Scale model testing of eco-friendly scour protections for offshore foundations and cables

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ABSTRACT

The dimensions and composition of scour protections can be further optimized to boost their ecological value as hard substrate habitats, for example, by incorporating artificial reef structures to create shelter for mobile species or by using materials that stimulate settlement of specific biota. These elements can, however, influence the hydraulic performance. To understand the behavior of eco-friendly monopile scour protections and cable rock berms, scale model test campaigns were performed on a large-scale in a wave flume and on smaller scale with wave-current conditions and a mobile seabed. These test campaigns led to useful insights for the design of eco-friendly scour protections. The way that ecological materials are incorporated in a scour protection and their hydraulic properties are design aspects that require special attention. Proper hydraulic design is crucial for minimizing risks that concern the integrity of surrounding infrastructure, such as exposed cables and foundations and of the eco-friendly scour protection itself.

INTRODUCTION

Increasing attention is currently given to Nature-Inclusive Design (NID) of offshore wind farms, for which, scour protection design around offshore foundations and cables plays an important role. Based on monitoring surveys of existing wind farms, conventional loose rock scour protections are known to form successful hard substrate habitats in the otherwise sandy environments where offshore wind farms are typically constructed, by providing space for marine growth, food and shelter for fish and by acting as hotspots for kickstarting reefs (Glarou et al. 2020). The common design parameters of a scour protection, such as the dimensions and composition of rock layers, together with the local environmental conditions determine the type of the habitat that is available, and hence the ecological community that will be eventually attracted and colonize these hard substrates. The design of scour protections can thus be optimized to promote local biodiversity and boost the development of specific species of high conservation status (Langhamer 2012).

Lengkeek et al. (2017) investigated the opportunities for eco-friendly design of scour protection in North Sea offshore wind farms and identified two umbrella species as targets for ecosystem restoration – European flat oyster (*Ostrea edulis*) and Atlantic cod (*Gadus morhua*). Although these are focal species in the North Sea, they also represent wider groups of species, reef-builders and reef-users respectively, that are distinguished based on their different habitat requirements. Drawing on the knowledge about these species and the historical hard substrates in the North Sea, it is possible to design scour protections that would be more attractive for certain types of species.

Design principles concerning eco-friendly scour protections stem from previous research. To promote shelter for reef-using mobile species, like the Atlantic cod, it is advised to provide at the surface of the scour protection numerous crevices that have a generally large and variable size in order to support mobile species at various life stages (Lengkeek et al. 2017, Bos et al. 2021). On the other hand, to promote colonization and kick-start the reef-building process of species such as the European flat oyster, Pogoda et al. (2019) recommend introducing materials associated with certain chemical cues that enhance settlement. Materials with a high calcareous content such as shells and limestone rock can promote the settlement of oyster larvae (Casoli et al. 2015). Furthermore, Potet et al. (2021) stress the importance of microstructures at the surface. Where local populations are scarce or functionally extinct, settlement material must be combined with active introduction of adult specimens. Finally, it is advised to increase the complexity and three-dimensionality of scour protections to increase biodiversity around scour protections overall.

There are many concepts and scour protection layouts that can support the above-mentioned optimizations. Nevertheless, these should not compromise the primary function of the scour protection. Since eco-friendly scour protection designs are typically more complex than conventional designs, it will often be required to validate their technical performance by means of physical model tests before applying them in the field. Additionally, physical model tests can provide useful information for the performance of various introduced elements from an ecological perspective too. The physical model tests performed are the first of their kind at this scale and provide useful insights about the design of eco-friendly scour protections.

DESIGN REQUIREMENTS FOR ECO-FRIENDLY SCOUR PROTECTIONS

Eco-friendly scour protections must meet both technical and ecological requirements and thus can be more challenging to design, validate, and install compared to conventional layouts. The technical requirements for loose-rock scour protections are well established and are reviewed in Steijn et al. (2023). In short, these include external stability, interface stability and flexibility. Ecological considerations for scour protections have emerged from research studies and experiences in offshore pilots (Hermans et al. 2020). In the form of specific requirements, they have been already introduced in the Dutch North Sea and are specific to mobile species (RVO 2021). Some key recommendations available in literature are summarized below and are used as the starting point for the design of conceptual layouts employed in the two test campaigns.

Firstly, the use of potentially harmful material for the environment should be avoided in scour protections intended to function as hubs for ecological restoration through nature-inclusive design (Lengkeek et al. 2017). Moreover, NID measures in general, but also concerning scour protections, should target appropriate species for the site-specific environmental conditions. For example, reef building species such as the European flat oyster, have specific habitat requirements (Hughes et al. 2023). NID concepts should promote self-proliferation of such biogenic structures and including options to target such species when the environment is e.g. too morphodynamically active, will never be successful.

In addition, sufficiently large cavities available at the uppermost layer of the scour protection, e.g. RVO (2021) specifically state crevice diameters between 10 and 30 cm. This requirement aims at providing shelter space for mobile target species. A way to provide large crevices would be to employ a large narrow rock grading. Larger pores will form between rocks of larger as opposed to smaller sizes (large grading) and the absence of relatively smaller rocks (narrow grading) in the mixture means that such pores can remain open. The need for a coarse and narrow rock grading is also demonstrated by a simplified mathematical model which gives a crude estimation for the magnitude of opening sizes for various commercial rock gradings (see Figure 1). By assuming perfectly spherical rocks and the top layer of the scour protection as a nearly horizontal plane, any combination of three touching rocks contained in a certain rock grading will form a triangle, whose sides may be used to estimate the size of the resulting crevices.

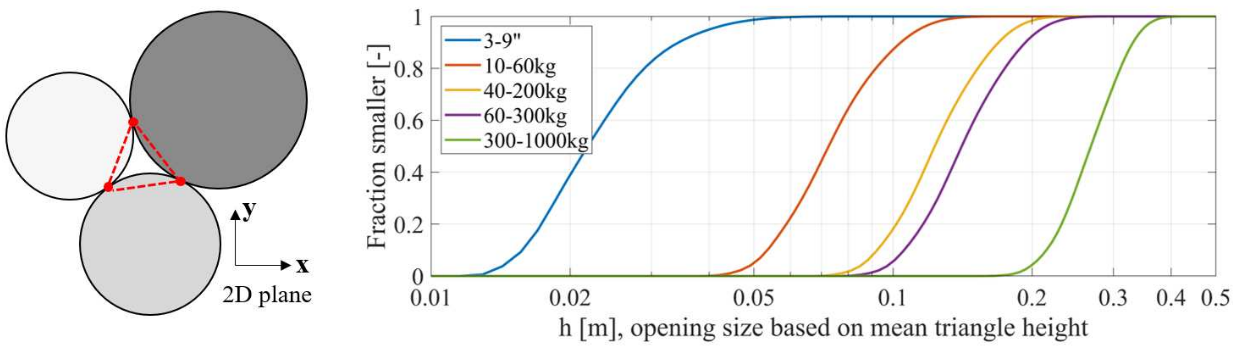

Figure 1 Crude estimation of opening size distributions for various standard rock gradings, after employing one million random combinations of horizontal planes with 3 perfect spheres.

Given that a wide grading will likely not provide suitable shelter for most adult mobile species (see 3-9" in Figure 1), a suitable rock grading for certain target species can be applied by adopting a double-layered scour protection with a properly dimensioned armour layer (e.g., 60-300kg) or by installing a topping layer of large rocks (e.g., 300-1000kg). However, it may be challenging and possibly inefficient to install very large rocks very close to offshore foundations. An alternative method to ensure the required crevices involves the installation of artificial structures at the top of the scour protection. The advantage of such structures is that they can be custom-made and hence provide any size and configuration of desired crevices.

Another requirement is that rock layers at the uppermost level of the scour protection should remain stable under frequently occurring storms, e.g. RVO (2021) indicates yearly storm conditions. This ensures that species that find shelter inside the crevices of a loose rock scour protection are not disturbed due to frequent movement of rocks. For most conventional loose-rock scour protections, this requirement will be easily satisfied given that they are already designed to remain stable under much more severe storms, with return period equal to or larger than 50 years.

Similar to the rock layers, any ecological elements integrated in the scour protection should also demonstrate limited or no movement. For ecological elements like large rocks and artificial reef structures, it is important that they remain stable even under severe storm conditions. From a technical perspective, any heavy introduced elements like artificial reef structures may cause damage to surrounding infrastructure if displaced. Therefore, for these no movement may be tolerated. From an ecological perspective, it is important that elements remain in place throughout the lifetime of the structure and accessible to target species. For example, given the light-weight nature of oysters and loose shells, even under mild storms they may become significantly displaced. For many locations deploying loose shells is therefore not an option.

Finally, only very limited sedimentation can be accepted around scour protections that are optimized to support ecology. Scour protections are prone to sedimentation especially when introduced in a morphodynamically active environment, due to migrating bedforms. Therefore, ecological design should prevent the clogging of crevices or the burial of settlement material from sand. Micro-siting of foundations to more favorable locations in terms of morphodynamics, and potentially even increasing the thickness of the scour protection layer could prevent sedimentation for rock protections with a large sediment infill potential. In general, this infill potential is larger for rock protections around cables compared to foundations, where significant flow amplification and hence erosion is expected.

EXPERIMENTAL SET-UP OF PHYSICAL MODEL TESTS

Using the ecological design considerations presented above as a starting point, several conceptual layouts of eco-friendly scour protections were designed and tested during two hydraulic laboratory test campaigns on large and medium scale, in the framework of JIP HaSPro. The hydrodynamic conditions in the two test campaigns were selected to be generally representative of the North Sea conditions. Rocks were scaled to demonstrate a similar mobility to scour protections in the field. Other elements were scaled linearly, with some exceptions discussed below.

The first test campaign was performed in a wave flume with scale factor approximately 1:6. This large scale allows the testing of scour protection stability with minimal scale effects. In this test campaign, the hydrodynamic conditions were limited to wave-only conditions. The focus of this test programme was solely on the stability of the loose rock and reef elements on top of monopile and cable rock protections. The second test campaign was performed on a much smaller scale (approximately 1:30), in a wave-current basin with mobile bed. The aim of this test campaign was to expand the understanding of scour protection and reef elements stability under combined wave and current conditions, and to assess the effect of the edge scour on the stability of the elements.

Large scale test campaign – Delta Flume

The first test campaign was performed at the Deltares Delta Flume (DF). This flume has a width of 5 m and depth of 9 m. The tested eco-friendly scour protection concepts are presented in Figure 2. These are monopile scour and cable protection layouts with integrated artificial reef elements (reef balls and pipes) as well as loose shells. The tests were performed with a range of irregular wave conditions of increasing severity (see Table 1).

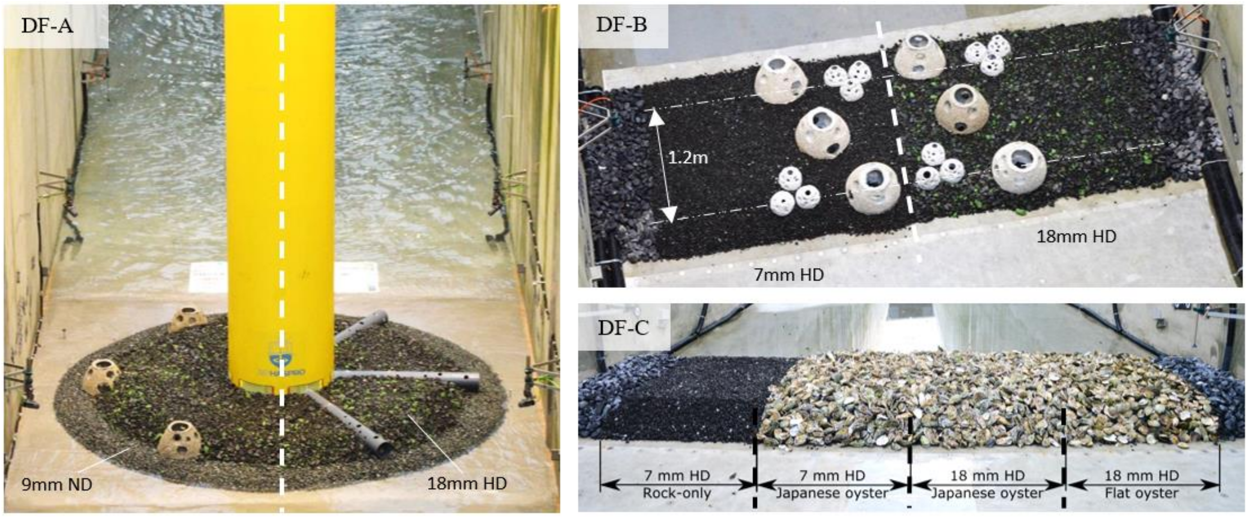

Figure 2. Delta Flume campaign: layouts tested around monopile (left) and cable (right) protections.

The test setup in test series DF-A consisted of a monopile scale model (diameter D=1m) and artificial structures (reef balls and pipes with holes) integrated in a double-graded scour protection, with an armour (E_{top}=3D) and a filter layer (E_{top}=4D). Three reef elements were integrated in the armour layer on each side of the scour protection with respect to the incoming wave direction, yielding two distinct layouts. The reef elements were designed to be virtually immobile in these tests, such that only rock deformation around them could be evaluated.

In the first cable protection layout tested in series DF-B reef elements were placed on top of a loose rock berm with different rock gradings in each half of the test section. This allowed the assessment of rock deformation around reef elements for different rock sizes. Two different types of reef ball elements were employed: large (25 x 43 cm, same as in DF-A) and small (13 x 19 cm).

In a second cable protection test setup, tested in series DF-C and DF-D, loose shells (European flat and Japanese oysters) were installed on top a loose rock cable protection. The shells were real-size and were not scaled for practical reasons. The median submerged shell weight was measured around 12.2g. The shells were installed with a 5 cm layer thickness over the rock protection. This test setup was designed to test the stability and modes of motion of loose oyster shells.

<u>Medium-scale test campaign – Atlantic Basin</u>

The second test campaign was performed at the Deltares Atlantic Basin (AB) on a smaller scale compared to the DF tests (approximately 1:30) and it was focused on monopile scour protections. The concepts tested here are shown in Figure 3 and included loose rock scour protections with incorporated reef elements. Pile 1 included reef ball elements (57 x 68 mm) installed on top of armour or filter rock layers. Pile 2 included large rock clusters installed on top of the armour rock layer (left) and pipe elements installed within the armour or on top of filter rock layers (right).

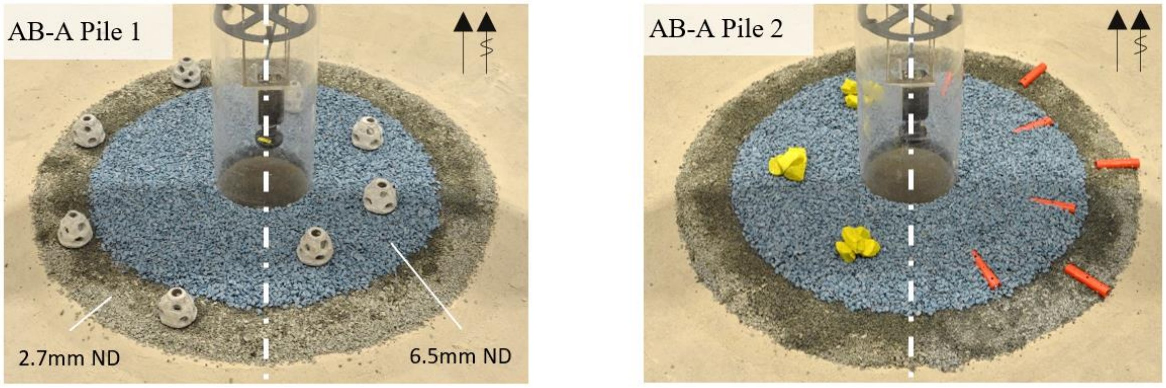

Figure 3. Test campaign in the Atlantic Basin: eco-friendly scour protection around monopiles.

In test series AB-A in the Atlantic Basin, all layouts were made of identical loose rock scour protections around a monopile with a diameter of D=0.2 m. The protections consisted of an armour layer (E_{top}=3D) and filter (E_{top}=4.35D) layer. All layouts were tested under identical hydrodynamic conditions of increasing severity, as shown in Table 1.

Test programme and measurements

The measured hydrodynamic conditions per test series are shown in Table 1. The wave- and current-induced flow velocities and water level fluctuations were measured with electro-magnetic flow meters and resistance-type wave gauges. The scour protection deformation was quantified using bathymetric measurements taken before and after each test by means of 3D stereophotography (Raaijmakers et al. (2012). Underwater cameras were used to continuously monitor the test set-up and thus any motions of introduced ecological elements during the tests.

Table 1. Achieved hydrodynamic conditions in the physical model tests (on test scale).

Test Series	Test Layout	h_w [m]	H_{m0} [m]	T_p [s]	Uc [m/s]
DF-A	Monopile (reef structures)	5.11	1.13-1.38	4.55-5.24	0
DF-B	Cable (reef structures)	6.02	1.08-1.39	4.44-5.11	0
DF-C	Cable (loose shells)	6.06	0.37-0.54	2.66-7.15	0
DF-D	Cable (loose shells)	6.06	0.70-0.94	3.77-4.74	0
AB-A	Monopiles (reef structures, large rocks)	0.69	0.20-0.25	1.88-2.70	0.15-0.17

ANALYSIS OF TEST RESULTS

The discussion of the results obtained from the various tested layouts focuses predominantly on the following aspects of the hydraulic performance of eco-friendly scour protections: i) rock deformation patterns, ii) stability of reef elements. Evaluating these two aspects allow us to draw general conclusions on the performance of this type of eco-friendly scour protections.

Figure 4 shows the bathymetry difference before and after test series DF-A (left), and a reference case with similar rock protection and hydrodynamic conditions but without any reef elements (middle). In the reef ball section, the deformation pattern near the pile is similar and no extra deformation is observed compared to the reference case. However, some limited deformation was observed at the filter layer around the reef balls. At the pipe section, the deformation pattern is shifted compared to the reference case, and more deformation is observed towards the transverse side of the monopile relative to the incoming waves. The difference in the two sections is explained by the different placement of the reef structures relative to the flow amplification zone around the monopile. In general, integrated reef elements will induce additional turbulence in their vicinity, which in turn amplifies the hydraulic loading experienced by the scour protection. Obviously, this additional loading increases with increasing flow obstruction from the introduced elements.

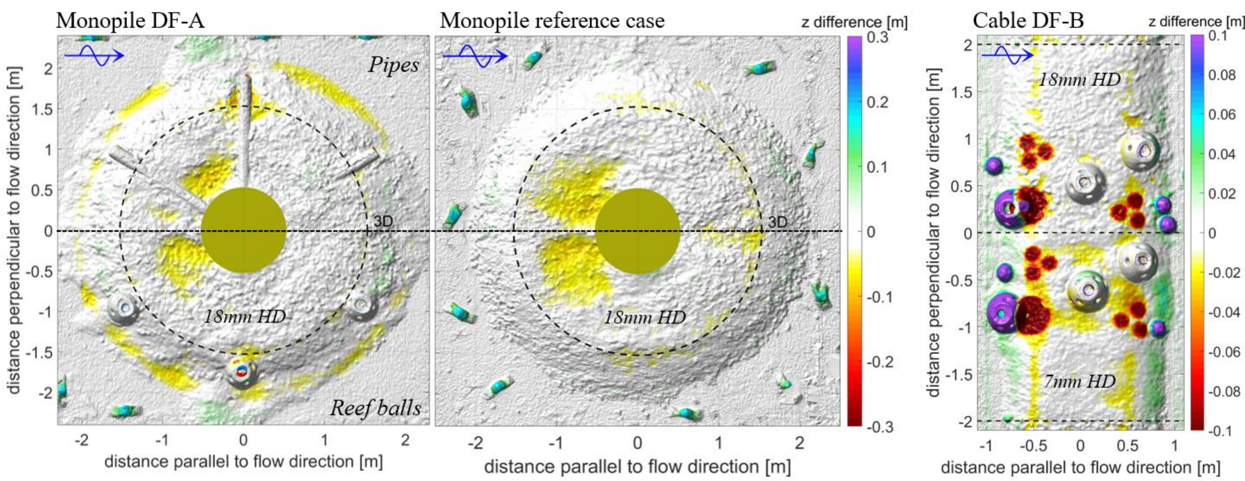

Figure 4. Bathymetry difference before and after test series obtained with stereophotography. From left to right: i) monopile scour protection before and after DF-A, ii) reference case for DF-A (no reef elements), iii) cable protection with reef elements before and after DF-B.

In test series DF-B, the cable protection rock berm is subjected to milder flow amplification compared to the rock protection tested in DF-A, given the absence of a large vertical obstruction like the monopile. In the test section with a similar rock grading as in in DF-A (18 mm HD), and under slightly less severe hydrodynamic conditions (see Table 1), no deformation is observed at the crest in Figure 4 (right, top section). However, at the section with smaller rock (7 mm HD) some deformation is observed around the large reef ball placed at the crest. The differences between the observed deformation in the two sections is due to the difference in the employed rock gradings (7 mm rock being more mobile than the 18 mm rock). This highlights the need for a more conservative choice in the loose rock material, where reef structures will be introduced.

Another highlight from the DF-B tests, is that the reef balls placed close to the edge of the rock berm crest were displaced towards the seabed during the tests. From a technical perspective this is not expected to introduce further risks for the integrity of the rock protection or the underlying cables. This movement was due to a combination of hydrodynamic loads and the local reshaping of the cable protection from the initial trapezoidal cross section to a more natural convex shape. This has implications for the placement of reef structures around monopile scour protections too. Avoiding a placement inside the monopile amplification zone (3D) as discussed previously, means that such elements would in many cases be placed on top of the extending (filter) layer. The latter is typically designed with relatively smaller rock and may deform in response to edge scour.

Next, Figure 5 shows the bathymetry of the model with reef balls placed around Pile 1 before and after the tests in AB-A with waves, current and a mobile seabed. Figure 5 shows that two of the reef balls placed inside the amplification zone (3D) and closest to the deformation pits (yellow areas in right panel) were completely displaced by the end of the tests towards the filter layer, whereas the other two only slightly moved. All reef balls placed on top of the filter layer have slightly rotated mainly due to the reshaping filter layer (pre-installed edge scour is visible in the left panel) but were not significantly displaced from their initial position.

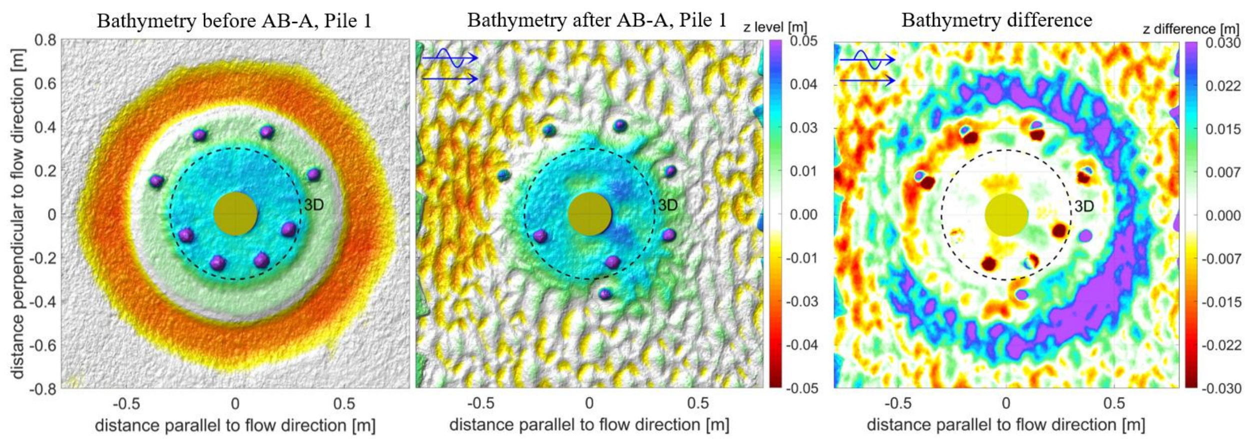

Figure 5. Bathymetry measurements obtained before (left) and after (middle) AB-A at Pile 1. Bathymetry difference is shown at the right panel.

Figure 6 shows similar bathymetry plots from the same test series, but for large rock clusters and pipes tested around Pile 2. For the clusters of large rocks, although placed inside the monopile amplification zone (3D), only very limited movement is observed. Again, this concerns the cluster closest to the scour protection deformation pit, which had a similar position as in Pile 1. The pipes inside the amplification zone also remained in their initial position throughout the tests. However, the pipes placed on top of the filter layer were displaced significantly even under milder conditions, following the orbital motion of the waves, before being deposited and covered by sand ripples at the outer edges of the scour protection. This difference is explained by the fact that the pipes placed within 3D were almost fully embedded into the armour rock and hence sheltered as opposed to the ones further away from the monopile that were free to roll on top of the filter layer. These results highlight the potential collision risks of moving reef structures with infrastructure (e.g. free hanging cables near the monopile), as well as the importance of proper embedment or anchoring of potential artificial reef structures in the scour protection rock layers to improve their hydraulic stability. Compared to reef balls tested in Pile 1, pipe elements demonstrated much larger potential for sand infill, due to their more streamlined and open structure. It should be noted, however, that on such small scale the sand infill process is not fully representative of field conditions where sand has much smaller relative grain size.

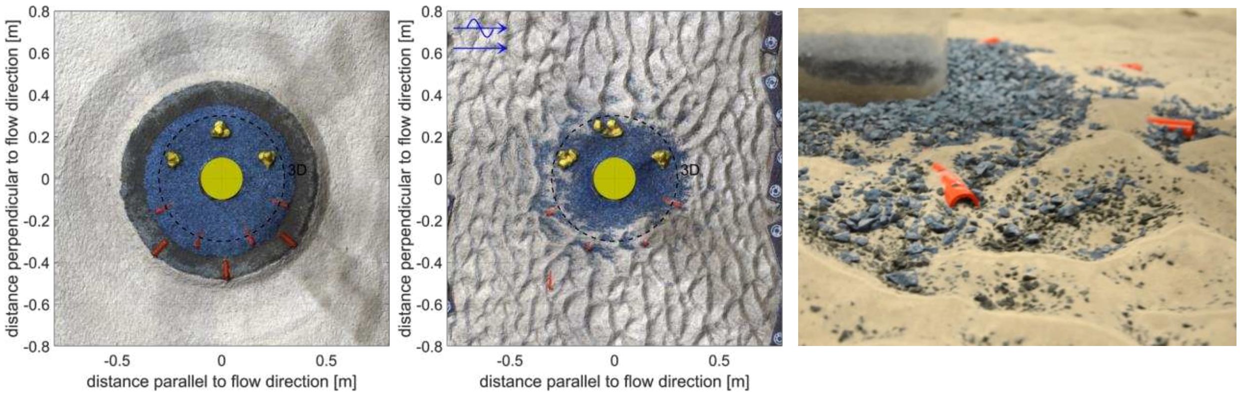

Figure 6. Color plots obtained with stereophotography before (left) and after (middle) test series AB-A at Pile 2. Photograph of the pipes taken at the end of the tests (right).

Finally, the stability of loose oyster shells sprinkled on top of the cable protection in DF-C and DF-D was evaluated by means of observations of the underwater camera recordings (see Figure 9). These can only provide qualitative results on the shell displacement. Little or no difference in the stability of flat oyster and Pacific oyster shells was observed. By the end of DF-C, shells were only observed to show some rocking motions. Nevertheless, significant displacement of shells away from their initial position was observed during the conditions tested in DF-D. No detrimental effects on the scour protection were observed here, which highlights the limited technical risks concerning this concept as opposed to the introduction of relatively large artificial reef structures.

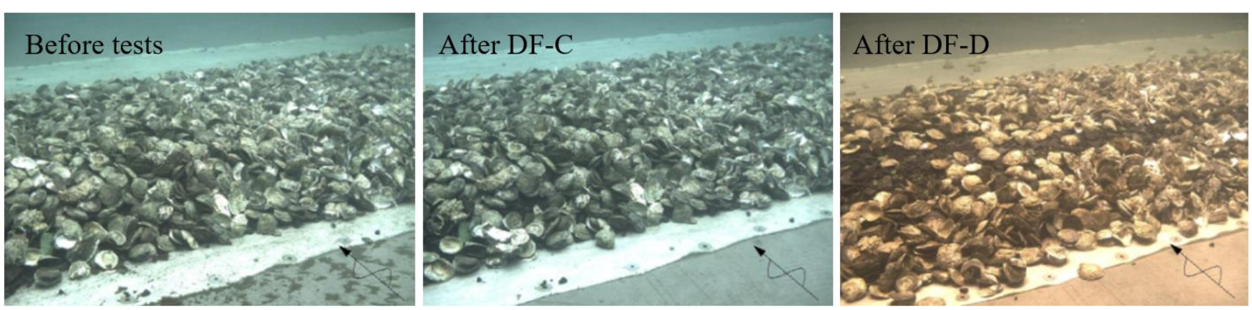

Figure 9. Observations from underwater cameras next to the cable protection test section before the start of the tests (left) and after DF-C (middle) and after DF-D (right).

CONCLUSIONS

This paper presents research on eco-friendly rock protections around monopiles and cables for different target species. Several eco-friendly scour protection layouts were tested for hydraulic performance in two physical model test campaigns under wave and combined wave-current conditions. Insights are gained from these tests concerning the stability of ecological elements integrated in rock protections and the potential technical risks that emerge from such eco-friendly scour protections. Test results show that artificial reef structures may influence the local rock deformation patterns. The integrated ecological elements could themselves become unstable under heavy hydrodynamic loading, which may lead to collisions and damage of surrounding infrastructure. The way that such elements are introduced, their hydraulic properties, and the properties of the rock protection are design parameters that require attention for minimizing any technical risks. Test results highlight the importance of avoiding areas of the scour protection where significant flow amplification is expected such as near the monopile face as well as areas with large reshaping potential, either due to ambient hydraulic loading or due to edge effects. Next to accounting for the hydrodynamic shape and submerged weight of introduced materials, embedment into the rock layers and potentially even anchoring may be required to keep such elements stable, which is beneficial from an ecological perspective too. Tests finally highlight the importance of accounting in eco-friendly scour protection design for sediment infill, which may compromise the effectiveness of providing shelter holes for biota and attachment substrate.

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