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COMPOSITE ROCK BAG SOLUTION FOR SCOUR PROTECTION AT A VERY EXPOSED LOCATION

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ABSTRACT

The present paper illustrates the different “alternative” scour protection options which were designed for a project at a location with extreme environmental loads. Geotextile bags were designed and tested in a model laboratory with different sizes and configurations. The laboratory tests showed extensive damage. The feasibility of a rock bag solution was then assessed. The main challenge was that little had been done in the past; rock bags have been primarily used in rivers, and little was known on how they behave under wave loading. Challenges were the scaling of the rock bags and obtaining a layout which could be constructed at the site. A composite solution was adopted at the end, whereas the rock bag extent was limited to the area around the monopile where the amplification of the flow is the largest, with the rest consisting in an armour rock berm over a filter layer. Layouts, design challenges and constructability matters are discussed in this paper.

1. INTRODUCTION

As the world sees a boom in renewable energy, more and more projects are being designed and executed at locations which are challenging and would otherwise have been discarded in the past. These are sites having difficult geotechnical conditions (presence of soft clay or hard rock, with large moving morphological features, risk of earthquakes) or extreme metocean conditions (large waves, breaking waves, risk of tsunami etc.) or very shallow water.

The authors has recently been involved in the design of an offshore wind farm in an area subject to severe hydrodynamic loading due to large typhoon waves in relatively shallow water. The impracticality of using the typical rock protection led to an experimental campaign to first design and then test the stability of alternative scour protection solutions. The campaign proved to be particularly difficult given the insufficient literature and as-built examples available for the selected alternatives. Even when examples were available, it was not possible to scale them to the extreme conditions at the site, or these had not been in place long enough to be exposed to extreme conditions proving they were correctly designed. Constructability proved to be a showstopper for many alternatives, given the high installation costs.

As part of this paper, the authors will go through the design steps which led to the applied solution, this consist of a combination with rock bags and a rock berm. The solution was obtained after several rounds of discussions with the client, the contractor, the vendors and finally the laboratory where the solution was tested.

The following disclaimers are needed prior the start of the paper:

1) The following paper has no intention to provide a guideline on design for rock bags. The scaling of such units is complex, and the placement depends on the contractor's experience and construction equipment. Caution should be made in case it is to be replicated elsewhere.
2) It is not possible to disclose the name of the project nor the exact location where it was constructed. Some specific information has thus intentionally been left vague or slightly re-adjusted for the sake of anonymity. The authors have nevertheless carefully kept all relevant information, which is of importance for understanding this paper.
3) The paper focuses on design aspects, challenges in the laboratory and constructability aspects. It is not the intention of the paper to discuss matters related to the scaling of the rock bags in a model laboratory, and reference is made to extensive literature (for example Riezebos H. (2021)) which has been produced by the research in part generated by this project a year after its execution.

2. THE SETTING

The offshore wind farm was planned to be located at an exposed site, having water depths between 14 m and 28 m on a seabed with a slope of about 1:200. The seabed was composed of mostly sand and silt or a mixture of these, and thus considered susceptible to large scour depths. The seabed was also considered stable with no moving morphological features, and thus with no risk of seabed lowering.

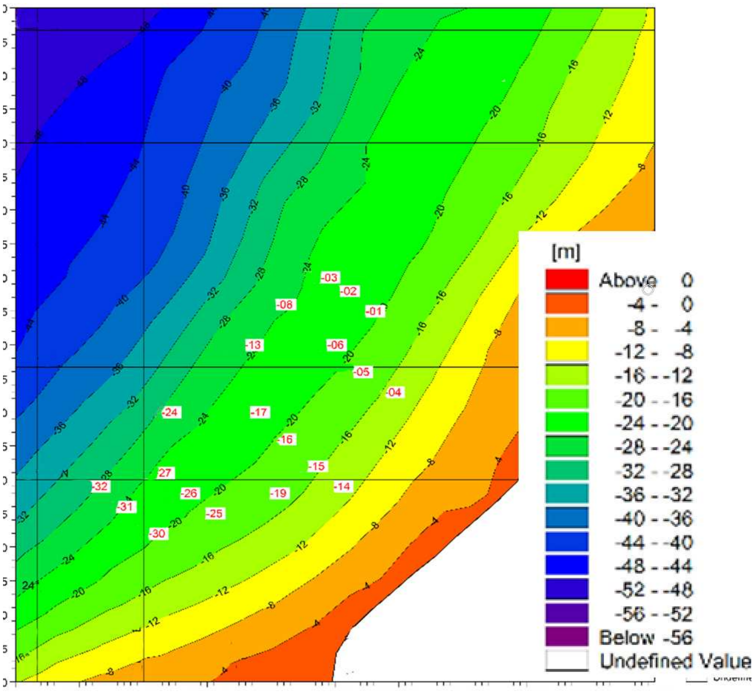


Figure 1 Locations (numbered) of WTGs on bathymetry.

With offshore design waves conditions in the order of 12m, see Table 1, 70% of the monopile locations was located at less than 24m water depth, with a design low water level of about 2m. The site was classified as a "shallow water site" subject to breaking waves. The shallowest location had a depth of about ~16m during the 50 year RP event, the deepest ~30m.

Table 1 Design wave conditions at offshore buoy located at 24m depth.

Design conditions	Return period [Years]			
	1	10	50	Overload
H_s [m]	4.2	10.0	**12.0**	13.2
T_p [s]	8.7	13.4	14.4	15.1
u_c [m/s]	0.8	1.1	1.4	1.4

3. FIRST DESIGN ITERATION

The first challenge for the design of the scour protection, was to determine the design wave conditions. The waves in Table 1 were in fact valid for a location at 24m water depth, while most of the WTGs were in shallower water. Waves were determined, as a fist attempt, by using the GODA wave transformation theory. The obtained waves were then transformed into wave orbital velocities by using the stream function formulations. Calculations showed that nearbed orbital velocities were well beyond 3.5m/s at the shallower locations.

The Shields parameter was calculated based on Mutlu (2002) with wave friction factors determined with Roulund (2016). The design of armour stones was then carried out by COWI's best practice, based on similarity of the armour stone mobility number between the project conditions and selected physical model test results from COWI's database. As common practice, similarity was based on the Shields parameter, θ, and the Keulegan-Carpenter number, K_C, which is the dimensionless expression for the wave particle stroke length relative to the monopile diameter D_p. If two locations have close K_C number this means that the flow patterns and stress amplification are similar; a smaller K_C gives more benign impact, while larger K_C values call for conservatism regarding the armour stone size. Calculations were made for different water levels, water depths and design conditions.

It was apparent from the start that similarity was not possible, given that for most cases, the K_C number calculated was outside the database. Even disregarding this, which is not correct, the rock size using mobility ranges known to COWI for the project, resulted in rock size for the shallow water in the order of 3-6t rock and 200-500kg for the deep-water locations. Rock sizes are larger than what is used in the Offshore Wind industry and in any case outside the range of applicability of the design methodology itself.

In conclusion, the preliminary assessment showed that conventional scour protection was not a solution. Alternative systems had to be investigated with physical model to be performed to verify them.

4. ALTERNATIVE MATERIALS TO ROCK

Alternative systems to the rock protection are geotextile sand containers, rock bags (also called filter units), artificial fronds, concrete blocks, concrete mattresses, ballast mattresses etc. Of these, three solutions were initially selected: sandbags, rock bags and concrete blocks.

Geobags (or sandbags) are large geotextile containers filled with sand, which are sized to be hydraulically stable against displacement from currents and/or waves. The fabric for the geobags is a heavy-duty needle punched non –woven material, which is permeable to water but not to sand. An example of sandbags is shown in Figure 2- left side. Apart from easy construction, one of the main advantages of the geobags, is that there is no need of a filter layer between the protection and the seabed. Furthermore, winnowing (loss of sand through the filter and armour layers) will not occur. The thickness of the protection is relatively small leading to a reduced risk in secondary scour effects around the protection and where the cables are buried.

Rock bags consist of large, wired bags filled with small aggregate. They are primarily used in rivers, especially at bridge abutments, or in offshore wind as cable protection (though at the time of the project their application in offshore wind was limited). Differently from geobags, rock bags have the characteristic of having a large base with a relatively small height (ratio of about 4:1). The main vendor is Kyowa co Ltd, who produces the bags standards sizes: 2t, 4t and 8t. The size of the bags and the rock filling is shown in Table 2. Figure 2-right side shows an example of rock bags protecting a riverbank.

Figure 2 Example of geobags (left) and rock bag protecting a river bank (right) (from the web)

Table 2 Characteristics of rock bags as per Kyowa website.

Type	Mesh size	Stuffing stones*1 Particle diameter	Unit weight, Filter Unit empty	Dimensions in meters, Filter Unit installed		
				Diameter	Height	Vol
2t type	25mm	50～200mm	6kg	1.9m	0.4m	1.24m^3
4t type	25mm	50～200mm	13kg	2.4m	0.6m	2.5m^3
8t type	50mm	75～200mm	48kg	3.0m	0.7m	5.0m^3

Concrete mattress consists in a geotextile with interconnected articulating concrete blocks of different sizes. For application in offshore wind a grouted connection is applied between the mattresses and the surface of the monopile, see Figure 3. Concrete mattresses have typically been applied for propeller scour protection in harbours with limited application in offshore engineering.

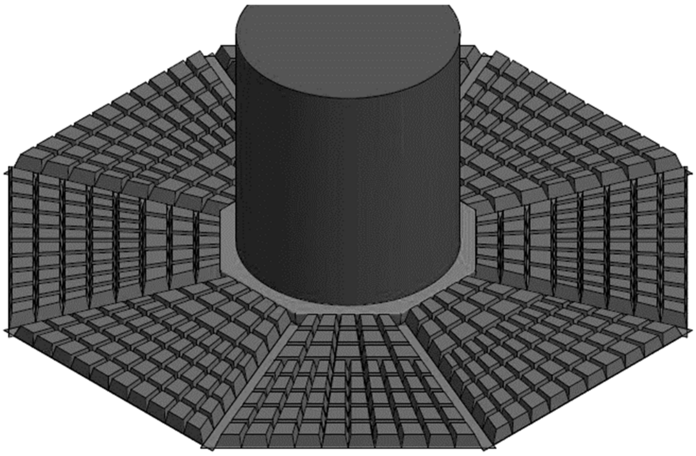


Figure 3 Ideal configuration with concrete mattress around a monopile.

5. SCOUR PROTECTION DESIGN

Of the above three alternatives, due project and laboratory related time constrains and material availability, only two solutions were brought forward to the concept design stage: The geobags and the rock bags.

5.1 Scour protection using geobags

COWI has extensive experience with the use of geobags in river engineering in conditions experiencing high loads, as for example geobags working as part of river training structures along the river Padma in Bangladesh and thus subject to a >5m/s design flow speed or as scour protection for the Sutong Bridge, O.Jensen (2006), with velocities up to 3m/s.

Also there is experience with the use of geosynthetics for:

- toe protection /falling apron for permanent structures exposed to current only conditions
- temporary beach protection for small wave/cross currents conditions
- breakwater core filling

The authors did not, at the time of the project, have experience with the use of geobags in offshore engineering in wave dominated conditions. The only project example available in literature was a paper form Peters (2012) describing how geobags had been used in the Amrumbank West offshore project. This was a project with monopiles with a diameter of D_p=3.5m, depths of around 23m and geobags of up to 1m^3 in volume.

Several questions remained un-answered in the paper:

1. What formulations had been used for the sizing of the bags? Geosystems are typically designed using Pilarczyk (2000), yet the structures treated here are slopes and not horizontal submerged scour protection systems around monopiles.
2. It seemed unlikely that geobags have ever been used for structures experiencing breaking waves and orbital velocities up to and above 3.5m/s.
3. Even assuming that the bags themselves could be manufactured large enough, to be stable (external stability), how to assure the inner stability of the bags (i.e. the sand migrating inside the bags) does not lead to rolling failure?
4. What about the layouts? Geobags are typically placed in orderly patterns on slopes, this being possible given land-based equipment (though for toe protection they are dumped from barges). But what about at >24m water depths? Can the bags simply be dumped and expect that a full covering layer is achieved?
5. Assuming bags are dumped from the surface, how much are they displaced by currents and do they deform and change shape due to impact?

With the aim of later performing model tests, a design with 2 sizes of geobags was prepared: 1m^3 and 2.5m^3. The geobags were placed in 2 layers over an extent of 4-5 $D_{p.}$ Two layouts were considered: one with a chess like patter and one with scatter configuration, see Figure 4. Knowing that the configuration with a chess-like pattern would be difficult to construct. This configuration was tested with the purpose to get an understanding of the behaviour when exposed to current /wave conditions and the failure mode. It was not possible to gather any information regarding the internal failure due to sand displacement within the bag. This thus remained a project risk.

"Drop" tests were executed by the Contractor to understand the sinking behaviour of the bags under different current conditions and different drop scenarios (bags can be dropped horizontal, vertical, or sideways) and the changes in the shape and compaction of the bags due to the fall.

This enabled the contractor to gain an understanding on how the bags should be placed in case the solution proved feasible after the model tests.

Figure 4 Layout patterns for placement of geobags (right side shows construction in the lab).

4.3 Scour protection with rock bags

The rock bags/filter units are rock filled mesh nets. No specification of rock grading is provided by the vendor other than 'particle size' corresponding to lower bound vales given in Table 2. Particle size ranges 50–200 mm for the 2t and 4t, and particle size range 75–200 mm for Type 8t, with no further detail. The vendor provided, at the time of the design, threshold velocities for the units, see Table 3. The threshold velocity was valid for "grouped units" and for steady current in channels, i.e., not directly applicable to near-bottom wave orbital velocities.

Table 3 Rock bag types and dimensions (sources: http://www.kyowa-filterunit.com/feature.html)

Type	Mesh size (mm)	Height (m)	Dia (m)	Vol (m^3)	Particle size (mm)	Threshold velocity (m/s)
2 t	25	0.4	1.9	1.25	50-200	4.7
4 t	25	0.6	2.4	2.5	50-200	5.3
8 t	50	0.7	3.0	5.0	75-200	5.9

There was some literature available by HR Wallingford (2012), on the use of rock bags around a monopiles. These were general model tests where rock bags had been placed following different configurations (1, 2 or 3 layers) but all having a radial type of layout with the units placed in compact rings. The modelled wave conditions were mild with currents ranging, in prototype,

between 1.1 m/s – 2.5 m/s. For the given test conditions the observed damage was caused by edge scour rather than stability of the units. No test resulted in failure of the protection hence it was not possible to deduce the limiting conditions for stability.
Several questions remained un-answered:

1. What formulations to be used for sizing the units?
2. Rock bags may be stable for currents up to 5-6m/s but have they ever been used for structures experiencing breaking waves and orbital velocities up to and above 3.5m/s?
3. Assuming that the rock bags themselves could be constructed large enough to be stable (external stability), how to assure that the inner stability of the bags (rocks moving with the bag) does not lead to rolling failure?
4. What about the layouts? Is it cost effective and practical to place rock bags in rings?
5. And what about winnowing. Do rock bags need a filter layer underneath?

Aiming at performing model tests, scour protection around the monopile considering 2 sizes of rock bags, 4t and 8t, placed in 2 layers over an extent of 4-5 D_p was designed. Rock bags work in groups thus it was important to select a pattern whereas units were next to each other and at the same time on top of each other. This was performed to avoid suction through the gaps between units (this being inevitable given that units are round and not rectangular as the geobags). Furthermore, the pattern had to be constructable (rock bags cannot be dumped from a barge like geobags).

After several studies and discussion with the contractor, COWI designed a pattern that combined a square mesh and a triangular mesh concept, see Figure 5. This was prepared considering the following requirements:

- *constructability*: the units must be placed in lines using a beam, see Figure 6, considering one or max two directions only. This direction is dictated by the current on the day of construction.
- *high packing density and reduced gaps*: the units need to be placed such that they are tightly packed together. The units of the 2nd layer need to be placed on top of the gaps between units of the 1st layer while preserving the mesh pattern.
- At the outer perimeter, the units from the 2nd layer need to be restrained by units from the 1st layer, meaning that the width of the 1st layer is larger than the 2nd
- *tight placement at the monopile*: the units at the monopile need to be placed tightly in a ring for both layers. It is preferred these units are placed as single units or with a 2-beam system.
- s*mooth finished surface* with no/limited protruding units needs to be achieved

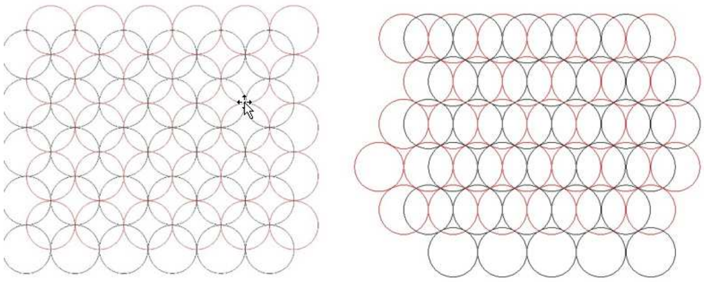


Figure 5 Example of triangular mesh and square mesh. Colours define the layer (2 in total)

Figure 6 Installation of rock bags in lines using a beam and single units placed with a rope.

To achieve the above, some minor overlap between units was necessary. Such overlap was tested in mock-up tests by the Contractor on land, whereas it was examined how much overlap it was possible to achieve without one unit ending up sitting on top of the neighbouring one with a large gap under it, see an example in Figure 7.

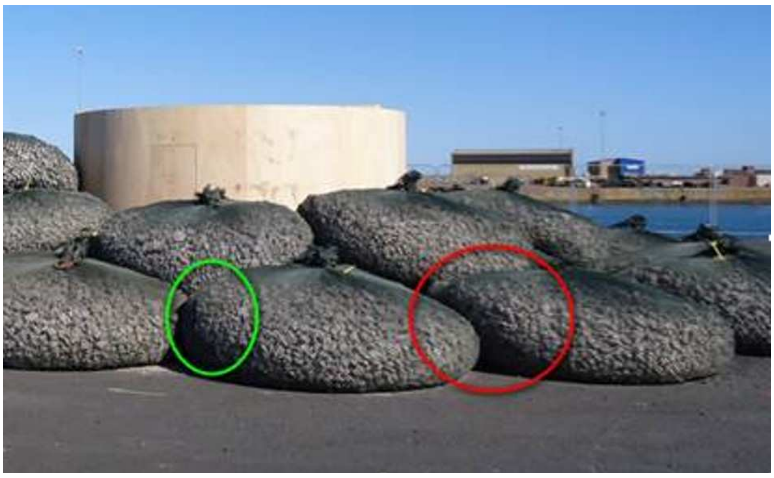


Figure 7 Example of a mock-up test with rock bags overlapping creating a gap underneath.

The layout for different monopile diameters and different rock bag units, the 4t and 8t was designed. It was unknown, during the design stage, which of the two sizes would work. Figure 8 shows an example of a monopile layout for one of the monopiles. Configurations are monopile specific as they depend on the monopile outer diameter D_p and the bag size. Figure 8 also gives a reflection on the number of lifts required to construct the scour protection with rock bags. In the specific case below the following was needed: 16 operations with a 2 unit beam, 31 operations with a 3 unit beam and 6 operations with a 4 unit beam for a total of ~ 150 units on the first layer only!

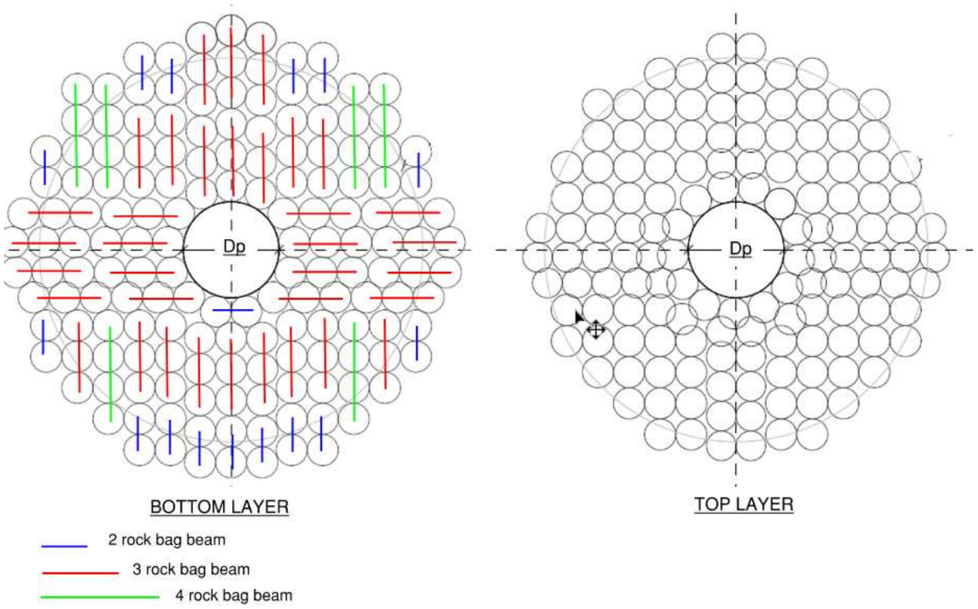


Figure 8 Example of pattern for placing rock bags with 1st and 2nd layer having triangular and square mesh and overlapping units. For the bottom layer, beam operations are shown.

4.3 Concept design of hybrid solution

Prior to the verification in the lab of both the geobag and rock bag solutions, it was obvious from the concept design study that the cost for building the scour protection with rock bags was not only very onerous, but also very time consuming. Even employing larger beams (holding up to 5 units) the number of operations was still large. Causing a significant construction period, which was not feasible given the narrow window for the construction phase. In case of geobags, it was unclear, even after the drop tests, if the geobags would cover the seabed in an effective way when dumped from the surface. Also, there was no clarity in the internal stability due to sand migration within the bags.

A hybrid solution was thus investigated, whereas the use for the rock bags was restricted to an area of $1D_p$ around the monopile, which is the area where the horseshoe vortex is the largest, and the rest was covered by the maximum rock size which can be installed with a fall pipe: the 60-

300kg grading. Figure 9 shows the construction sequence for the hybrid solution. This consists in:

1. placement of a mat of filter layer (gravel bed), this having an extent of about $5D_p$
2. placement of a donut shaped berm of 60-300kg rock around the monopile with a fall pipe. Side slopes achievable were 1:2.5. The outer edge of the berm was $4D_p$
3. Placement of first layer rock bags according to a pre-defined pattern (triangular/square mesh) between the berm and the monopile.
4. Placement of second layer of rock bags according to a pre-defined pattern (triangular/square mesh covering the gaps of the 1st layer) on top of the 1st layer and the inner side slope of the rock berm. Overall extent of second layer was $3D_p$.

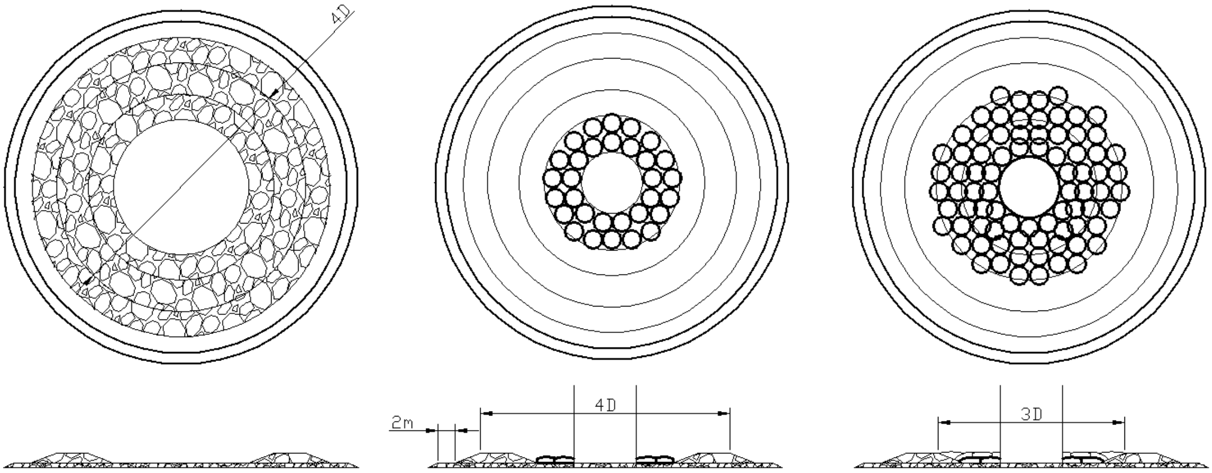


Figure 9 Hybrid concept with 60-300kg rock and rock bags in 2 layers, 4t size.

Though the number of materials for the hybrid solution was increased to three (gravel bed, 60-300kg rock and rock bags), the number of units was significantly reduced. This enabled the contractor to operate and complete the placement of the scour protection during the available weather window for construction. Also, the solution was preferable as it included a rock outer perimeter, this being able to mitigate edge scour.

6. PHYSICAL MODEL TESTS

The design was taken into a detailed design stage whereas all solutions were tested in a physical model laboratory. The largest challenges in the laboratory were to obtain the correct wave conditions at the shallow locations and to scale the units correctly so that all (or rather most) modes of failure were represented. The latter will not be discussed in this paper, given that the matter has object of many papers produced after the completion of this (Riezebos H. (2021) for example) and similar projects.

6.1 Wave transformation

As part of the scope in the physical model campaign, a wave transformation study was carried out in a long but narrow flume with a concrete floor to obtain the design conditions at the shallowest locations. A bathymetry with a 1:200 slope was constructed, see Figure 10, and along the slope, wave heights, and orbital velocities at four water depths, were recorded by means of wave gauges and electromagnetic velocity meter (EMS).

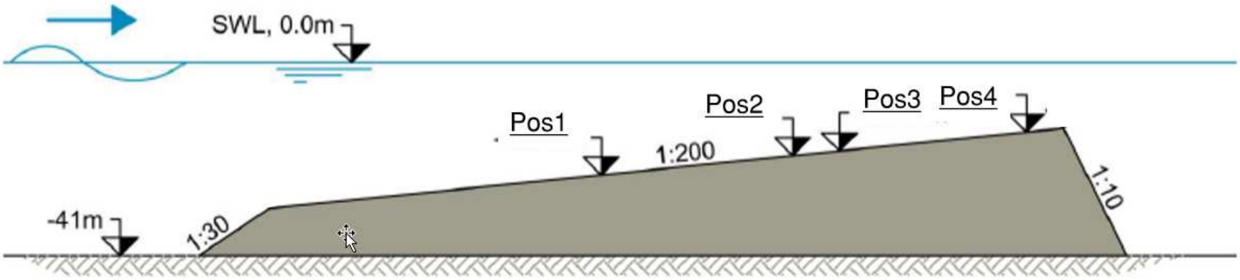


Figure 10 Bathymetry used in the flume (distorted scale) with four measuring positions.

Figure 11 shows the wave heights obtained for the different depths and return periods (left) and the orbital velocities (right). It is interesting to see that orbital velocity at almost all locations shallower than 24m was between 3.0m-3.6m/s for the 50 year RP conditions. Thus the increase of the water depth did not have a big impact on reducing the velocity.

The challenge came when the wave conditions measured in the narrow flume had to be reproduced in the larger basin where the scour protection model tests were to be carried out on a sandy seabed. In fact preliminary trials in the larger basin, showed that the maximum breaker parameter H_{mo}/d (wave height versus water depth) ratio that could be obtained in the basin was in the order of O(0.35). It was observed that in the basin wave breaking at the paddles was already present for the 10 year RP event.

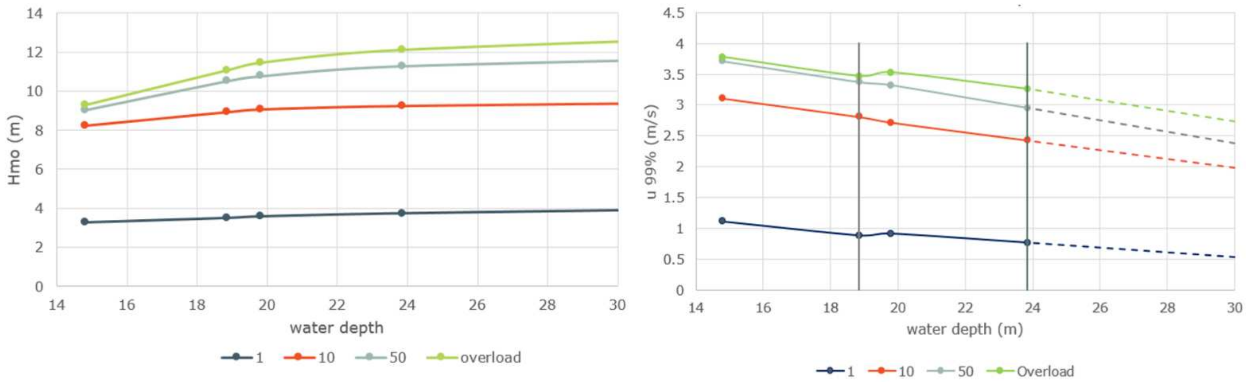


Figure 11 Results from wave transformation study, Hmo and wave orbital velocities.

It is well-known that basins are not able to reproduce the same wave breaker parameter as in prototype conditions, especially on a flat horizontal seabed. This is due to many reasons, including the friction from, side walls, bottom of the flume, and wave reflection etc. Which make wave generation very different from the prototype condition equivalent to in place conditions. This meant that it was not possible to reproduce the same wave spectrum in the large basin as that obtained in the narrow flume on a slope. As a solution, the calibration of the metocean conditions in the large basin focused on the wave orbital velocities rather than the wave heights.

6.2 Model tests

Once the basin was calibrated, three test series were considered:

- Test Series TS-A: waves only conditions
- Test Series TS-B: waves + following currents
- Test Series TS-C: waves + opposing currents

Each test series consisted of 6 runs with an increasing return event, this including a 5- and 20-year RP events. These additional runs were included to extrapolate results for deep water locations. The overload condition was not performed since velocities were like the 50-year RP event. A long duration test with tidal current was included at the very start (with a current u_c=0.4m/s) to have edge scour forming around the scour protection prior to the storm events. No repairs of the scour protection systems were done between test runs belonging to the same test series.

Initially three systems were tested, consisting of 2 sandbag sizes (1m^3 and 2.5m^3) and 1 rock bag (4t), each covering an extent of 5xD_p. For the sandbags, half the protection was modelled with a chess-like pattern and the other half with a random pattern. During the execution of TS-A, it became apparent that the scour protection solution with geobags was unstable, regardless the pattern, see Figure 12. Both the 1m^3 and 2.5m^3 sandbags were lifted and transported away from the monopile exposing the seabed. It was noted that the random patterns showed more damage than the chess-like pattern. It was thus decided to stop test TS-A and run TS-B with the 4t and 8t rock bags and the hybrid solution. Also, the scour protection extent was checked by splitting the layout of the rock bags solutions in half with a 4D_p on one side and a 5D_p on the other.

At the end of the test series, both the 4t and 8t configurations showed no considerable damage, apart from some rock bags having fallen into the edge scour hole. Inspection of hybrid solution showed instead that deformation to the 60-300kg armour rocks during the RP 50 had occurred with some loss of armour rocks at the outer edge of the berm on both the up-wave side and the in the wake (down-wave side) of the monopile. The armour rocks were indeed already mobile for return periods smaller than 50 years. Though at some spot locations it was found that the thickness of the rock berm had decreased by almost half. Yet the solution was accepted as suitable given that it kept its function as a support for the $1D_p$ layer of rock bags.

Additional test showed that rock bags can become unstable, if unfavourable placed. It was thus recommended that that special attention was taken with respect to the installation of the rock bags, such that no/little deviations to the installation pattern were introduced. With the strict installation tolerances and the introduction of a monitoring and maintenance strategy, the hybrid solution was implemented.

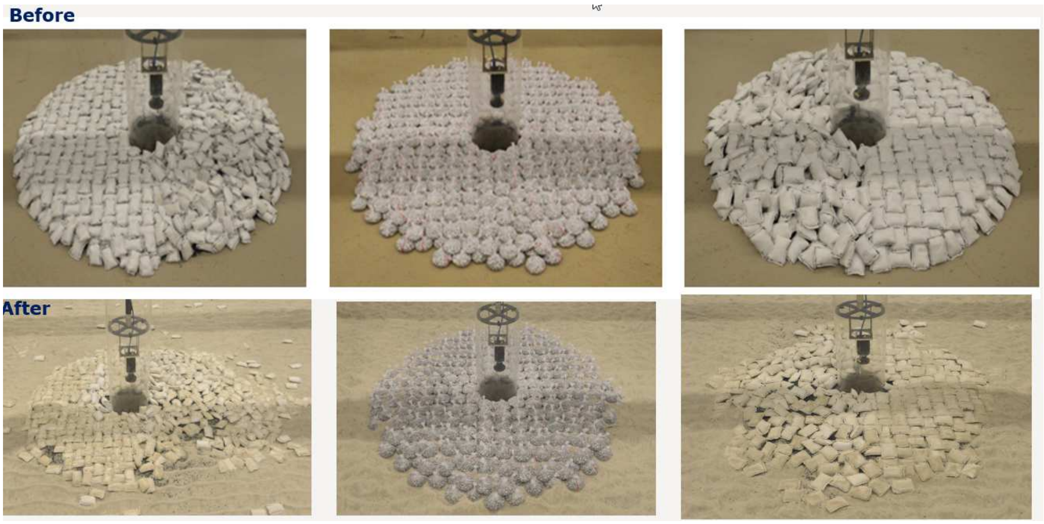
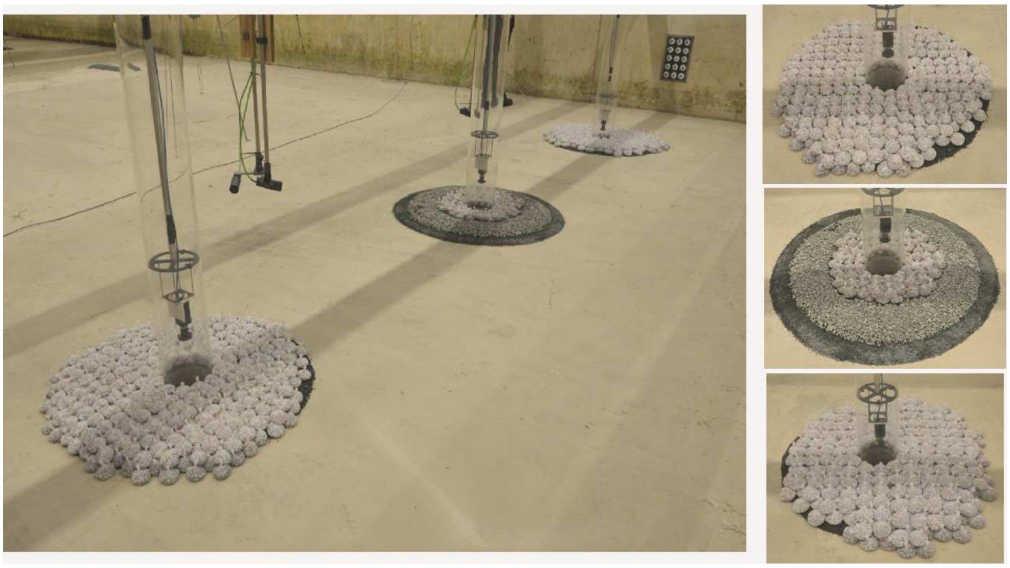


Figure 12 TS-A: $1m^3$ geobags (left), 4t rock bags over $5D_p$ (centre) and $2.5m^3$ geobags (right).



4t rock bags over $4\text{-}5D_p$

Hybrid solution with 4t rock bags over $3D_p$

8t rock bags over $4\text{-}5D_p$

Figure 13 TS-B: 4t rock bags, hybrid solution and 8t rock bags.

CONCLUSION

This work studied possible layouts for the scour protection systems at a very exposed location. Different scour protection systems were investigated: sand-filled geotextile bags, rock bags and a hybrid solution based on loose rocks and rock bags. The study was performed in a step approach, with constructability aspects considered together with design related matters. The combined performance of the hybrid solution (rocks and rock bags) appears to be the most suitable solution, conditioned by survey and maintenance of the armour rocks.

ACKNOWLEDGMENTS

COWI would like to thank the Client for allowing COWI to prepare this paper and share the findings of this very interesting project. COWI would like to thank the Contractor for the joint work in finding a solution which could be constructed at such an exposed location. Finally, COWI thanks the laboratory who assisted COWI with testing the solutions, both which were done as a first-time basis and thus required a lot of interaction and discussions with all parties.

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