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Scour Monitoring and Scour Protection Solution for Offshore Gravity Based Foundations

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ABSTRACT

In the first phase of C-Power's offshore wind farm project, six gravity based foundations (GBFs) have been installed 30km offshore of the Belgian Coast, on the Thornton bank in the North Sea. To guarantee the stability of the GBFs, a static scour protection system is designed. One of the challenges during construction is to define a realistic method so that the minimum required layers thicknesses are guaranteed, without placing excessive amounts of material. The feasibility of certain solutions, in relation to the applied equipment and the accuracy of measurements, all have to be taken into account. As a result of numerous discussions between client and contractor, the design has been optimised, been agreed on and immediately tested in practice, during construction of the first phase. Combined with an extensive monitoring program, this allows evaluation of the applied methods.

THE WIND FARM

Location & Construction

C-Power obtained a concession to build and operate a 300MW offshore wind farm for sixty 5MW wind turbines in the Exclusive Economical Zone of Belgium Continental Shelf. The concession area is located on the western part of the Thornton Bank, a sand bank situated approximately 30 km off the Belgian Coast (see Figure 1). During the first phase of the project, six 5MW wind turbines generators (WTGs) are built in sub-area A. The distance between the WTGs is about 500m. Depths vary on this location from -25m TAW to -18m TAW. TAW is the Belgian reference system which islocated 0.18m below mean low low water spring (MLLWS), and 2.29m below mean sea level (MSL) in sub-area A. The tidal range at spring tide is about 4m.

GBFs have been chosen since the design is less sensitive to a particular wind turbine type. Monopiles would have been costly and very difficult to install because of the presence of dense sand layers and stiff clay below the seabed. The GBFs consist of concrete caisson structures ballasted with infill material. Each GBF is composed of a base plate (Ø 23.5m), a conical section (Ø 17m to 6.5m), a cylindrical section and a top plate. The top plate is situated at +17m TAW (Figure 2). The height of the structure varies according to the depth at each location.

Placement

The foundation level of each GBF is 3.50m below Reference Seabed Level (RSBL). The RSBL is defined as the lowest seabed level during the life time (30 years) of the foundation, including the effect of migrating sand waves and the erosion of the entire area.

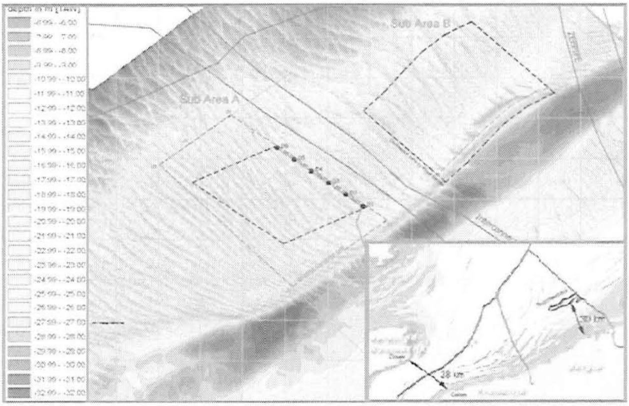

Figure 1 – Location of the 6 GBFs and bathymetry of the Thornton Bank.

For each GBF a foundation pit measured 50m x 80m at the bottom, is dredged some 4.8m below RSBL, with the main axis heading NE – SW. This layout is inspired by the prevailing current directions. Dredging occurred in two stages: (i) bulk dredging to remove the sand dunes and the top layer, followed by (ii) precision dredging to obtain a surface within the specified tolerances. On average, some 90000m^3 is dredged per foundation pit.

The foundation bed consist of two circular layers: (i) a filter layer from the dredged level up to 0.55m below foundation level, and (ii) a gravel layer up to target foundation level (Figure 2). The foundation beds are installed using a Dynamically Positioned Fallpipe Vessel. Per location, an average of 2500 tonnes of filter material and 1200 tonnes of gravel is placed. The maximum inclination of the gravel bed surface is <0.75° to assure verticality of the turbine towers and a proper transfer of the weight of the GBF to the subsoil. Precision levelling is achieved with a purpose designed tool, attached to the lower end of the fallpipe.

The GBFs are constructed onshore in Ostend. From there the foundations of about 3000 tonnes each, are transported towards the Thornton Bank by means of the heavy lift vessel *Rambiz*. At the location, the foundations are lowered on the previously prepared foundation bed. This is followed by the backfill and the placement of the scour protection.

THE SCOUR PROTECTION – DESIGN PROCES

The design of the scour protection is made for a 1 in 100 years return period. Design conditions are significant wave height H_{m0} = 6.3m, peak period T_p = 11s (duration 3 hours) and water level +1m TAW in combination with a maximum depth averaged current velocity of 1.2 m/s. Waves are non-breaking and waves and currents are assumed to be coincident. Maintenance has to be minimized and therefore a static design is chosen. Since for practical reasons, the stone size cannot vary from wind turbine to wind turbine, one stone size has been used. Stones should have a minimum weight of 2700kg/m^3 and a high crack resistance (e.g. >190MPa). The design of the scour protection is based on theoretical concepts and has been tested afterwards in a physical model. Due to restricted availability of material and execution methods, some modifications have been made afterwards.

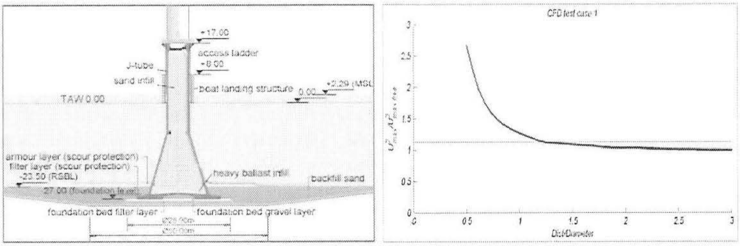

Figure 2 - Wind turbine foundation D6 (left); relative shear stress vs. the distance from the GBF centre (right).

Theoretical design

Given the design conditions and the water depth at each foundation, the required stone size for the armour layer is determined using the Shields criterion (Shields, 1936). As long as the Shields parameters due to waves and currents are smaller than the critical value, the stones are stable. For large grain size (dimensionless grain size $D^*>200$, corresponding to diameter $d>10mm$ for quartz grains in seawater), the critical Shields parameter equals 0.055 (Soulsby, 1997).

The calculation is performed for two locations: close to the GBF, and at the edges of the scour protection. Close to the GBF the current velocities are amplified due to the presence of the structure (factor 2 for a typical current profile around a pile); the bed is assumed to be flat here. For a 100 years return period, armour stones should have diameter 0.25m (or bigger) to be stable at the shallowest location (-18m TAW). At the edges the "normal" current velocities occur, in combination with a slope 1:5 of the armour stones. This leads to a reduction factor 0.75 of the critical bed shear stress, resulting in stones with a diameter $\geq$ 0.35m. The layer thickness of the armour layer is at least 2 times the median grain size D_{50}, which is 0.70m for this case (Hofmans and Verheij, 1997).

To guarantee a stable scour protection and to prevent stones sinking into the seabed, a filter layer is foreseen. A geometrically open filter is applied in order to avoid too strict criteria for the filter material, difficult placement and/or a second filter layer. The following filter material is proposed: standard grading 10/80mm, $D_{50,f}$ = 50mm with a wide gradation ($D_{85,f}/D_{15,f} > 5$). This has as consequence that the filter criteria for the original seabed material cannot be met. The coastal engineering manual (USACE, 2006) advises for these filters a thickness of at least 0.30m. However, to guarantee an effective clogging effect to stop migration of material through the filter pores and taking into the precision of bathymetric measurements, a minimum layer thickness of 0.60m was specified.

The extent of the scour protection has initially been chosen according to the guidelines in literature, mostly for monopiles. The diameter for the scour protection around a monopile is often taken at $4xD_{pile}$ (Sumer and Fredsoe, 2002; Escarameia, 1998). However, since the GBF is much wider and CFD modelling shows that an amplification factor = 1.12 of the shear stress is found at a distance of $1.2D_{GBF}$ (see figure 2) instead of at a distance $2xD_{pile}$ as for monopiles, the theoretical diameter of the scour protection could possibly be reduced to $3.5D_{GBF}$.

Physical Model

Physical model tests have been carried out at DHI (2007) to test the stability of the designed scour protection, the backfill and the filter bed during construction. The flume is 35m long, 5.5m wide and has a re-circulating current-flow generating system with generation of co-directional long-crested waves. Froude scaling law is applied and the tests are conducted at a linear scale of 1:52. The differences in densitiy of rock and water in model and nature were taken into account, and the gradings specified in the design were reproduced by combination of different gradations of sand and stones. The water depth in the model was 0.33m, corresponding to 17.18m in prototype. Since the backfill material is relatively too coarse for Froude scale modelling, the current is amplified by a factor 1.75-2.1 to obtain live-bed conditions. With such conditions, the scour in the backfill material will develop geometrically correct but with another time scale than calculated according to Froude scaling. So the time scale was corrected when interpreting the results. The velocity in the model varied from 1.2 to 3.6m/s.

The tests give an indication of the amount of scour to be expected in the backfill and the filter during construction. It is found that two big lobes form around the GBF under the average conditions, and that the filter material is vulnerable under moderate storm conditions, leading to local scour around the GBF (Bolle et al., 2009). This erosion pits also have consequences for the amounts of materials for the layer placed on top.

To check the armour stability tests are performed with the top of the armour layer 17m and 16m below the design water level. In both tests the armour layer was stable, although with the reduced water depth more erosion occurred at the outer rim of the protection (see Figure 3).

Scour protection lay-outs with different diameters are compared. Erosion occurred in all cases mainly at the rim, on the upstream side. The erosion is larger in tests with a reduced protection diameter, but the tests with diameters $2.5D_{GBF}$ (=37.5m) and $2D_{GBF}$ (=30m) show almost identical erosion. In all tests the rock displaced from the rim served as armour protection of the gentle outer slope.

Furthermore, the slope of the seabed at the edge of the scour protection is measured. In the performed tests a slope of about 1:4 developed.

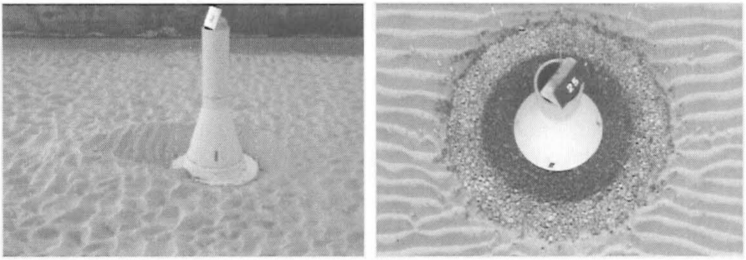

Figure 3 – left: backfill after test run with U_c=2.5m/s, without waves; right: scour protection with armour layer diameter 37.5m after 6 hours test with H_s=6.32m, T_p=11.6s, U_c=1.2m/s and water depth=17.18m.

First design proposal

Based on the results of the numerical and physical model tests a first design proposal is made. The scour protection system should be installed in four phases: (i) backfill of the foundation pits until -0.30m RSBL, (ii) installation of the filter layer (iii) installation of the armour layer up to maximum +1.00m RSBL and (iii) backfill of the area around the scour protection up to a level of +1.00m

RSBL (see Figure 4). The latter operation is proposed to create a smooth transition between the stones and the seabed, in order to minimise edge scour.

The characteristics of this design are summarised in Table 2. The extent of the filter layer is based on the diameter of the armour layer extended all around with about 2m to fully support the armour layer.

Besides the materials, layer thicknesses and extent; also execution tolerances are defined. The tolerances on the layer thickness are defined to guarantee the minimum required layer thickness. Therefore the tolerance on the filter layer thickness was defined as -0.0m and +0.25m, while for the armour layer thickness the tolerances were -0.0m and +0.35m. Concerning the diameter, only a minimum extent is defined.

For the geotechnical design of the GBFs the bottom levels that can be relied on should be specified. Therefore, a design line (see Figure 6) is defined based on following assumptions: the minimum level of the scour protection will be RSBL + 1.0m; the rim of the armour layer will smooth down to a slope of 1:5; at the edge of the scour protection 1m is taken downwards starting from RSBL; from this point on a critical slope (1:4) is taken based on the physical model tests. The further away from the edge of the scour protection, the less the local bathymetry will be affected. In order not to be too conservative the design line starts rising again after reaching a level of 7.0m below RSBL.

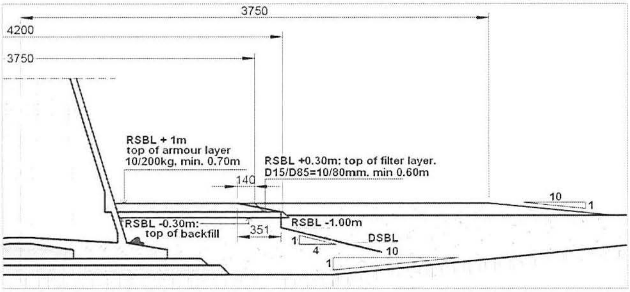

Figure 4 – First proposal scour protection system.

Modifications due to availability of materials

During construction the available material did not fit the initial requirements. On overview of target and actual properties of the filter and armour layer is shown in Table 2. For example the actual grading of the filter did not fit the requirements: although the D_{15} is small enough, the D_{50} and D_{85} are significantly smaller than those required in the final design. The advantage of the small D_{50} is a positive effect on the stability of the geometrically open filter.

To guarantee good functionality, this filter is however only acceptable in combination with a 10/200kg grading for the armour layer. A suitable grading for the armour layer is obtained by mixing 80% 40/200kg with 20% 5/40kg grading. Using this final armour grading, the filter rules between armour and filter material for a geometrically closed filter are fulfilled.

Concerning the extent of the scour protection, $2.5xD_{GBF}$ is not enough for geotechnical purposes. Due to edge scour, material (and thus weight) will disappear around the scour protection. To guarantee the stability of the foundations, the extent is increased to 44 to 58m, depending on location.

Table 1: Target and actual material specifications of the scour protection

target and actual specifications scour protection *(when different: actual in italics)*			
		filter layer	**armour layer**
mate-rial	**type**	crushed gravel *(hard, compact limestone rock)*	stones *(hard, compact limestone rock)*
	dimen-sions	10/80mm, D_{50} = 50mm, wide gradation $D_{85}/D_{15} > 5$ *(0/120mm, standard quarry material)*	10/200 kg, D_{50} = 350mm, wide gradation $D_{85}/D_{15} >5$ *(5-40kg and 40-200kg: 20% / 80% stone mixture)*
layer thickness or level		min. 0.60m	min 0.70m, top level = RSBL +1.30m / 1.45m
diameter or extent of layer		diameter min 42.0m *(48.5-62.5m for geotechnical purposes)*	diameter min 37.5m (=2.5D_{GBF}) *(44-58m for geotechnical purposes)*

Modifications due to execution methods

Based on discussions with the Contractor the first proposal is optimised to obtain a more economical execution. The installation of the scour protection in 4 phases was too time consuming and one stage is eliminated by installing the scour protection on top of the backfill installed up to RSBL. As a result the total scour protection is situated above the surrounding seabed. This implies that edge scour can become more important, and should be closely monitored. On the other hand this solution provides more weight on the edges of the foundation, which positively contributes to the overall stability of the GBFs. Allowing this modification requires execution tolerances to be strictly met in order to guarantee the stability of the armour stones under the design conditions. Not achieving the tolerances would lead to a too high top level of the armour layer, resulting in an instable armour layer at the shallowest locations.

For the area with the cable entrances it is discussed that additional scour protection should be installed over an area of at least 10m wide and 15m further from the GBF (see Figure 5). This adjustment is needed in order to guarantee the required cable burial depth of 2m.

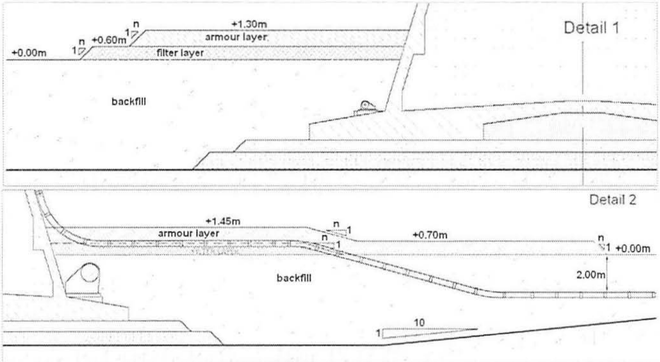

Figure 5 – modified scour protection system: detail 1 - normal configuration; detail 2 - at cable entry.

The tolerances for construction of the scour protection are defined to assure the minimum specified layer thickness, which is needed to guarantee the design seabed level for the geotechnical design. The originally defined tolerances of -0/+0.25m on the filter layer thickness and -0/+0.35m on the armour layer thickness are maintained, although hard to accept by the contractor.

Placement of the scour protection according to the method statement

The scour protection works are executed with an automotive fallpipe barge equipped with a fallpipe for rock placement and assisted by two anchor handling and general support vessels. One of these support vessels is equipped with a multi-beam survey launch. The automotive fallpipe barge has a main deck cargo hold capacity of approximately 3000T of rock materials, and has also been used for the backfill around the GBFs and the hydraulic infill of the GBFs. Furthermore a supply vessel, capable of transporting 2000T of rock material, was used for the supply, offloading and transfer of filter materials and armour stones. The hopper well of this vessel is equipped with an appropriate protection system against impact damage, especially when handling the armour rock stones.

Prior to the start of the offshore execution, stock piles of both filter and armour material are made onshore on a quay wall. These materials are then loaded inside the hopper well, from where they are transferred onto the main deck cargo hold of the automotive fallpipe barge by means of an offloading crane installed on board the supply vessel, while moored alongside the barge. The supply vessel is kept securely moored via the two constant tension mooring winches installed on the main deck of the barge, allowing easy offloading of filter and armour materials.

Six computer-controlled, hydraulically driven anchor winches allow movement along a predefined track. The six anchors are placed in advance and consisted of two 12T Delta Flipper anchors (bow and aft anchor), and four 9T Delta Flipper side anchors. One location is divided in six segments. For each segment a different anchor pattern is applicable, where positioning and tracking of the barge is executed by means of the 6 winches.

These are automatically controlled by a computer system that uses as input, among others, the LRK satellite positioning system and the gyrocompass installed on board. This continuously provides the actual position of the barge.

For storage of the rock materials on deck of the barge, a rectangular cargo hold is created by means of 2 meter high cargo hold coamings. This cargo hold is accessible for the materials handling crane for further manipulation of the materials inside the hold. Filter materials and armour rock are transferred from the cargo hold towards the fallpipe's feeding hopper using a conveyor belt and vibratory feeder system. The materials are discharged into the fallpipe chute and fall inside the fallpipe towards the seabed. A weighing device is installed at a belt section and included in the conveyor belt system, allowing the continuous monitoring of the rock quantities transferred and installed. This data serves as an input for the computer controlled automotive moving of the fallpipe barge along a predefined stone dump track.

The fallpipe height (typically 1 to 2 m above the target level of the layer to be realized) is automatically corrected for tidal fluctuations and swell using a hydraulic winch system steered by the board computer and supplied with the actual z elevation from the LRK satellite positioning system. Intermediate bathymetric surveys are performed after completion of each intermediate layer and the updated seabed survey introduced into the hauling computer.

In a first step a filter layer is placed in all sectors, after which the armour layer followed (in reverse order). Armour installation works excluded initially the installation of rock material in the segments at the bell-mouth locations and along the cable routes. At those locations, the armour layer is only placed after the installation of the cables. At the J-tube positions a trench is left open in order to ensure a smooth cable pull-in. After the cable installation (with cable protectors) the scour protection is then finalized.

MONITORING PROGRAM

During construction

The seabed around the foundations is extensively monitored during the works. For the six GBF's, multi-beam surveys are available from the seabed before the works, as well as the in- and out surveys of the different stages of construction, such as dredging of the foundation pit (April 2008), placement of the filterbed, gravelbed, GBF, backfill, filter and armour (end of January 2009). For the same period the hydrodynamic conditions are available from the stations from the Flemisch banks monitoring network, and an additional directional wave buoy installed on the Thornton Bank.

Operation and Maintenance program (O&M)

The O&M program consists of the execution of a multi-beam bathymetric survey of the scour protection and surrounding seabed in an area of 200m diameter around the six GBFs. This survey will be executed twice a year, at the start and the end of the good weather period, with roughly 6 months in-between each other. To verify the possible seabed evolutions in between the new foundations and to monitor the morphological evolution of the Thornton Bank as a natural feature, the inspection program shall once a year include a bathymetrical survey of a wider zone. This zone comprises next to the cable routing, also an area of 2700m (NW-SE direction along the centre points of the GBFs) by 800m. The first bathymetrical follow-up survey was executed in September 2009.

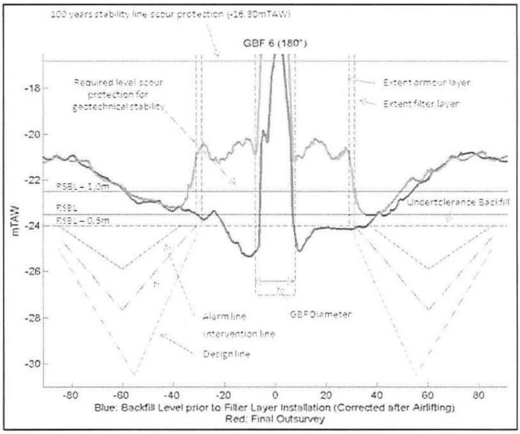

Figure 6: Concept of alarm line, intervention line and design line.

MONITORING RESULTS

During construction

The wave data from the Thornton Bank have been used for the analysis of the stability of the backfill material in relation to summer storm exposure and the stability of the (temporary exposed) filter material in late autumn, begin winter. The backfill and filter behaved during exposure very much as expected. Lobes were formed in the backfill, and local scour around the GBF in the filter was observed, as predicted with the physical model tests (Bolle et al. 2009).

Layer thicknesses are evaluated based on the in- and outsurveys. Figure 6 compares for one cross section the situation prior to the installation of the scour protection with the final out-survey after all works were finished. This type of figure is used to evaluate the different steps of the works. With regard to the stability of the scour protection itself, the level below which the scour protection should remain in order to guarantee the stability during the 100 years return period event is also indicated. For GBF 6 it can be seen from the figure that the top of the armour stays well below the stability line for the scour protection. However, the top of the scour protection lies about 2m above the minimum required level (RSBL +1m), which could be unfavourable for edge scour.

During operation

Obviously, the design line should not only be guaranteed by the end of the works, but also during the entire project's lifetime. Therefore, a dedicated monitoring program has been set up. Distinction is made between two areas: the area above the scour protection and the remaining area inside a diameter of 150m.

In the first area, i.e. close to the structure, displacement of the armour rock is allowable but the level should be at least 1.0m above RSBL. If in a zone the first layer of the armour stones is eroded over an area of 4 x D_{n50}^2 (with D_{n50} = the nominal diameter) without the filter layer being exposed, an alarm situation is reached. If in a zone the first layer of the armour stones is eroded over an area of 8 x D_{n50}^2 without the filter layer being exposed, an intervention situation is reached. The system is damaged when the second layer of armour stones is absent and the filter layer is exposed.

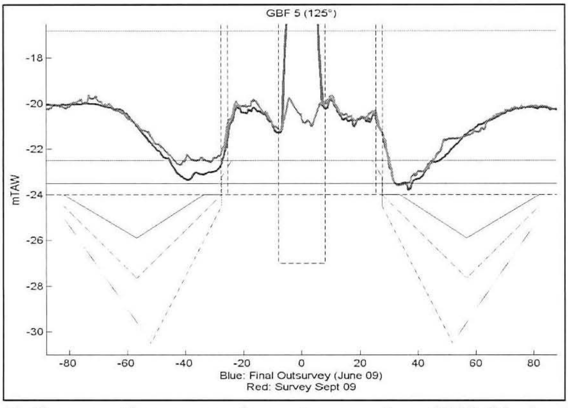

Figure 7: Cross section comparing outsurvey June 2009 (blue) with first monitoring results September 2009 (red).

To evaluate the second area, two lines related to intervention decisions are defined in addition to the design line: the alarm and intervention line. The slope of the intervention line is twice as gentle as the one of the design line: 1:8 instead of 1:4. The slope of the alarm line is 1:12. Both lines are also indicated in Figure 6.

Based on the alarm – intervention – design line concept results of monitoring campaigns can quickly be evaluated and it can easily be examined if further action is required. After the final out-surveys in June 2009, one monitoring campaign took place, namely in September 2009. A typical cross section comparing the results of both surveys is given in Figure 7. From the survey results it can be concluded that in the summer months no significant edge scour did occur, if at all. Instead, it seems that there is a sedimentation tendency in some parts. Hence, the first monitoring campaign showed no need for any urgent action.

CONCLUSIONS

During the first phase of C-Power's wind farm project, the scour protection design has been optimised. Starting from the theoretical design, supported by physical model tests, numerous discussions with the contractor resulted in a more economical design. It became important to minimise the operational time on sea, which led to the elimination of the second phase of the backfill. However, even with state of the art equipment, it was very difficult to perform the scour protection installation on the North Sea within the specified tolerances. Maintaining a minimum layer thickness (to guarantee stability), without placing too much material (to avoid rising costs) is still a point of interest. For future designs, these aspects should be addressed right from the start. For the GBFs already in place on the Thornton Bank, the first monitoring results showed a stable behaviour of the scour protection and the seabed around. Nevertheless, monitoring continues to be able to intervene in time, if necessary.

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