small slenderness ratios of monopiles, loss of soil support in the order of two pile diameters could significantly impair the monopile's capacity to resist design loads and alter the structural response of the entire assembly consisting of monopile, transition piece, and turbine tower.

Beyond the reduction in embedded pile length, scour changes the stress history of the remaining soils, and reduces the foundation stiffness which alters the natural frequency of the structure (Zhang et al., 2021). The monopiles are designed to fit within very specific frequency ranges and scour-driven changes in the dynamic stiffness of the structure may have detrimental consequences. The risk of resonance and fatigue not only increase due to the changes in dynamic stiffness but also due to reduced damping caused by the loss of the confining soil cover around the pile. The reduction in damping might yield larger vibration amplitudes which can further accelerate structural degradation (He et al., 2022). The moment capacity of the monopile is also significantly reduced due to erosion as shown in recent geo-centrifuge studies (Li et al., 2020; Li et al., 2021). Consequently, current provisions such as DNVGL-RP-C212 (2019) state that scour will reduce the bearing capacity, stiffness and damping of the monopile. Given these scour-induced deficiencies, safeguarding offshore wind assets necessitates a thorough understanding and effective mitigation of scour throughout the structure's service life.

Commonly utilized design approaches may require at least two visits of the rock dumping vessel to the offshore windfarm site (once to install the filter material and second time to place the armour material around the monopiles). One of the research questions the forthcoming contribution seeks to address is if the monopile can be penetrated through the entirety of the scour protection layer which is placed in a single visit by a rock dumping vessel. This would not only reduce the costs and carbon footprint of a project but also mitigate any adverse effects and risks of dumping rock next to an existing monopile. With this primary research question in mind, a series of plate penetration tests have been conducted to understand the penetration behavior of intruders into different scour protection systems. It is assumed that the plates used are an analogy for a slice of the monopile penetrating in to the rock material. In the test series, the penetration resistance behaviors of single-layer and double-layer scour systems were investigated. The effects of rock grain density (normal and high-density rock) were investigated by employing rocks of granite and eclogite origin in the experimental program. Furthermore, in order to study the effects of the ratio of the intruder thickness ($t$) to the mean particle diameter ($d_{50}$), a wide selection of plate sizes and geometries were considered.

## 2 EXPERIMENTAL METHOD

A detailed account of the experimental method including the experimental assembly, materials used, and methods applied are given in (Cengiz et al., 2024). Therefore, only the aspects necessary to interpret the results presented are recalled in the present contribution. 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 varied between 6.5 mm and 32 mm. The zones described above were constructed in a 2.4 m wide flume section with a total length of 31 m. The rock layers were funded on 1-m-thick sand layers (loose and dense sand). In plate penetration tests, the tests were done with displacement control, at a rate of 11 mm/s. The experimental program utilized plates with a width to length ratio of 0.5 with plate thickness varying between 5 and 30 mm. Figure 1 illustrates a photograph of the penetration tests where different aspects of penetration into granular media was studied. In the following sections these aspects will be elaborated.

*Figure 1. An impression of the testing assembly with an instrumented intruder (plate)*

# 3 RESULTS

## 3.1 Effects of Sub-soil Stiffness

Figure 2 illustrates the penetrologger results for the two sand beds prepared for the plate penetration tests. Penetrologger is a hand-held device which logs the tip resistance of a cone against the displacement. The relative densities of these layers are estimated to be 40 and 80% for loose and dense sand layers, respectively. The difference this stiffness contrast introduced in the maximum penetration resistance is depicted in Figure 3 where a clear difference between the penetration resistances registered for loose and dense soil is visible. On average, the penetration resistance within dense soil is 1.5 to 2 times larger than that of the rock supported by loose sand. In Figure 3, the penetration resistance is normalized to the maximum resistance obtained for the 30-mm-thick plate penetrating in Zone-D. The data suggests that there is a significant effect of the underlying layer on the penetration resistance of the rock layer.

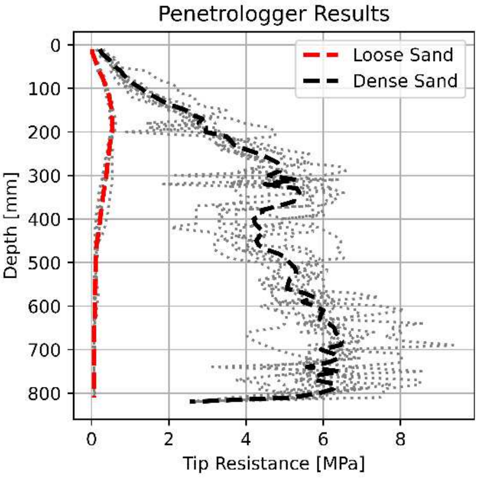

*Figure 2. Penetrologger profiles of loose and dense sand layers (dotted lines are individual measurements and dashed lines are averages of the measurements)*

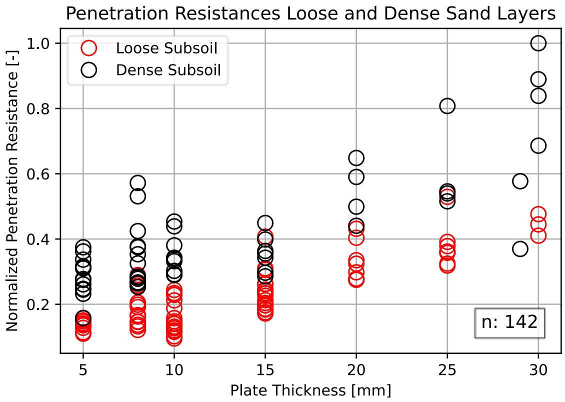

*Figure 3. Normalized maximum penetration resistances of rock supported by loose and dense sand subsoil for all zones*

## 3.2 Repeated Penetration Into Rock Layer

In offshore operations, it is not uncommon to attempt to repenetrate the pile if self-weight penetration fails in the first attempt. Figure 4 illustrates a series of plate penetration tests where a 10-mm-thick plate was repeatedly penetrated into Zone-C. The initial test was placed in-between previously tested or disturbed zone to enhance the realism associated with the re-penetration tests. The following repeated penetration tests designated as ‘r1’ to ‘r5’ revealed important insights: (1) as the intruder repeatedly penetrated, the touchdown distance increased, indicating the occurrence of progressive settlement of the soil model and (2) the penetration resistance increased with each successive penetration and the peak was observed in the fourth penetration where the penetration resistance was more than doubled. The penetration resistance increase could be related to the densification/compaction of the material and dragging down of the rock materials where increased effective stresses might provide larger restraint for the rock. Figure 5 illustrates the deformation of the rock layer surface for single and repeated penetration tests.

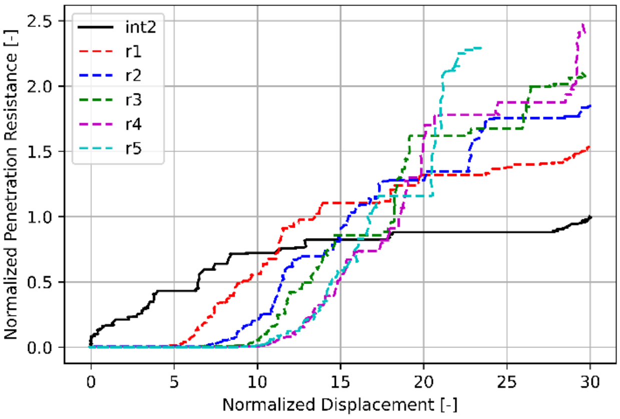

*Figure 4. Repeated penetration testing of a 10 mm plate over the same footprint*

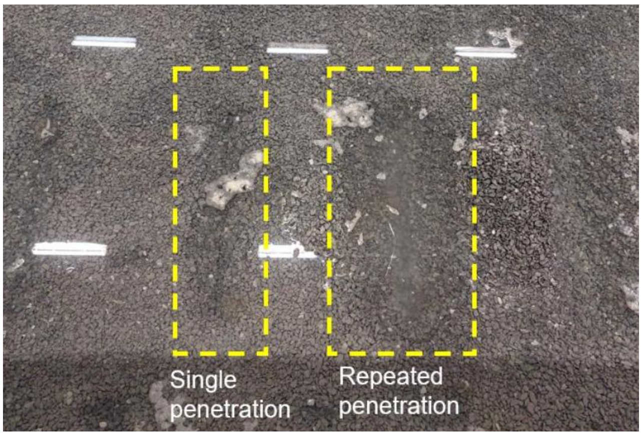

*Figure 5. Indents left after single and repeated penetration*

### 3.3 Neighbouring Tests: How close is too close?

One of the challenges in the experimental campaign was to utilize the testing volume in the most efficient way possible to maximize the learning outcomes. The testing volume (Water-Soil Flume at Deltares) used in this study was 31 by 2.4 m in plan and 2.5 m deep. The use of a crawler loading frame along the entire flume length allowed for a large amount of tests in quick succession. In order to understand the minimum stand-off distance between the neighbouring tests, a bisection search was conducted where the distance between the successive tests was halved in each repetition. Figure 6 and Figure 7 illustrate the methods and outcomes of this study, respectively.

The testing sequence shown in Figure 6 is applied throughout the testing program in the exact sequence for all soil zones (Zone-A to Zone-D) supported over dense sand. The minimum distance to ascertain the undisturbed conditions were examined with preliminary testing and according to these tests, the minimum distance required is 600, 600, 650, and 700 mm for Zones, A, B, C, and D, respectively. These distances are halved for the so-called 'int1' tests and then the remaining distance was further reduced by half (i.e., quarter of the initial distance) for 'int2' tests.

In Figure 6, the zone shown by the blue dotted line indicates the relative dimensions of the plate together with a portion of the testing area, and testing locations drawn to scale. The locations marked with an 'x' mark the testing locations, and the labels indicate the test number. Figure 7 shows a clear pattern of decreasing penetration resistance in int1 and int2 zones (half and quarter distance away from previously penetrated zones). Furthermore, the int1 zones yield similar penetration resistances in both wall and window alignments. These alignments are used as main testing alignment along the length of the flume. Since the flume is equipped with a transparent window, the alignment closer to the window side is designated as the ‚window‘. Lastly, repeated penetration causes successively increasing penetration resistance trend. It should also be noted that coarser rocks exhibit a larger penetration resistance where it is seen that the normalized penetration resistances increase with increasing rock size. Based on the testing carried out, a clear grouping of the data was observed and the minimum distances to yield undisturbed results are verified. Observed trends are consistent throughout the testing program for different scour protection material types.

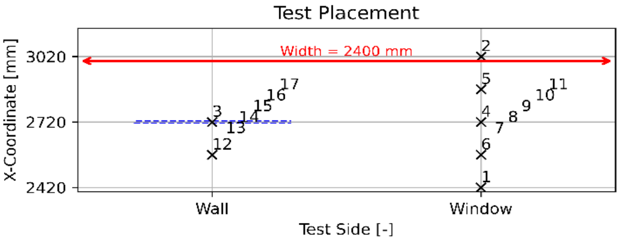

*Figure 6. Plan view of the test placement over the flume (two alignments over the flume were used these are called the wall and the window side)*

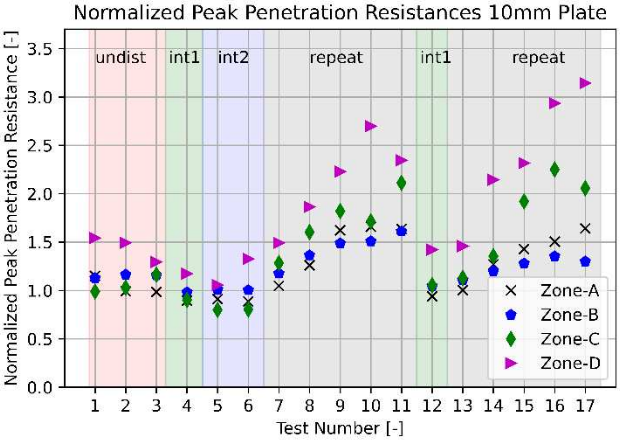

*Figure 7. Distribution of the normalized penetration resistances over different tests.*

### 3.4 Effects of Sand Ingress

In most cases, the scour protection material is placed ahead of pile installation time and the gap between the scour material placement and pile installation could be as large as a year. Due to the hydrodynamic conditions, it is believed that the voids in the rock material might be 'fouled' with finer material. The ingress of sand into the voids may increase the number of contact points each rock can derive and consequently increase the penetration resistance. With the OPIS project, the effects of sand ingress was simulated by applying 10 and 20 kg of fine sand per square meter of the rock material which are denoted as z1 and z2.

The comparison of the normalized penetration resistance are illustrated in Figure 8. The results pertaining to undisturbed tests and the so called intermediate distance tests (int1 and int2) yield patterns as expected where the undisturbed tests have a higher resistance than that of the int1 and int2 tests. The tests denoted with z1 and z2 were conducted on positions where the soil was disturbed and the disturbance conditions were akin to int1 tests. When the scatter plot shown in Figure 8 is examined with this information, it is seen that the addition of sand significantly increases the penetration resistance of the rock layer. This is especially true for a sand addition level of 10 kg/m$^2$, where the results on average are higher than that of 20 kg/m$^2$ (z2) sand addition. This may be indicative of a critical optimum sand amount resulting in higher penetration resistance. The sand particles at the critical level might increase the number of contact points between the rock and allow for an enhanced force chain to develop. It could also be speculated that if the sand amount goes above the critical level, then the sand particles cause the interface between the rock to become more 'slippery' and consequently lead to lower penetration resistances that that of the critical case.

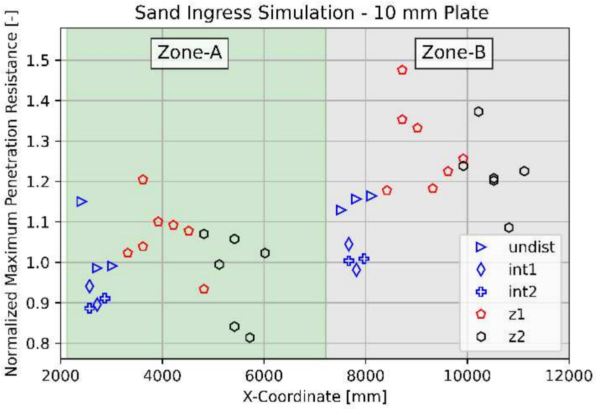

*Figure 8. Effects of sand ingress on the normalized penetration resistance*

### 3.5 Effects of Bevelled Edge Geometry

For CPT testing, it is known that the cone apex angle has a significant influence on the penetration resistance with blunt or flat tips generating greater penetration resistances (Hunt et al., 2023). Similar findings on the tip shape effects are also reported in the field of bio-inspired geotechnics (Mishra et al., 2018; Martinez et al., 2022). Furthermore, Wu et al. (2021) have shown that internal bevels at the tip can reduce penetration resistance for suction caissons. While streamlined tip geometries are associated with beneficial reductions in penetration or burrowing resistances, in the field of offshore geotechnics, especially, for bevelled tip designs of piles, the bevelled edges are known to trigger extrusion buckling (Nietiedt et al., 2023). Despite the known drawbacks of a bevelled tip design, the testing program accommodated a small number of tests to investigate the relative effects of a bevelled tip. The 30-mm-thick plate was selected as a benchmark case for these tests.

Figure 9 illustrates the results of the 30-mm-thick plate penetration results for square-edged and bevelled tips. Although the bevelling applied is rather blunt, the results of the penetration tests carried out over undisturbed rock shows a clear trend of reduction in penetration resistances when bevelled edge is used. The difference in normalized penetration resistances are as large as two folds when the bevelled edge results are compared against the square edges. The difference in the penetration resistances over disturbed zones (int1) are less pronounced but there is still a discernible difference between the penetration resistance when square and bevelled edge results are compared.

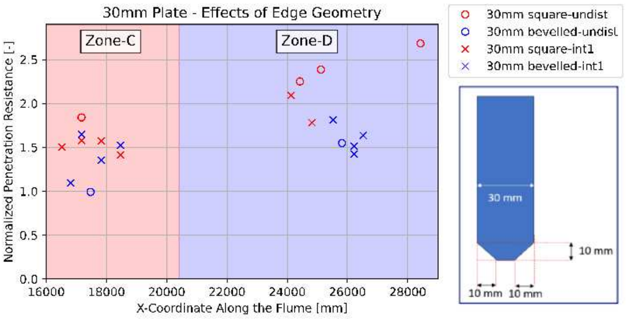

*Figure 9. Normalized penetration resistances for 30 mm thick plates (see a sketch of the bevelled edge on the right)*

## 4 CONCLUSIONS

In OPIS project a large number of penetration tests were conducted to understand the force required to penetrate scour protection layers.

Following conclusions were drawn from the experimental program:

- The stiffness of the underlying (supporting) soil layer significantly affected the maximum penetration resistance of the rock layer. In general, denser sand layers underlying the rock resulted in higher penetration resistances.
- Repeated penetration tests over the same footprint yielded two important findings: (1) repeated penetration caused a 'crater' like deformed soil surface where the touch-down distance for the intruder increased with each successive step; (2) the penetration resistance increased with each repeat test. The increase in penetration resistance is likely due to the greater confinement of rock particles at deeper depths and the densification of the soil beneath the intruder.
- The tests have also yielded minimum stand-off distances of neighbouring tests to ascertain undisturbed conditions. The adopted values and acquired results can shed light into the future studies in this topic.
- Sand ingress might significantly increase the penetration resistance of the rock layer. The tests showed that there is an optimum amount

of sand which increases the penetration resistance. Beyond this value, the penetration resistance tends to decrease.

- Although bevelled edge geometry is associated with extrusion buckling, the results have shown significant reduction in penetration resistance with a bevelled edge. Streamlined steel sections can be applied to reduce the penetration resistance further. Local bucking and tearing of the steel should be kept in mind in such applications.

## AUTHOR CONTRIBUTION STATEMENT

**Cihan Cengiz**: Data curation, Methodology, Formal Analysis, Writing- Original draft. **Additional Authors**: Writing – review & editing

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