LARGE SCALE EXPERIMENTS TO IMPROVE MONOPILE SCOUR PROTECTION DESIGN ADAPTED TO CLIMATE CHANGE

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This study aims to improve the design of scour protection around offshore wind turbine monopiles, as well as future-proofing them against the impacts of climate change. A series of large scale experiments have been performed in the context of the PROTEUS (PRotection of Offshore wind Turbine monopilEs against Scouring) project in the Fast Flow Facility in H.R. Wallingford. These experiments make use of state of the art optical and acoustic measurement techniques to assess the damage of scour protections under the combined action of waves and currents.

1. INTRODUCTION AND OBJECTIVES

A series of large scale experiments have been performed in the context of the PROTEUS (PRotection of Offshore wind Turbine monopilEs against Scouring) project in the Fast Flow Facility in H.R. Wallingford in the United Kingdom. The PROTEUS testing campaign is a collaborative effort between the Department of Civil Engineering at Ghent University (Belgium), HR Wallingford (UK), the Ludwig-Franzius Institute for Hydraulic, Estuarine and Coastal Engineering at the University of Hannover (Germany), the Faculty of Engineering at the University of Porto (Portugal), the Geotechnics division of the Belgian Department of Mobility and Public Works (Belgium), and the International Marine and Dredging Consultants (IMDC nv) (Belgium). PROTEUS is performed in the context of the European Hydralab+ programme and funded by the EU's Horizon 2020 Research and Innovation Programme.

De Vos et al. (2012) studied the disintegration failure mode of an armor layer over a geotextile under different hydrodynamic conditions. Static and dynamic stability of the armor layer were tested in a model scale of 1:50 (all the scale factors consider a prototype monopile diameter of 5 m) under different waves, currents and a combined action of both flows. Loosveldt & Vannieuwenhuyse (2012) extended the test dataset of De Vos et al. (2012) by including larger grain sizes, by varying the water depth and by performing a parametric analysis of the pile diameter (scales of 1:100, 1:50, 1:40) on the scour protection damage. Nielsen et al. (2013) focused on the winnowing of scour protection under different waves and currents. The testing scales used for the current experiments were 1:35.7, 1:9 and 1:5. Nielsen et al. (2013) provided an answer to the sinking of the scour protections in the "Horns Rev 1" wind farm and gave improved guidelines for the design of filter layers through the mobility parameter. Whitehouse et al. (2014) evoked an optimization of scour protection design taking into account rock size, density, number of layers and width of the cover. Finally, Petersen et al. (2014) performed experiments using physical models with a scale 1:100 to 1:50 for the study of edge scour under waves and currents.

Schendel et al. (2014, 2016) presented large scale experiments of scour protection design under waves and currents. The scale used for wave tests which included a monopile was 1:5, whereas, the scale for current tests without a monopile was 1:1. In the latter case, the material tested as scour protection was the actual prototype material. This work introduced a single armor layer composed of a wide-graded material. 'Wide-graded' refers to a large geometric standard deviation of the granular material composing the scour protection (D_{84}/D_{16} > 1.5, for wide graded material

and D84/D16 >2.5 for very wide graded material, where D84 and D16 account for the diameter larger than 84 % and 16 % of the mass of the material, see Rock Manual (2007) Table 3.4). The usage of this novel technique could show itself easier to install, as well as cost effective compared to a traditional two-layer scour protection design (filter and armor). Nevertheless, it is concluded that more experiments should be carried out to fully understand the stabilizing process of using wide-graded materials as scour protection. In this direction, Petersen et al. (2018) studied different compositions of scour protection material in small scale experiments (scales of 1:100 – 1:45.45) under a unidirectional current.
Deterministic design criteria exist for the classic narrow graded two-layer scour protection (De Vos et al. (2012), Nielsen et al. (2013)) but none has been established for wide-graded materials. Fazeres Ferradosa et al. 2018 proposed a reliability analysis of the scour protection failure and proposed a probabilistic design, without considering the gradation of the scour protection material.
The aim of this manuscript is to present the PROTEUS project, and specifically to present the experimental setup, the methodology followed throughout the study and quality of the unique dataset acquired during the testing campaign, which addresses the data and knowledge gaps in scour protection studies. The novel PROTEUS experiments, presented further in this paper, test the static and dynamic stability of different scour protection designs including monopiles at two different large scales 1:16.66 and 1:8.33, under the combined action of waves and currents.

2. EXPERIMENTAL SET-UP

The FFF experimental facility is a race-track shaped flume (illustrated in Figure 1). It comprises a main working channel, 4.0 m wide and 57.0 m long, and a secondary channel, 2.6 m wide and 50.0 m long. The hinge flat type multi-element wave generator with active wave absorption (located at the left in Figure 1) can deliver significant wave heights up to 0.5 m and a maximum wave height up to 1.0 m, depending on the water depth. The water depth can be set in the range of 0.85-2.00 m. At the opposite side of the wave generator (at the right in Figure 1), a beach made of sponge material passively absorbs the generated wave trains. The axial pumps (located in the secondary channel) can deliver a discharge of up to 3.5 m3/s and their reversible nature can provide a current propagation following or opposing the waves.

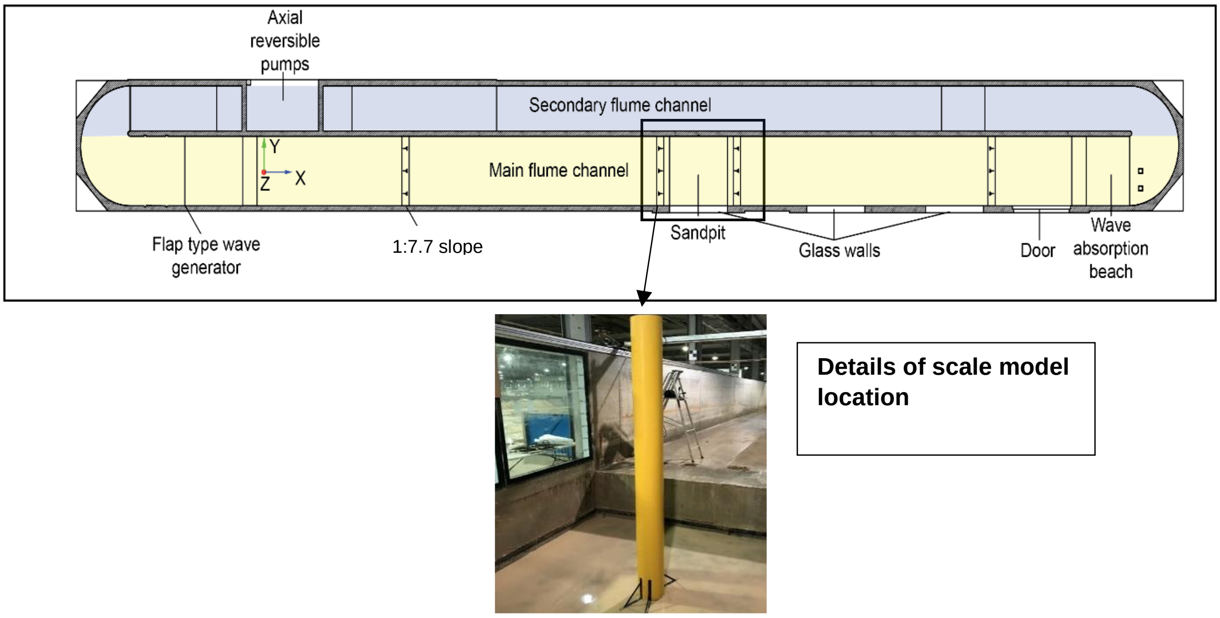


Figure 1. Sketch of the FFF flume channels presenting the position of the scale models.

A local reference system was established with the origin being at the front of the wave maker, in the middle of the channel on the flume floor. The positive x-axis points into the wave propagation direction (from left to right in Figure 1), the positive y-axis points upwards in the top view in Figure 1 and the positive z-axis follows the gravity vector. In the sketch of the main channel (**Error! Reference source not found.**), the position of the resistive Wave Gauges (abbreviated as WGs), the Acoustic Doppler Velocity meters (ADVs) and the scale model of a monopile are indicated.

There are two variants of monopile scale models with two different diameters, D_p= 0.3 and D_p= 0.6 m, and are constructed from thin-walled metal (**Error! Reference source not found.**b). Each monopile model is placed in the wave flume with its center at x=30 m and y = 0 m, following the local reference system presented in Figure 1. The sand pit consists of a 4.0 m long, 4.0 m wide and 1.0 m high box. This sand pit size provides the necessary area for testing large scale scour protection models over a sand bed, which is composed of uniform sand, d_{50} = 0.21 mm, for all tests.

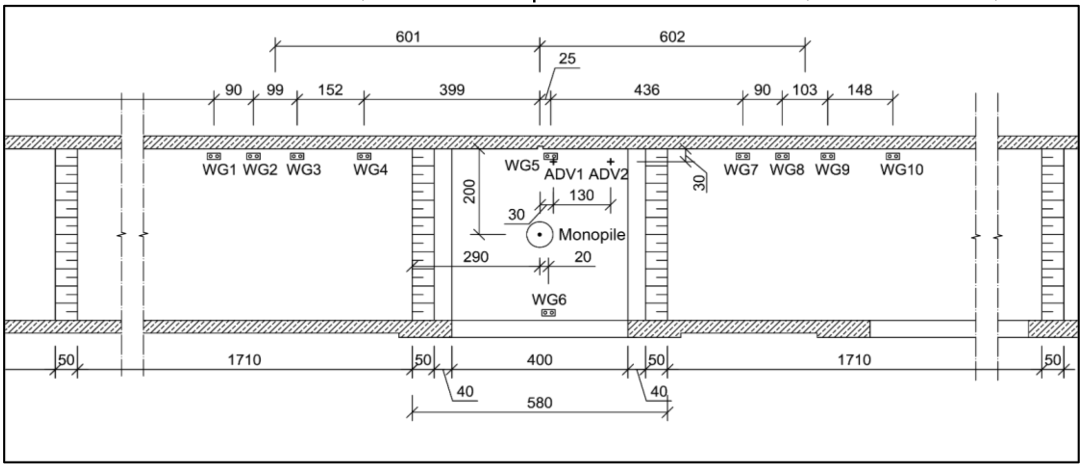


Figure 2. Positions of the 10 resistive wave gauges (WG1-WG10) and the 2 Acoustic Doppler Velocity meters (ADV1 and ADV2) in the main flume channel. Dimensions are in mm.

During the testing campaign data is recorded in both the main and the secondary flume channels. In the main flume channel, in order to characterize the flow in the vicinity of the monopile, the free surface elevations and 3D flow velocities are recorded at ten and two (point velocity measurements) locations, respectively (see Figure). In the secondary channel, in order to characterize the current characteristics in the facility, profile of horizontal flow velocities and free surface elevation are measured at one location, respectively. Before the onset of motion test and after every damage development tests, the topography of the scour protection model is measured. The topography measurements provide the initial, intermediary and final state of the scour protection model. Photographic material is produced before the filling and after the draining of the flume. These measured quantities, the instruments used and the sampling frequency of the instruments are presented in Table 1.

Table 1. Measured parameters and instrumentation

Measured parameter		Instrumentation	Sampling frequency
Free surface elevation		Resistive Wave Gauges (WGs)	100 Hz
Flow velocities	3D point measurements	Acoustic Doppler Velocity meters (ADVs)	100 Hz
	Profile measurements of the horizontal velocity	Aquadopp profiler	1 Hz
Scour protection model topography		ULS-200 laser scanner	7 Hz (7mm/s)
Photographic material		Cameras	-

4. EXPERIMENTAL TEST PROGRAMME

Two types of tests are carried out during this testing campaign, namely, onset of motion and damage development tests for each of the scour protection models. The testing programme objectives are (i) to compare the performance of single-layer wide-graded material used against scouring with current design practices, and (ii) to verify the stability of the scour protection designs under extreme weather conditions. Hereafter, the experimental conditions are presented and summarized in Table 2, Table 3 and Table 4. In Table 2 and Table 3, the experiments' basic hydrodynamic conditions and the hydrodynamic variants are included. The variants of a test are performed successively, for which the wave height and wave period are modified for onset of motion tests, and the number of waves changes for damage developments tests.

4.1 Onset of motion tests

Onset of motion experiments assess the stability of the scour protection from a statically stable design point of view. From this perspective, failure is considered if armoring material is removed over a minimum area of four armor units (4xD502, D50 is the mean stone diameter of the scour protection model). Such design of the scour protection allows very little motion of the scour protection material. During onset of motion tests, when the desired current velocity is reached and stable, short regular wave trains (12 waves) are generated. The scour protection is observed throughout the propagation of the wave train in order to spot motion of the scour protection material. Motion of scour protection material (stones) refers to the displacement of a stone which size, ds, is larger or equal to the mean stone diameter (ds>D50) for a distance at least equal to two times the mean stone diameter De Vos et al. (2012). Once it has been established if motion of the stones occurred, new wave conditions are tested, while the current generation is not interrupted in-between applying different wave conditions. The test conditions for the onset of motion tests are shown in Table 2.

Table 2. Onset of motion test conditions. The highlighted conditions are the ones where motion of scour protection material is spotted.

Test no.	Water depth	Monopile diameter	Current Velocity	Test variant	Wave height	Wave period
S/N	d [m]	Dp [m]	Uc [m/s]	S/N	H [m]	T [s]
03	1.2	0.3	-0.25	A	0.22	2.94
				B	0.28	2.94
				C	0.27	2.94
				D	0.33	2.47
				E	0.39	2.47
05	1.5	0.3	0.27	A	0.20	2.91
				B	0.22	2.93
				C	0.28	2.98
				D	0.32	2.94
				E	0.35	2.94
				F	0.32	2.51
				G	0.37	2.48
07	1.2	0.3	-0.23	A	0.25	2.94
				B	0.29	2.94
				C	0.33	2.46
				D	0.31	2.46
09	0.9	0.3	-0.23	A	0.20	2.46
				B	0.22	2.06
				C	0.26	2.08
11	1.8	0.6	-0.39	A	0.50	3.50
				B	0.37	3.48
				C	0.42	3.48
				D	0.54	3.48
				E	0.41	2.84
				F	0.46	2.85
				G	0.50	2.83
				H	0.56	2.85

4.2 Damage development tests

Damage development assess a dynamically stable design of scour protections. Such design allows some motion of the scour protection material. The criteria for considering the failure of the scour protection is the global damage number, S3D. Following the methodology De Vos et al. (2012), the scour protection model is subdivided into subsections with an area equal to the area of the monopile as shown in Figure 2.

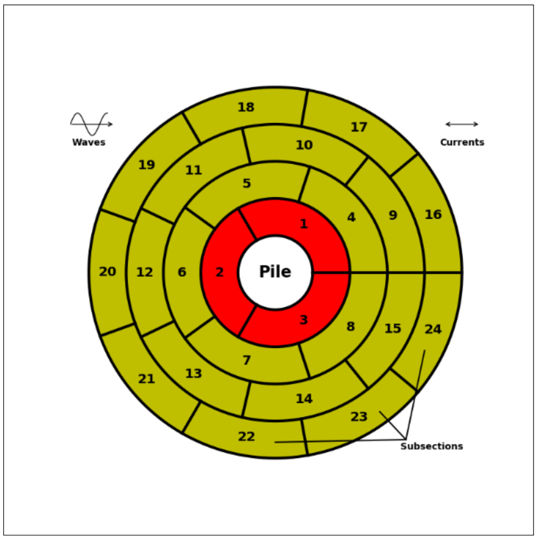


Figure 2. Sketch of the scour protection model around the monopile divided in subsections as in De Vos et al. (2012), with the inner ring in red. The wave and current propagation directions are also indicated.

The damage number of each of the subsections is calculated from the eroded volume, V_e, the nominal mean diameter, D_{n50}, and the monopile diameter, D_p, using the formula:

$$S_{3D,sub} = \frac{V_e}{D_{n50}\,\pi\,\frac{{D_p}^2}{4}} \tag{1}$$

The global damage number is obtained by considering the maximum damage number of the subsections:

$$S_{3D} = \max(S_{3D,sub}) \tag{2}$$

Damage development tests are performed in a similar way as the onset of motion test; when the current has reached the desired velocity, a long wave train is generated (1000 irregular waves). The current is stopped and a topography laser scan takes place. Then, a longer wave train of 2000 irregular waves is generated and, finally, the last laser scan is performed. Test 14 has an additional 2000 waves wave train, followed by a laser scan (Table 3). V_e will be determined by the comparison of the topography laser scans. The test conditions for the damage development tests are shown in Table 3.

Table 3. Damage development test conditions

					Test Variant	A	B	C
	Water depth	Monopile diameter	Significant wave height	Peak wave period	Current mean velocity	Number of waves		
Test no.	d [m]	Dp [m]	Hs [m]	Tp [s]	Uc [m/s]	N [-]	N [-]	N [-]
04	1,2	0,3	0,225	2,46	-0,5	1000	2000	
06	1,5	0,3	0,37	2,2	0,34	1000	2000	
08	1,2	0,3	0,17	2,46	-0,5	1000	2000	
10	0,9	0,3	0,175	2	-0,34	1000	2000	
12	1,8	0,6	0,35	2,83	-0,49	1000	2000	
13	1,5	0,6	0,37	2,2	-0,58	1000	2000	
14	1,8	0,6	0,35	2,83	-0,49	1000	2000	2000
15	1,8	0,6	0,35	2,83	-0,49	1000	2000	

Other than the hydrodynamic conditions, the properties of the scour protection material are tested. The intrinsic properties of the scour protection material the mean stone diameter, D50, geometric standard deviation of the material composition, D84/D16, are stated in Table 4.

Table 4. Properties of scour protection composition and indication of usage

Scour protection Mixture no.	Test no.	Mean diameter	Geometric standard deviation of the material
S/N	S/N	D50 [mm]	D84/D16 [-]
1	03/04	12.5	2.48
2	05/06	6.75	2.48
3	07/08/09/10	6.75	2.48
4	11/12/13	13.5	2.48
5	14	13.5	6
6	15	13.5	12
7 (Geotextile)	03/04/07/08	-	-

Mixture 1 is the scale model of a standardize grading 2-80 kg. A wide-graded material with a mean diameter of 110 mm in prototype scale is studied at intermediate model scale by Mixture 2 and 3 and at large scale model by Mixtures 4, 5 and 6. The variable between Mixtures 4, 5 and 6 is the geometric standard deviation of the material. Figure 3 presents the grain size distribution of the mixtures, as obtained from the fabrication of the mixtures.

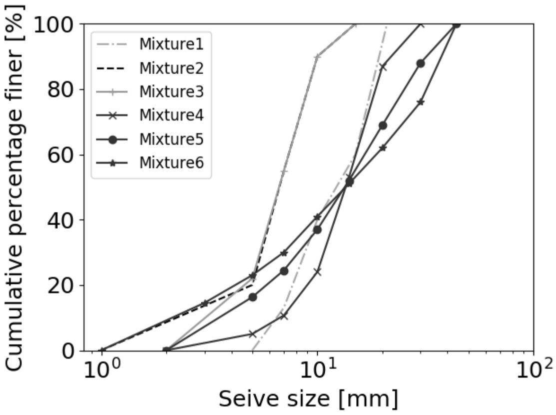


Figure 3. Percentage finer against the sieve size for the 6 tested mixtures

The use of geotextile as an installation method was studied in tests 03/04/07/08 at intermediate model scale.

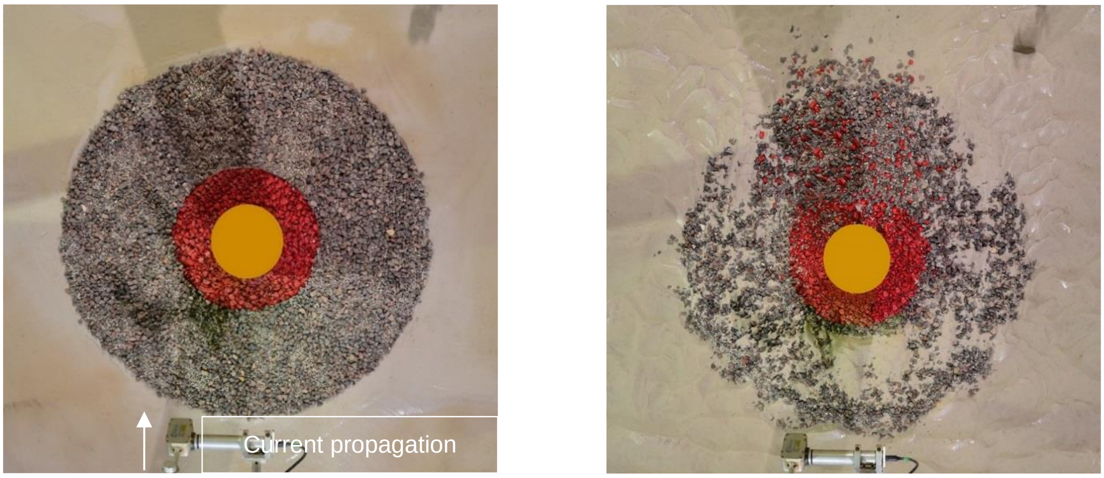
5. RESULTS AND DISCUSSION

Results from Test 04 are presented in the present manuscript. During Test 04, the hydrodynamic conditions represent an extreme climate change driven condition of a current with a velocity Uc = 2 m/s at prototype scale. The scour protection model is subjected to considerable hydrodynamic loads. The visual assessment of the damage is of “Level 3” (damage without failure) following the criteria presented in by De Vos et al. (2012) used for visual assessment of the damage levels:

- Level 1: no movement of the stones
- Level 2: very limited movement of stones
- Level 3: significant movement of stones, without failure of the protection
- Level 4: failure of the protection

The static stability of the scour protection models are assessed in the onset of motion test shown in Table 2, where tests where motion of the scour protection material (stones) was spotted, are highlighted. The visibility in the facility was not appropriate when the current was established, once the wave generation started, the sediment transport was enhanced and the turbidity of the water increased substantially. Therefore, the results of the onset of motion test need to be considered with care because of their qualitative nature.

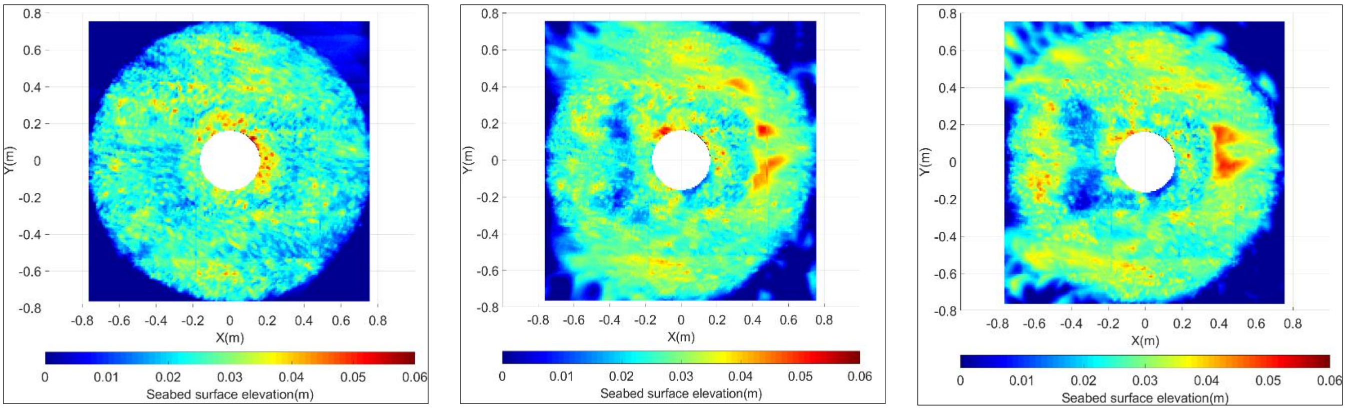
Scour protection damage development tests, such as Test 04, are composed of at least two wave trains. In the Section 3, it has been stated that optical material is collected before and after the tests. In Figure 4, the merged optical material is shown for Test 04. The initial state of the scour protection model can be seen in the left panel (Figure 18a), and the final state on the right panel (Figure 18b). In Figure 4b the displacement of the scour protection material of the inner ring (red stones) can be clearly be observed in the direction of the current propagation. Furthermore, deposition of sediment material is seen on top of the scour protection, outside of the inner ring region.



(**a**) (**b**)

Figure 4. Merged picture of the scour protection scale model Tests 0 4 before (left) and after (right) the test.

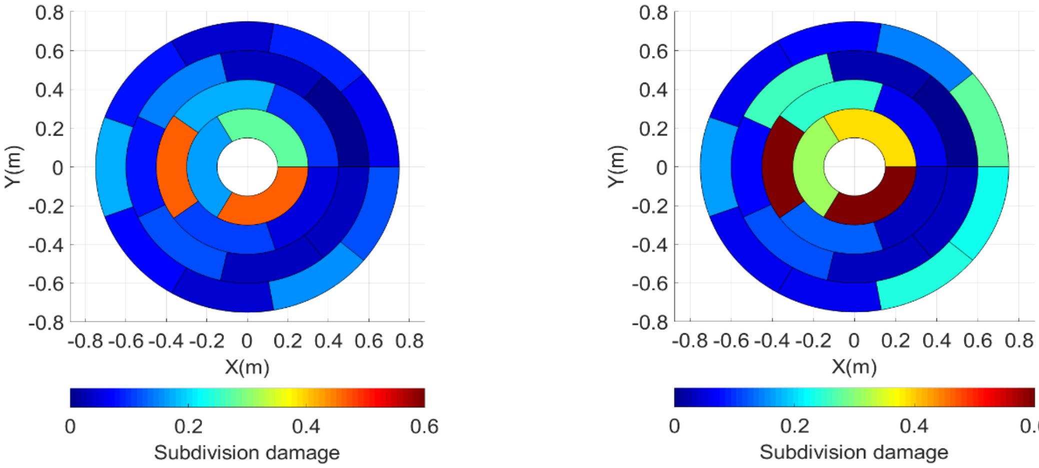
This initial visual assessment of the damage of the scour protection is corroborated by the topographic laser scans shown in Figure 5. In Figure 5 topography of the scour protection material at the initial state, after 1000 waves (Test 04_A) and after 3000 waves (Test 04_B) are shown. Regions with higher elevation are shown in red color, while the lower elevation regions are shown in blue color. Through Test 04, in Figure 5, the development of two symmetrically eroded zones can be observed in the wake of the monopile, in the direction of the current. Upstream, just in front of the monopile in Figure 5, the development of scour is clear and shown by an increasing dark blue region. Furthermore, upstream of the monopile, the sedimentation outside the inner ring is clearly progressing from the middle laser scan (Figure 19b) to the right scan (Figure 19c).



(a) (b) (c)

Figure 5. Topography of the scour protection material and of the sand pit measured by the laser scanner before Test 03 (a), after the first 1000 waves of Test 04_A (b) and after 3000 waves at the end of Test 04_B (c). The current propagation in this set of figures is from right to left.

From Figure 4 and Figure 5 it is clear that the scour protection material has undergone damage caused by the hydrodynamic action of the flow. This damage development becomes even clearer when each subsection considered separately, in Figure 6.



(a) (b)

Figure 6. Test 04 subdivision damage number: after 1000 waves Test 04_A (a) and after 3000 waves Test 04_B (b). The current propagation in this set of figures is from right to left.

From the tested hydrodynamic conditions, the measured damage and the predicted damage of the scour protection material are presented in Table 5. The S_{3D} number is the indicator that characterise the scour protection material damage. The predicted damage of the scour protection material is obtained from the damage prediction formula (Equation 3) presented by De Vos et al. (2012):

$$\frac{S_{3D}}{N^{b_0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{\frac{3}{2}} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{\left(\frac{U_c}{w_s}\right)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \quad (3)$$

More information on Equations 3 can be found in De Vos et al. (2012). A significant deviation in magnitude of the predicted and the measured S3D for the scour protection material can be seen from Table 5. It is important to note that the damage prediction formula, Equation 3, was established for a scale 1:50 while the scale of Test 04 is 1:16.667. This deviation can be accounted for the scale effects introduced by the present testing campaign.

Table 5. Measured and predicted S3D number for Test 04_A and 4_B

	Mean grain size	Geometric standard deviation	Number of waves	Pile diameter	Water depth	Significant wave height	Peak period	Mean current velocity	Predicted damage number	Measured damage number
Test no.	D50 [mm]	D84/D16 [-]	N [-]	Dp [m]	d [m]	Hs [m]	Tp [m]	Uc [m/s]	Predicted S3D	Measured S3D
Test 04_A	12.5	2.48	1000	0.3	1.2	0.25	2.45	-0.461	1.834	0.465
Test 04_B	12.5	2.48	2000	0.3	1.2	0.24	2.48	-0.462	2.141	0.675

6. CONCLUSIONS

The experiments performed at the FFF at HR Wallingford have yielded a large dataset that provide a benchmark for large scale experiments of scour protection designs around monopiles. The full extent of the obtained results will be made available in future studies that will focus in more detail on the impact of specific parameters and methodologies of damage assessment. The comparison of the basic analysis of the damage development results and the predicted damage, shows that scale effect are not accounted by the prediction formula, Equation 3. Further analysis of the acquired data will provide valuable insight in scale effects and the performance of wide-graded materials.

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