Eco-friendly Scour Protection Design Around Offshore Foundations

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ABSTRACT

Increasing offshore wind farm developments have several effects on the surrounding marine environment. The presence of offshore wind farm foundations may influence the marine ecosystem.

The offshore wind farm foundations are protected against scour by installing scour protection systems. These traditional scour protection systems can be optimized by introducing eco-friendly solutions which increase the native biodiversity and population of the targeted species. In this paper, the details of this optimization are elaborated based on a planned offshore wind farm project in the North Sea. Following a systematic literature review on eco-friendly scour protection solutions, the published guidelines were assessed to determine the most suitable nature-based solution for the project, yielding two options that would best satisfy the project requirements. Based on an overall assessment, the summary of the pros and cons identified for each proposed solution are presented.

In this paper, following a systematic literature review on eco-friendly scour protection solutions, the methodology adopted for designing eco-friendly scour protection around monopile foundation is presented.

INTRODUCTION

It is a fact that offshore wind farms (OWFs) are proliferating globally. However, the footprint of these structures may affect the natural habitat and damage the marine life. Therefore, new ways of integrating the structural elements with marine life are arising more and more in the offshore wind industry. A nature inclusive design (NID) refers to options that can be integrated in or added to the design of an offshore wind infrastructure to create suitable habitat for native communities whose natural habitat has been reduced. NID options can be part of a foundation structure, a scour protection layer, or a cable protection measure (Hermans et al (2020)).

The development of benthic communities on hard substrates including rocks around the foundation of the turbines for scour protection was qualitatively (species composition and covering percentages) and quantitatively (numbers and biomasses of species present) assessed by Bouma, S et al, (2012) approximately two years after the construction of the Egmond aan Zee (OWEZ) wind farm. The results of this study were compared with the results of similar studies in the C-power wind farm in Belgium and the Horns Rev offshore wind farm in Denmark. Results indicated that with the introduction of hard substrates in the form of scour protection layers was facilitated the establishment of hard substrate communities with characteristic hard substrate species that were not present before the realisation of the wind farm. At least 55 hard substrate species were identified on hard substrates within OWEZ.

Clear definition on which NID options should contribute to the native biodiversity on what scale has not been present in the literature. However, there are number of detailed studies sharing the research results which created base for this study. Hermans et al. (2020) presented reference estimations based on a reference offshore wind farm located in the Dutch North Sea, to address the concept of scale in relation to the ecological benefits of an NID option, as well as its cost. Another detailed study by Lengkeek, W et all, (2017) was performed providing explicit steps towards realizing an eco-friendly design of scour protection and a practical field experiment to allow for scientific evaluation. It is concluded by Lengkeek, W et all, (2017) that scour protection design could be altered to benefit the ecology, but that new designs will require additional testing for anti-scouring effects.

Scour protection elements might be used to act as an artificial reef in OWFs, but this needs further assessment and research from the industry. In this paper, a case study of a scour protection eco-friendly design is presented, where different alternatives were considered. Traditionally in a scour protection design, there are many inputs to consider, such as structural dimensions, shapes, seabed composition and hydrodynamic climate. However, in the project that is presented in this paper, an assessment was done to decide what NID elements could be best integrated into the conventional or base scour protection design. The assessment was done considering particularities of the project like seabed mobility, metocean conditions and structural geometry. The project presented in this case study was on a pre-FEED stage.

PROJECT DESCRIPTION AND LOCAL CONDITIONS

The OWF of this case study is projected to be located in the Dutch North Sea and the wind turbine generators (WTGs) were intended to be built with monopile foundations. It was defined by the developer that scour protection was needed for all the monopiles.

It was identified that the shallowest location was at 24.6 mMSL and the deepest location at 32.4 mMSL. The distribution of water depths at the project site is presented in Figure 1.

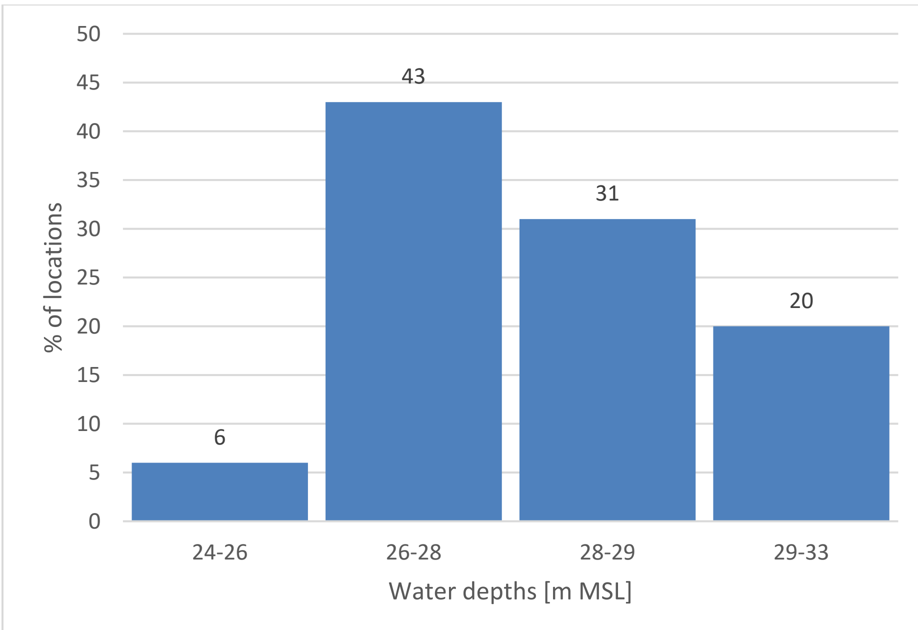

Figure 1 - Distribution of water depths at the project site

The topsoil at the site consisted of mainly fine and medium sand with a D_{50} between 0.150 and 0.250 mm. Regarding the metocean conditions, a desk study provided by the employer in Fery N. et al (2020) gave the approximate extreme metocean conditions in Table 1. A return period of 50 years was considered in the design.

Table 1 - Extreme metocean conditions, Fery N. et al (2020)

$H_{s,50}$	$T_{p,50}$	$U_{c,av50}$	HWL	LWL
7.5 m	12.2 s	1.0	2.6	-1.6

A special concern in the project was the seabed mobility. According to a desk study provided by the employer, sand waves are a dominant seabed feature in the site. It is expected that sand waves of up to 6 m might occur. A detailed investigation of the morphodynamics in the site was delivered by the developer, where expected seabed lowering, and rising maps were created for the period of 40 years.

It was a requirement for the proposal of the NID elements to ensure that they wouldn't be covered by sediment, slide or roll off the scour protection during the service life of the project.

Therefore, the coordinates of the WTGs were combined with the expected seabed rising maps and a zone was assigned to each location depending on which zone it would be installed on. Accounting the scour protection footprint, a conservative coverage area with 50 m diameter was chosen for each WTG coordinate point.

35% of the WTG locations were expected to lay within a zone where seabed rising or lowering is expected to be between 2 and 4 m.

DESIGN WORKFLOW

Like in every scour protection design, it is first recommended to do an assessment on the site conditions, considering the wave and wind climate, sediment properties and geotechnical conditions, among others. This should be followed by a traditional design of the scour protection and when these conditions are known, the eco-friendly solutions can be adapted to them.

The details of the process in the eco-friendly design are explained in the following sections but it is important to mention that these should always be adapted to the stability conditions of the base scour protection design and not the other way around. Figure 2 shows the recommended design workflow for an eco-friendly scour protection.

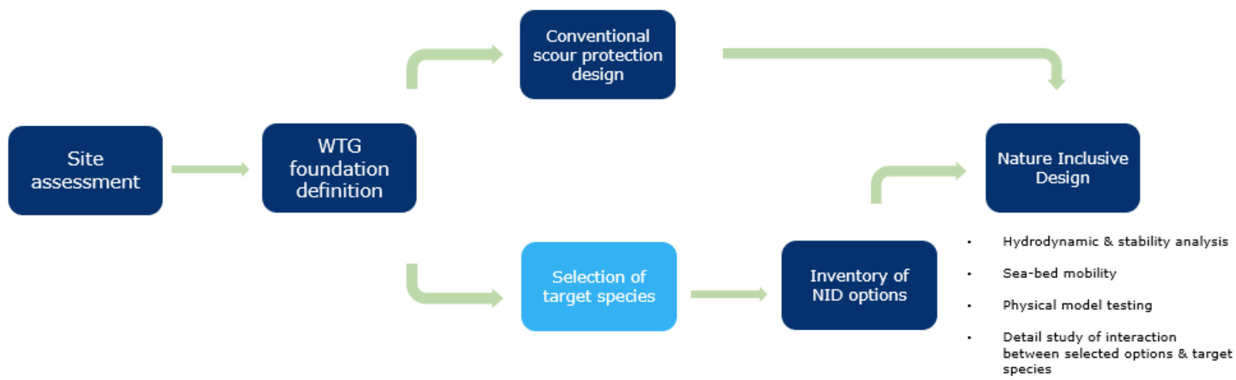

Figure 2 - Design workflow for an eco-friendly scour protection.

SCOUR PROTECTION CONVENTIONAL DESIGN

It is first recommended to define the dimensions and the minimum requirements of the scour protection. From that point, suitable NID elements would be proposed according to the scour protection characteristics.

A conventional design process for the scour protection was followed. For the rock stability, the design was based on the method suggested by Boon et al (2004), where threshold bed shear stresses for the stones are compared to the actual maximum shear stress.

The filter layer thickness was designed with the methodology given in Verheij et al. (2010), van de Sande S et al. (2014) which relates the required filter layer thickness to a characteristic diameter of the filter material considering the influence of the grading of the filter and base material, the influence of turbulence and the damping of the hydraulic load in the filter.

The filer layer top extent (radial distance from monopile center) was assumed to be 2 times the monopile diameter, while the top extent (radial distance from monopile center) of the armour layer is recommended to be 1.5 times the monopile diameter in reference to pile center

The rock stability of the armour layer is related to the water depth and if the required rock grading is large enough, a filter layer would be required to protect the seabed against winnowing and to increase the stability at the intersection of the armour layer and seabed. The rock gradings for the base scour protection design are presented in Table 2.

Table 2 - Rock gradings for the base scour protection design.

<table>
<tr><th colspan="2"></th><th>Rock grading</th></tr>
<tr><td colspan="2">1-Layer System</td><td>CP 90/250 mm</td></tr>
<tr><td rowspan="2">2-Layer System</td><td>Filter Layer</td><td>CP 63/180 mm</td></tr>
<tr><td>Armour Layer</td><td>LMA 40-200 kg</td></tr>
</table>

According to the design clusters, the 1-layer protection system was proposed to be applied in 20% of the locations, while the rest would require a 2-layer protection system.

ECO-FRIENDLY SCOUR PROTECTION DESIGN

The intention of the project was to optimize the conventional scour protection design by introducing eco-friendly solutions which would increase the native biodiversity and population of the targeted marine species. Therefore, several options were assessed to determine the most suitable NID solution for the project, yielding in two options that would best satisfy the project requirements.

A comparison of the available solutions in the market was done for the assessment. The first assessment criteria was based on the species that any given solution would attract. Target species were defined by the client as Atlantic Cod, Poor Cod, European Lobster and Crab. Furthermore, any solution which attracts oyster was not included in the preferred solutions since oyster was not the target species.

The cost of the solution was also considered, which was based in Hermans et al (2020). A cost based on a reference wind farm comprising of 60 monopiles with 2 elements per monopile and 20% of scour protection area was considered.

Table 3 and Table 4 and show the summary of the assessment on each solution. However, it was agreed with the developer that at this stage of the project, the chosen alternatives shouldn’t be defined by a specific brand or manufacturer, so a generic solution was proposed.

Two solutions were then proposed for further assessment:

1. **Protection layer with larger rock grading** (Figure 3)
    - This solution allows variation in crevices size and may accommodate better the targeted species.
    - The armour layer in the proposed 2-layer protection system can be used for this solution since the grading in the armour layer complies with the requirements for the crevices.
    - This solution would be the most practical/economical option; however, the solution doesn't fulfil the innovation criteria.

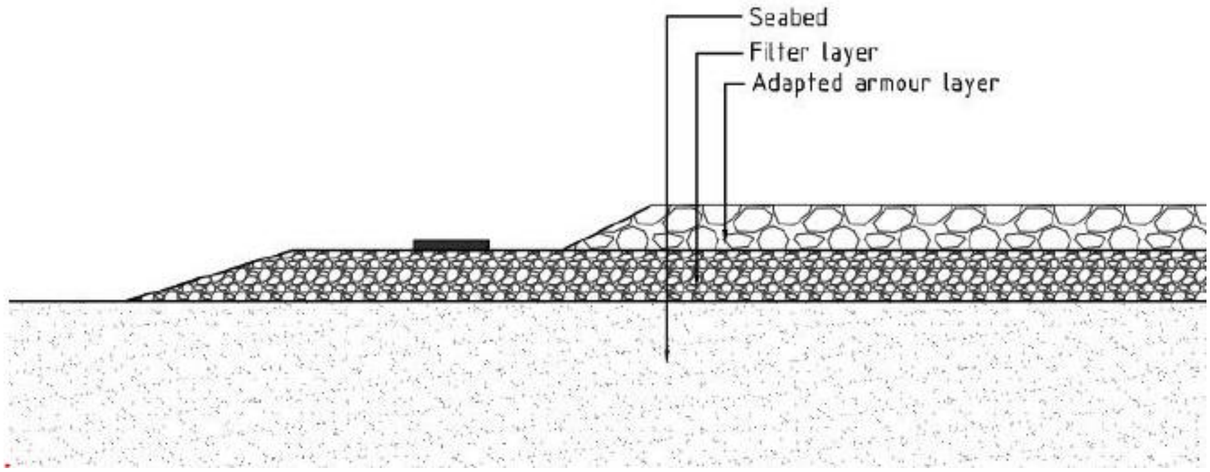

Figure 3 - Adapted grading armour layer, Hermans et al (2020).

2. **Habitat pipe** (Figure 4)
    The implementation cost for this solution is relatively low and it fulfils the innovation criteria as the project requirement. Some of the specifications for the units are provided in Hermans et al (2020). and are summarized here:
    - One of the pipe ends must always be accessible
    - The units should have min 4 holes with min 10 cm and max 30 cm to guarantee water exchange
    - Design geometry: 5m of length, 1m of diameter and 25-50 holes to enhance the effect on smaller pieces like juvenile cod and crab. The preferred material is steel, since it is a more suitable material for the target species. Concrete might be used as well; however, it would be more suitable for the settlement of oysters, which is not a target specie.
    - Proposed layout: 2 elements per monopile.

The habitat pipe solution needed to be assessed for its hydrodynamic stability and the likelihood for being covered by sedimentation. These assessments are presented in the coming sections. NID units should be located sufficiently far from the foundation structure so that they wouldn´t feel the impact of flow amplification effects.

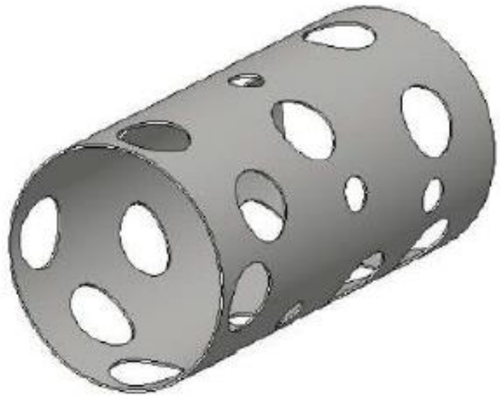

Figure 4 - Habitat steel pipes, Hermans et al (2020).

Table 3 - Comparison of eco-friendly solutions (1 of 2).

Solution	Target Species				Non-target Species	Innovation	Total cost per 2 NID elements	Pros	Cons
	Atlantic Cod	Poor Cod	European Lobster	Crab	Oyster				
Additional Rock Layer	yes	yes	yes	yes	No	No	€ 19,079.00	- 83% of the locations are within zone 1 of seabed rising, which means that in these locations it is less likely that the cavities would be covered by sediment - No need to look for more additional suppliers and the installation procedure is very well known	- No Innovation - High additional costos - More quarry material needed, which is not environmental friendly and would be contradictory to nature inclusive
Adapted grading armor layer	yes	yes	yes	yes	No	No	€ -	- 40-200 kg Grading is proposed in the base design with a rock density of 2,650 kg/m^3 - 40-200 kg Rock grading in the armor Layer satisfies the cavitiy requirements - 83% of the locations are within zone 1 of seabed rising, which means that in these locations it is less likely that the cavities would be covered by sediment - Additional costs are neglected. The 2-layer base design is already nature inclusive	- No innovation
Habitat Pipes	yes	yes	yes	yes	No	yes	€ 4,253.00	- Hydrodinamic stability to be assessed with supplier to determine size of elements. The technology with concrete pipes has been tested by Deltares - If steel pipes are used, it is not suitable for oysters which is not a target specie - Innovative solution	- MOSES project uses concrete pipes, which would also attract oyster - Steel would require a special coating to avoid corrosion

Table 4 - Comparison of eco-friendly solutions (2 of 2).

Solution	Target Species				Non-target Species	Innovation	Total cost per 2 NID elements	Pros	Cons
	Atlantic Cod	Poor Cod	European Lobster	Crab	Oyster				
3d printed reef	yes	yes	yes	yes	yes	yes	€ 8,546.00	- Flexibility in shape and size. Hydrodynamic stability could be reached if the correct shape is developed	- An investment in research would have to be made in order to find the correct size and shape of the elements - Higher costs of implementation - Uncertainty on its development
Reefballs/Layer cakes	yes	yes	yes	yes	yes	no	€ 6,558.00	- Well defined installation procedure	- Creates a growing habitat for oysters, which is a non-indigeneous species - Looks more suitable for shoreline projects
Fish hotel	yes	yes	yes	yes	No	yes	€ 3,179.00	- Cost effective - Innovative solution	- Looks more suitable for shoreline projects - Looks difficult to accommodate and stabilize in scour protection layer
Reef cube	yes	yes	yes	yes	yes	yes	€ 6,297.00	- Innovative solution - If the size is adjusted, hydrodynamic stability could be achieved - Good research on the product available.	- Material designed to enhance the settlement of european oyster
Eco Armour blocks	yes	yes	yes	yes	yes	yes	€ 8,347.00	- The molds can be adjustes to a required size for hydrodynamic stability - Concrete meets several standards - Inquire the supplier to see if texture could be modified or apply a coating to avoid settlement of oysters	- Higher cost of implementation

PROPOSED LOCATIONS FOR ECO-FRIENDLY SOLUTIONS

It is first assessed which locations would be suitable for a nature inclusive design. According to the seabed mobility (lowering and rising) assessment, 65% of the locations are qualified as suitable for an eco-friendly design. The rest of the locations are threatened by a change in seabed level greater than 2 m. Which means that if NID elements are placed in these locations, they would be either covered by sediment or have the risk to fallout from the protection layer.

As explained in the previous section, the seabed mobility maps were combined with the WTG coordinates. From these combined maps, the most suitable locations were chosen for eco-friendly design. These locations are shown in Figure 5, indicating the locations where installing the NID solution would be most beneficial.

Solution 1 would be applicable to only 2-layer scour protection system since large grading of armour layer is required. Solution 2 can be applied to both 1 and 2-layer scour protection systems.

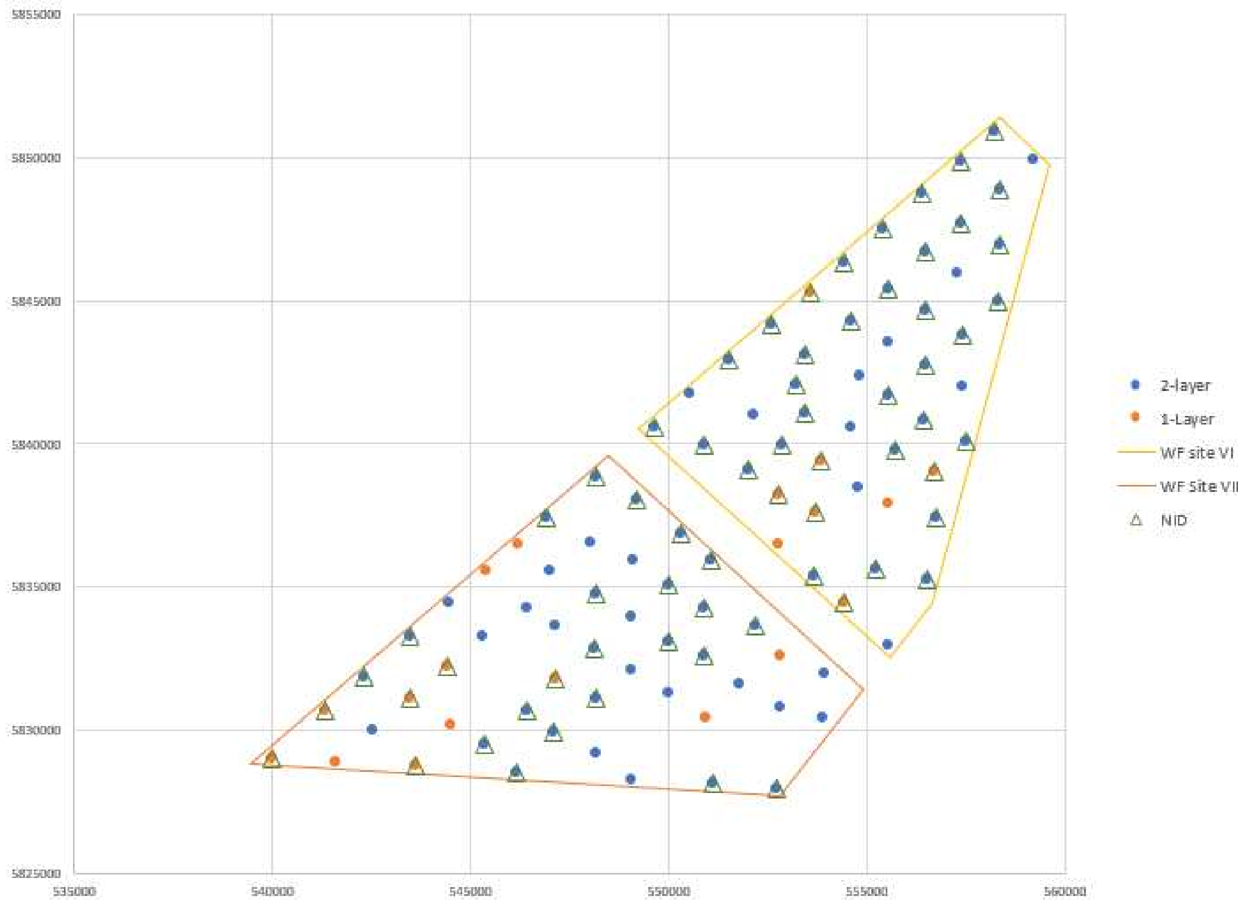

Figure 5 - Layout for Scour protection system and NID suitable locations

HYDRODYNAMIC STABILITY

Two solutions were proposed for an eco-friendly design. The first solution, which is the adapted grading armour layer, is already stable since its assessment was done in the scour protection conventional design.

The second solution, which is to include Habitat Pipes embedded into the armour layer, needed an assessment on its hydrodynamic stability. Stability conditions were assessed for combined current and waves conditions.

The pipes would be subjected to forces from the wave and current, and the assessed structure would have to remain stable against both drag and lift force. Stability for the horizontal forces is produced by the friction force created between the pipe and armour layer. The stability for the vertical force is produced simply by the submerged weight of the pipe. It was also assumed that the pipes would be partially buried in the armour layer, which would be positive for its stability.

The pipes were proposed with a diameter of 100 cm, steel thickness of 4 cm and 5 m long. These would be the required dimensions to reach the pipe hydrodynamic stability. It was recommended to bury the pipes as much as possible to reduce the disturbance in the flow area, however a minimum burial depth of 30 cm was given for the proposed dimensions. With these dimensions the hydrodynamic forces and stabilizing forces were calculated, yielding in the following results for a 1-yr extreme period and a 50-yr extreme period. The calculations were based on the theory by Mutlu and Fredsøe (2006).

It must be noted, that since the pipe should have holes to allow the species to settle, it is not a regular structure to assess with theoretical formulations. Thus, further investigations and possibly physical model testing would be required to assess the solution stability.

CONCLUSION

In the case study presented on this paper; the traditional scour protection design was adapted to an eco-friendly design to enhance the marine biodiversity within the OWF area. Two solutions were proposed to comply with the developers' requirements and industry recommendations.

The first solution is the most effective regarding the cost of implementation but has a lack of innovation. The second solution was a more innovative solution that would carry additional costs to the project. Both solutions are generic proposals due to the early stage of the project.

A theoretical approach was taken in this project to demonstrate that NID elements can be adapted to the traditional scour protection designs. However, there is still the need to complete pilot projects in order to fill the informational gaps regarding the documented benefits to marine environments where eco-friendly designs are implemented.

There is still a lack of research and literature about the effectiveness of the NID options available in the market. Most of them have been used on inshore areas and coastal protection projects, but there is very little information about the results obtained in offshore projects.

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