

From: [Dominika Phillips](#)
To: [Hornsea Project Three](#); [KJ Johansson](#); [Kay Sully](#)
Cc: [Andrew Guyton](#); [Stuart Livesey](#)
Subject: Hornsea Project Three (UK) Ltd response to Deadline 4 (Part 12)
Date: 15 January 2019 23:18:39
Attachments: [image001.png](#)
[D4_HOW03_Appendix 49_Roulund et al 2019a.pdf](#)
[D4_HOW03_Appendix 50_Roulund et al 2019b.pdf](#)
[D4_HOW03_Appendix 51_Defra MCZ Guidance 2010.pdf](#)
[D4_HOW03_Appendix 53_WO_2.1.3.pdf](#)
[D4_HOW03_Appendix 54_Aviation Assessments.pdf](#)
[D4_HOW03_Appendix 55_Development Principles_rev2.pdf](#)
[D4_HOW03_Appendix 56_Manwell et al 2009.pdf](#)
[D4_HOW03_Appendix 57_Helideck Certificates.pdf](#)
[D4_HOW03_Appendix 58_Indicative Array Layout.pdf](#)
[D4_HOW03_Appendix 59_FCLP_rev3.pdf](#)
[D4_HOW03_Appendix 60_Draft CID Budget Notice.pdf](#)
[D4_HOW03_Appendix 62_O2.2.34.pdf](#)
[D4_HOW03_Appendix 63_O2.2.7_O2.2.44.pdf](#)
[D4_HOW03_Appendix 64_Dogger Bank.pdf](#)

Dear Kay, K-J

Please find attached the 12th instalment of documents.

Best regards,
Dr Dominika Chalder PIEMA
Environment and Consent Manager



Environmental Management UK | Wind Power
5 Howick Place | London | SW1P 1WG



Please consider the environment before printing this e-mail

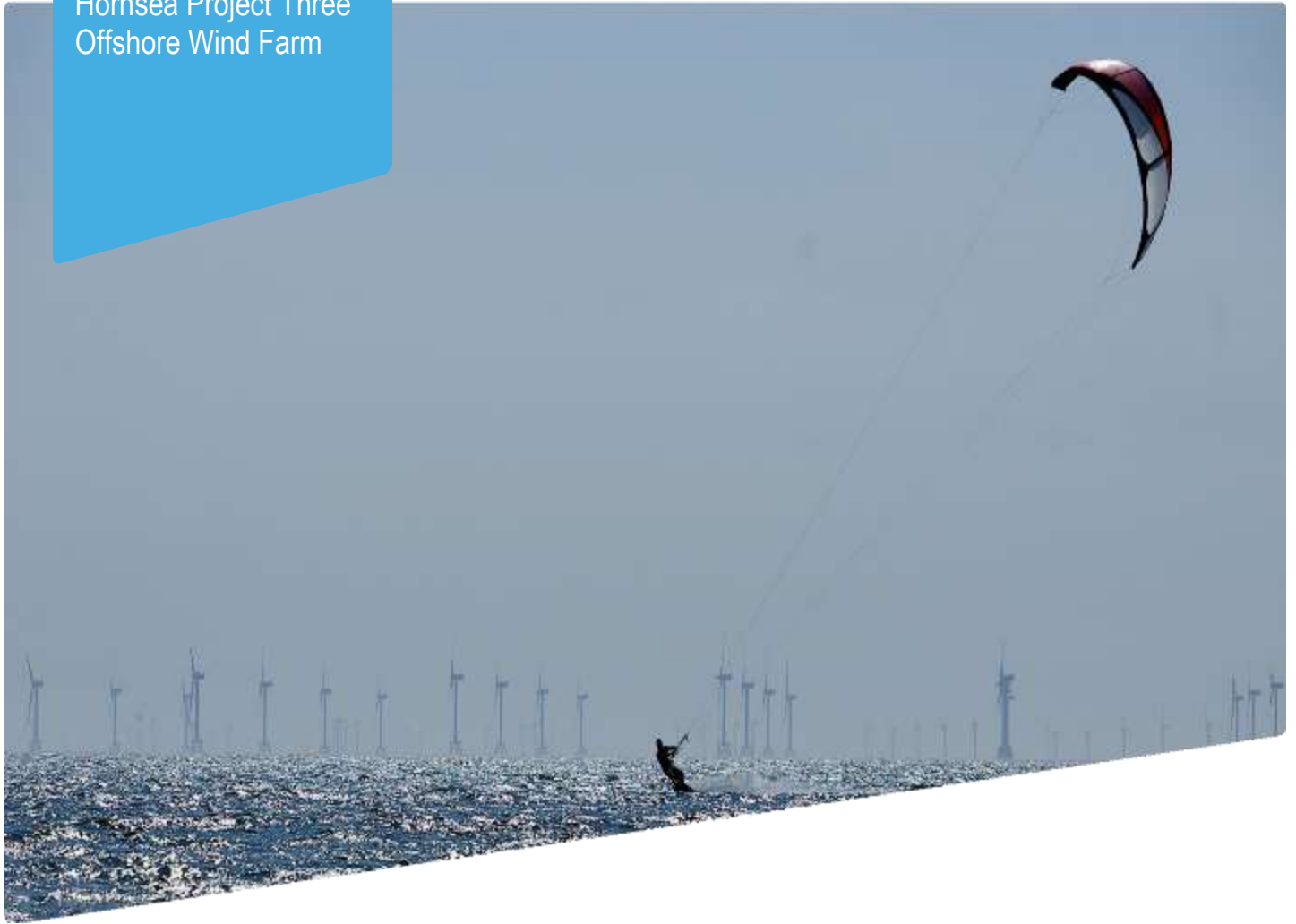
This communication contains information which is confidential and is for the exclusive use of the addressee(s).

If you are not a named addressee, please inform the sender immediately and also delete the communication from your system.

Orsted Power (UK) Limited is registered in England
Registered number: 04984787
Registered Address: 5 Howick Place, London, SW1P 1WG
The Company is a wholly owned subsidiary of Orsted A/S (a company registered in Denmark)
More information on the business of the Orsted group can be found at www.orsted.com
Disclaimer version 1.1

This email has been scanned by the Symantec Email Security.cloud service.
For more information please visit <http://www.symanteccloud.com>

Hornsea Project Three
Offshore Wind Farm



Hornsea Project Three Offshore Wind Farm

Appendix 49 to Deadline 4 Submission
– Roulund et al., 2019a

Date: 15th January 2019

Document Control			
Document Properties			
Organisation	Ørsted Hornsea Project Three		
Author	Roulund et al., 2019a		
Checked by	n/a		
Approved by	n/a		
Title	Appendix 49 to Deadline 4 Submission – Roulund et al., 2019a		
PINS Document Number	n/a		
Version History			
Date	Version	Status	Description / Changes
15/01/2019	A	Final	Submitted at Deadline 4 (15/01/2019)

Ørsted

5 Howick Place,

London, SW1P 1WG

© Orsted Power (UK) Ltd, 2019. All rights reserved

Front cover picture: Kite surfer near a UK offshore wind farm © Ørsted Hornsea Project Three (UK) Ltd., 2019.

Scour at cable protection rock berms—model test observations

A. Roulund & S.M. Larsen
Ørsted, Gentofte, Denmark

J. Sutherland & R.J.S. Whitehouse
HR Wallingford, Wallingford, UK

ABSTRACT: Rock berms or concrete mattresses have traditionally been applied for protection of shallow buried, surface laid or crossing pipelines and cables. In most cases the installed protection has worked satisfactorily, but under certain adverse conditions, field evidence has shown examples of severe scour both at mattresses and rock berms.

The paper presents and discusses physical model tests of rock berm scour in combined waves and current. Both single and double berm configurations were studied. The conclusions from the tests were two-fold addressing: 1) Scour development caused by rock berm(s), and 2) Structural robustness of the rock berm when subject to wave action and seabed model scale effects.

The model tests support field evidence that scour is prone to develop in strong current environments and when the protection is aligned oblique or perpendicular to the prevailing currents. The tests also demonstrate larger structural integrity of wide crested berms as opposed to sharp crested berms.

1 INTRODUCTION

Power cables are the veins of offshore wind, with power and revenue being transported from sea to shore across long distances. On the way, the cables will typically have to cross existing cables or pipelines. At such crossings the cables are installed surface laid and later typically covered by rock berms.

Soil conditions, installation spread performance or repair works may also locally leave the cable surface laid or with shallow burial.

Surface laid or shallow buried cables will often be protected by a rock berm cover layer. Such rock berms will in many conditions and particularly in deeper waters perform satisfactorily.

Field observations of rock berm scour Whitehouse et al (2006) and Roulund et al (2018) in shallow, high current speed conditions demonstrates however that proper rock berm performance cannot always be expected.

The hydraulic stability of rock berms was studied in Roulund et al (2017) based on rigid bed physical model tests. These tests were carried out in HR Wallingford's Fast Flow Facility (Whitehouse et al 2014). Within the same test program, a test series with mobile sediment bed was conducted to investigate rock berm induced seabed scour. Results from these tests are presented in this paper.

Limited, if any, rock berm scour model test results are available in literature (e.g. Escameia et al, 2015). As such the test series was set up inter-

rogatively to identify key parameters influencing rock berms scour.

Key parameter studied were:

- Berm height
- Flow regimes
- Berm alignment to flow
- Berm width
- Single vs. double berms

As a spin-off, robustness of the berms towards scour and wave loading was observed.

Seabed/rock size scale effects caused unforeseen berm degradation under high current conditions. When known, this effect can be mitigated through the choice of rock scaling approach using Shields rather than Froude scale.

Scour at a rock berm can be divided into trunk section scour (i.e. within the central length of the berm) and head scour (i.e. at the ends of the berm), and even the scour at these two locations may interact. The scour developing from a rock berm can be acceptable or not depending on its location.

For a crossed cable or pipeline, trunk section scour is most critical as this can expose the crossed asset.

The crossing cable will normally be unaffected by the trunk scour as long as the integrity of the rock berm remains. Head scour on the other hand may expose or cause a free-span of the crossing cable at the end of the rock berm.

From field evidence given in Whitehouse et al (2006) and Roulund et al (2018) it is observed that rock berm scour appears to be most excessive in strong current environments with high sediment transport rates.

High transport rates pose a practical challenge in a model test facility. While the test facility may be able to produce large sediment transport rates, the resulting sand relocation poses practical limitations if a sediment feed is not maintained throughout the test.

The capability to shovel large volumes of sand becomes a key qualification for those working on the practical execution of such model tests, notwithstanding their competences handling advanced measurements techniques and post processing algorithms.

On the above note, testing of scour development to equilibrium conditions were not achievable with the selected test set-up.

The presented results thus provide an inter-comparable assessment of the key parameters whilst remaining a starting point for further investigations beyond the initial scour response for a range of different conditions.

The non-scalability of sand and the noise that sand ripples impose on scour response in scale model tests are further challenges.

Ripples are considered not to impact the larger scale scour patterns. To better display these scour patterns, the ripple signal has been reduced by filtering in the scour analysis presented in this paper.

The inability to downscale sand grains means that the current can't be Froude scaled if field-like sediment mobility is desired in the flume.

In terms of non-dimensional properties, the necessity to have large model scale current speed leads to higher Froude numbers than would have otherwise been experienced in the field for the same value of the Shields parameter. Basically, the test flume becomes hydraulically shallower, when sediments are not scaled directly.

Compensation for the shift in Shields/Froude ratio caused by sediment scaling can be incorporated through running the test at higher water depth. This will also be favourable for the Reynolds number, normally suffering in Froude scaled model tests. A large water depth relative to berm height was therefore applied in the conducted model tests.

2 GOVERNING SEASTATE PARAMETERS

Rock berm scour is thought mainly to take place in current dominated conditions as discussed in Roulund et al (2018).

The scour potential of currents still makes the influence of waves all the more relevant to understand. This is because the potential suppression or

backfilling of rock berm scour by waves may prevent or mitigate against cable exposure.

The description of seastate parameters is performed through non-dimensional parameters. All the parameters involving the water depth are evaluated using the initial water depth in front of the rock berm(s).

The Reynolds number, Re , and Froude number, Fr are given by:

$$Fr = \frac{U_c}{\sqrt{gh}} \quad (1)$$

$$Re_h = \frac{U_c h}{\nu} \quad (2)$$

where g is acceleration due to gravity, h is the water depth in front of the rock berm, U_c is the depth averaged current velocity in front of the rock berm, and ν is the kinematic viscosity of water.

The influence of Re and Fr is in Roulund et al (2018) suggested to be marginal only for engineering application. The Froude and Reynolds numbers will be listed in description of the test conditions, but otherwise not interrogated.

In contrary to Re and Fr , the key seastate parameters governing the rock berm scour are considered to be the Shields parameter, θ , of the seabed sediments and the wave current ratio, U_{cw} of combined current and irregular waves.

$$\theta = \frac{\tau_{max}}{g(\rho_s - \rho)D_{50}} \quad (3)$$

$$U_{cw} = \frac{U_c}{U_m + U_c} \quad (4)$$

where τ_{max} is a representative bed shear stress for combined irregular waves and current, D_{50} is mean sediment or rock grain size and ρ_s and ρ are sediment particle density and water density.

The depth averaged current velocity, U_c , and the near bed wave orbital velocity, U_m , are applied for calculation of both θ and U_{cw} .

A thorough description of a parametric approach for calculation of θ and U_m is given in Roulund et al (2016) where U_m is calculated using Soulsby's (2006) expression:

$$U_m = \frac{H_s}{2\sqrt{2}} \sqrt{\frac{g}{h}} \exp \left\{ - \left[\frac{3.65}{T_z} \sqrt{\frac{h}{g}} \right]^{2.1} \right\} \quad (5)$$

where H_s is the significant wave height and T_z is the zero crossing wave period. T_z is, as an approximation, taken as:

$$T_z = \frac{T_p}{1.3} \quad (6)$$

where T_p is the peak wave period.
Reference is otherwise made to Roulund et al (2016, 2017) for the comprehensive set of equations used to calculate the Shields parameter in combined irregular waves and steady current.

3 EXPERIMENTAL SETUP

Two rock berm types—a sharp and a wide crested were tested in HR Wallingford’s 4 m wide Fast Flow Facility flume, see Figure 1, also showing flume instrumentation.
The rock berms were installed in a build-up 4.0 4.0 0.3 m sediment test section of the flume, indicated as hatched area in the flume plan. Reference is made to Roulund et al (2016, 2017) for details on instrumentation and measurement methods. The sediment test section was extended downstream by 3 m from test 7 onwards to allow installation of double berms.

Rock berm dimensions are given in Table 1. A shortened version (type A) of the sharp crested rock berm was used in the first test allowing for testing of 0 and 90 degree berm orientation within the same test. Remaining tests all had oblique berm orientation using longer berms.

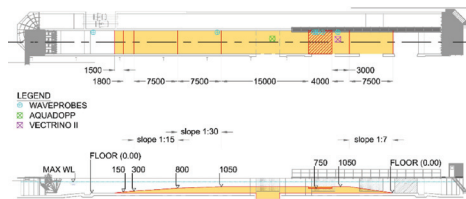


Figure 1. Fast flow facility plan and working channel longitudinal section showing build-up of the test section and location of rock berm tests in red hatched sand pit area. Dimensions in mm.

Table 1. Rock berm dimensions. Top width (B_{top}), top length (L_{top}) and berm height (t). Prototype values based on scale 1:32.

Berm Type	Model dimensions			Prototype dimensions		
	B_{top}	L_{top}	t	B_{top}	L_{top}	t
–	m	m	m	m	m	m
Sharp crest (A)	0.056	1.25	0.056	1.8	40.0	1.8
Sharp crest (B)	0.056	2.50	0.056	1.8	80.0	1.8
Wide crest	0.560	2.50	0.056	1.8	80.0	18

The rock berms were constructed of crushed rock with mean diameter, $D_{50,rock} = 5.5$ mm and $D_{90}/D_{10} = 2.8$ and rock particle density of $\rho_{s,rock} = 2620$ kg/m³.

Sediment properties were non-cohesive sand with mean grain size $D_{50,sand} = 0.14$ mm, $D_{90}/D_{10} = 2.7$ and sand particle density of $\rho_{s,sand} = 2660$ kg/m³.

A total of 10 tests were conducted, see Table 2. Each test consisted of four to six subtests, see Table 3, with hydraulic exposure increasing between tests.

Rock berm scour and any rock berm degradation was cumulative between subtests.

The tests differed in terms of berm type and orientation and included both single and double berm configurations.

The duration of each subtest was 5 hours model time corresponding to 28.5 hours in “prototype”. Equilibrium scour was not reached between subtests. The observed scour after each subtest should therefore not be applied to quantify the maximum scour potential for the given conditions, but solely used to compare scour response between tests.

Table 2. Test program. “Prototype” dimensions—scale 1:32.

Test No	Berm Type	No. of berms	Berm orient. Deg	Sand mound m	Total height m	Subtests
1	Sharp	Single	0, 90	1.0	2.8	A-F
2	Sharp	Single	22.5	1.0	2.8	C-F
3	Sharp	Single	45	1.0	2.8	A-F
4	Wide	Single	45	0.0	1.8	C-F
5	Wide	Single	45	1.0	2.8	C-F
6	Sharp	Single	67.5	1.0	2.8	C-F
7	Sharp	Double	45	0.0	1.8	A-F
8	Sharp	Double	45	1.0	2.8	C-F
9	Wide	Double	45	0.0	1.8	C-F
10	Wide	Double	45	2.0	3.8	A-F

Table 3. Test conditions—sub tests. Model conditions. Water depth maintained at 0.75 m throughout.

Test	U_c	H_s	T_p	U_m	U_{cw}	θ_{sand}	θ_{rock}	Fr	Re
–	m/s	m	s	m/s	–	–	–	–	10 ⁻⁵
A	0.21	0.13	1.6	0.09	0.71	0.082	0.013	0.08	1.6
B	0.07	0.17	1.9	0.14	0.34	0.089	0.015	0.03	0.5
C	0.36	0.13	1.6	0.09	0.81	0.138	0.017	0.13	2.7
D	0.07	0.24	2.2	0.22	0.24	0.158	0.027	0.03	0.5
E	0.49	–	–	–	1.0	0.166	0.011	0.18	3.7
F	0.63	–	–	–	1.0	0.275	0.018	0.23	4.7

To appreciate the magnitude of test scope, each of the tests on average required one week flume occupancy, thus the full test series totalled 2½ months of intensive large facility labtime.

With the intention to mimic the effect of general seabed lowering, the rock berms were installed onto sand mounds with “prototype” height of either 0, 1 and 2 m. Sand mounds were flush to the rock berm edge with the same slope 1:2.

Effectively, the sand mounds increased the height of the rock berms allowing the effect of different total rock berm/sand mound heights, h_{berm} , to be investigated.

No sediment supply or recirculation was applied. The upstream part of the sediment pit therefore saw some general degradation, mostly during the strong current condition of subtest F. Only moderate degradation was observed in subtest E, while no degradation was seen in subtests A to D.

No scour was observed for subtest A-B, these tests were therefore removed from most of the test program and have not been included in the pres-

entation of results. The sub tests A-B do however serve to suggest scour risk is minimal in deep water effectively experiencing only mild wave and current impact at seabed level.

Testing was conducted with combined irregular JONSWAP waves and steady currents.

Subtests A&B and C&D were paired in the sense that each pair had approximately the same Shields parameter but different wave current ratio. Tests A and C were current dominated while tests B and D were wave dominated.

The intention with shifts between current and wave domination was to investigate whether any scour developing under current dominated conditions would be reduced in the following wave dominated subtest.

The two final subtests E and F were pure current tests carrying much larger sediment transport rates, and thus producing more scour and allowing better comparison of scour development between the geometrically different rock berm set ups.

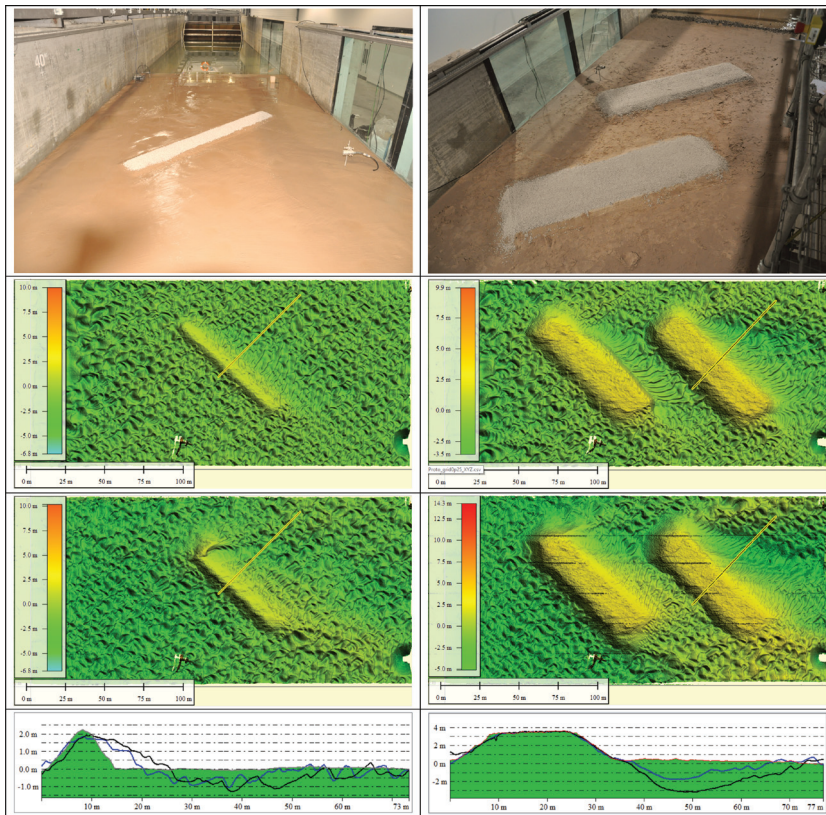


Figure 2. Footage and seabed scans. Left: Test 3 sharp crested single berm, Right: Test 10 wide crested double. Top: Initial conditions. Mid: post scans after subtest E and F. Bottom: Trunk section cross section (Green: Initial conditions, Blue: subtest E, Black: subtest F). Dimensions scaled to prototype using scale 1:32.

4 SEABED SCANS

A ULS200 underwater laser scanning system from 2G Robotics was used to scan the seabed and rock berms prior to testing and after each subtest. Scanned results were converted to ‘prototype’ by scaling 1:32.

Examples of seabed scans from test 3E&F and 10E&F are reproduced in Figure 2 which also includes footage of initial conditions as well as a trunk section cross sections. The presence of sand ripples demonstrate the live bed conditions of the tests.

The tested initial stage of scour is generally observed to emerge from the upstream head and trail down behind the berm where it reaches a maximum. Sediment deposition is observed just behind the rock berms.

A more uniform scour pattern was observed in the field observations in Roulund et al (2018), maybe due to the more variable flow conditions present in the field.

For sub tests F, erosion of the sand mound started to affect the robustness and integrity of the sharp crested rock berms upstream heads, corrupting the quality of results from subtest F in test 1, 2, 3, 6, 7 and 8. Conclusions from these tests should thus be made cautiously only.

5 NORMALISED CROSS SECTION PLOTS

Rock berm scour development is presented and discussed based on trunk and head section plots. In these plots ripple imprints have been reduced by moving average filtering to improve the scour signal of the scans.

The trunk section plots are made perpendicular to the berm at berm centre. The head plots are from the downstream head only. The head scour was generally small, thus focus is mostly on trunk section scour plots.

The section plots have been normalised by the total berm height using the scanned as-found berm height value.

Two berm height values have been applied for the normalisation. This was necessary due to berm degradation of the sharp crested berms during subtest D. The initial berm profile and subtest C vertical coordinates were normalised using pre-test scan, while the x-coordinates and subtest D to F vertical coordinates were normalised by post-subtest D berm height.

6 INFLUENCE OF BERM HEIGHT

Having used the total berm height for normalisation, the underlying assumption is that the scour development and location of scour will scale with berm height.

This assumption is tested and confirmed through comparison of tests with approximately same conditions except for total berm height: Test 4, 5, 9 and 10, see Figure 3.

All the tests are with wide berms and aligned at 45 degrees. The total berm height varies between 1.8, 2.8 and 3.8 m. This height includes sand mound of 0, 1 and 2 m. The comparison is made for trunk section scour for subtests E and F having the most pronounced scour response.

The larger robustness observed for the wide berms resulted in only minimal berm degradation during subtest F. Hence sub test F scour result are considered unaffected by seabed and berm degradation.

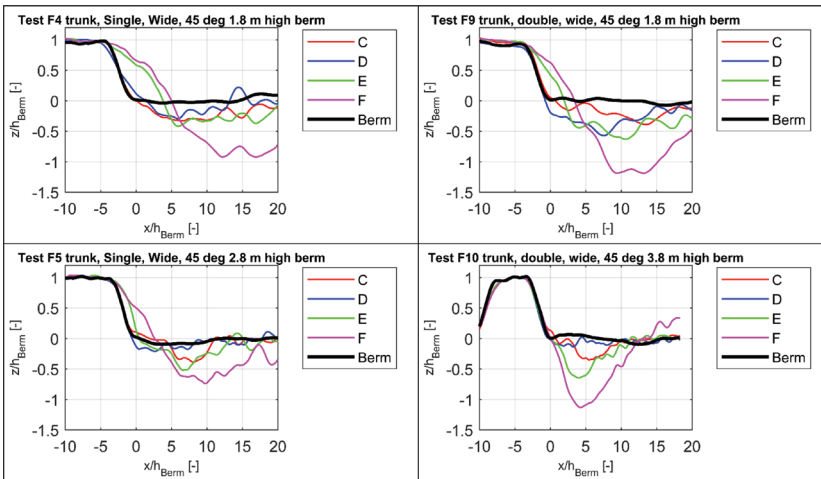


Figure 3. Berm height and seastate influence. Trunk sections for test 4, 5, 9 and 10. Wide berms, aligned at 45 degrees. Total berm height varies between 1.8, 2.8 and 3.8 m. Equilibrium scour is not reached between subtests. Trunk sections from double berm tests 9 and 10 are from downstream berm.

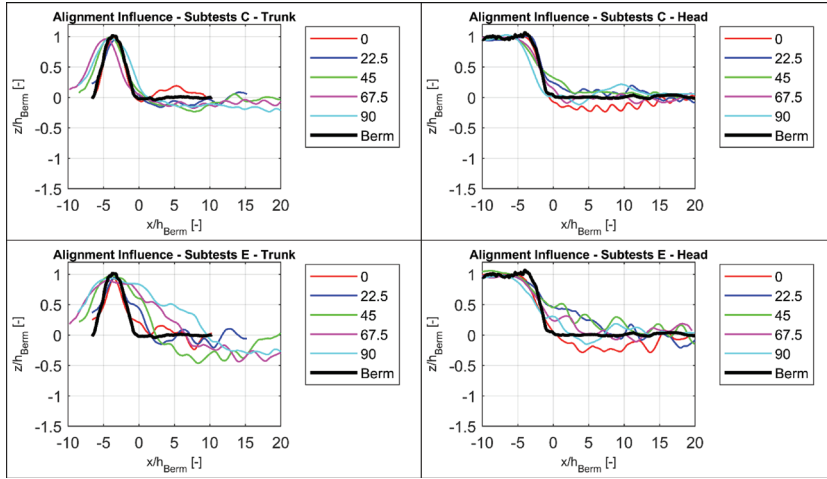


Figure 4. Berm alignment influence. Test 1, 2,3 and 6. Single, sharp crested berms with total berm height of 2.8 m. Left: Trunk sections. Right: Head sections. Note: Equilibrium scour is not reached.

Test 4 and 5 are with single berms while test 9 and 10 have double berms. For the double berms, the scour sections have been extracted at the downstream berm.

The timescale of scour increases with structure size. Since the scour tests have not been run to equilibrium, it will be expected that the tests with highest berm height (5 and 10) will exhibit the least normalised scour depth. This is the case for subtest F, but less so for subtest E. This indicates that subtest E is closer to equilibrium for that condition than subtest F.

7 INFLUENCE OF WAVE-CURRENT CONDITIONS

Influence of wave-current conditions is observed between subtest C (current dominated) and D (wave dominated) in Figure 3.

Though not fully consistent, it is observed that the wave dominated conditions tends to backfill the scour that developed under the current dominated conditions.

For current only, the scour magnitude is seen to increase significantly with current speed as seen in the scour developments between subtest E and F.

8 INFLUENCE OF BERM ALIGNMENT

The influence of berm alignment on trunk and head scour is assessed from test 1, 2, 3 and 6 in Figure 4.

All tests are with single, sharp crested berms and total berm height of 2.8 m. This height includes a 1.0 m high sand mound.

The berm alignment influence is demonstrated for current dominated conditions after subtest C and E.

Subtest F is not included due to influence of upstream berm and seabed degradation.

The influence of berm alignment was in Roulund et al (2018) for field observations seen to be significant in a setting with strong currents. The same is noted for the model test trunk section scour development.

The weak current conditions in subtest C produced very benign scour for all alignments. For the stronger current conditions in subtest E, substantial scour developed for the oblique 45 and 67.5 degree oriented berms.

Scour also developed for the perpendicular 90 degree orientation, but less than for the oblique berms.

Practically no trunk section scour developed for the parallel and near parallel berms with 0 and 22.5 degree orientation.

Head scour was only observed for the 0 degree parallel berm and was present for both weak and stronger currents. Head scour was not observed for any of the other berm alignments, but it is noted that field observations show, that head scour can also develop for non-parallel berm alignment.

9 INFLUENCE OF BERM WIDTH

Influence of berm width is assessed from test 3 (sharp crested) and 5 (wide crested) in Figure 5. The berms were aligned at 45 degrees and had total berm height of 1.8 m.

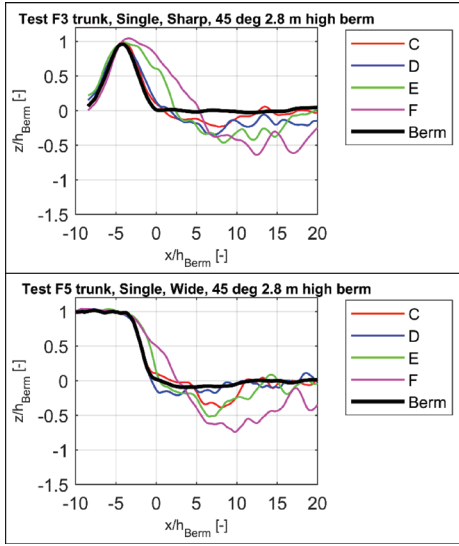


Figure 5. Berm width influence. Test F3 and F5. Note: Equilibrium scour is not reached between subtests.

The berm width does not appear to have large influence, though under strong currents (subtest F), sediment appear to pass across the sharp crested berm resulting in slightly less scour than observed for the wide crested berm.

10 INFLUENCE OF SINGLE/DOUBLE BERMS

Influence of single or double berm configuration is seen in Figure 3 for test 4 vs. 9 and 5 vs. 10 for wide crested berms. The scour depth is slightly but consistently larger for the downstream double berm.

The cause of this is likely that the upstream berm redirects or reduce sediment supply to the downstream berm thus causing larger scour for the double berm configuration than for single berm.

11 MODEL SCALE IMPACT ON ROCK BERM STABILITY

Seabed degradation and erosion of the sand berms saw the upstream end of the sharp crested berms start to degrade in subtest F.

Similar berm degradation was not seen in the field observations in Roulund et al (2018). This, even though rock berms in the field were exposed to similar and even higher sediment Shields parameter values than applied in the model tests.

The rock size for the model tests had been determined from Froude scaling of a rock size assessed stable or dynamically stable towards the wave loading of the tests. This worked fine under moderate currents and wave dominated conditions, but for strong currents, the rocks should obviously have been larger to ensure a correct stability performance on the sand slope.

The reason for the rock berm degradation in subtest F is thought to be due to a scale model effect as discussed in the following.

The rock size was Froude scaled by tradition, while the current was Shields scaled to achieve sediment mobility. Thus, the rocks became exposed to a much larger Shields parameter than would have been experienced in the field

For rocks lying on a sand slope the critical Shields parameter for mobility is reduced and was apparently exceeded in the tests, causing rock displacement in the model. In the field in contrary, it is observed that the rocks were stable on the sand slope.

A recommendation for future high current scour tests will therefore be to consider if the rock should be Shields scaled, rather than Froude scaled.

12 ROCK BERM HYDRAULIC STABILITY

Rock berm degradation/adaption to wave loading was observed for the sharp crested berms during subtest D having a Shields parameter value θ_{rock} of 0.027.

Referring to Roulund et al. (2017), this value of the Shields parameter corresponds to damage level 1 (minor reshaping of berm slope) for 90 degree berms with top width to height ratio of $B_{top}/h_{berm} = 6.0$.

The sharp crested berms of the present tests had $B_{top}/h_{berm} = 1.0$ and experienced berm lowering corresponding to damage level 3 or 4. Berm width is thus demonstrated to impact the hydraulic rock berm stability.

The damage description in Roulund et al (2017) was of a qualitative nature and for specific berm dimensions. The data has been re-analysed and recast in Figure 6. It was observed that the reshaped berms took on a parabolic form. Thus the berm shape can be uniquely described using the bottom berm width, B_{bottom} , to height, h_{berm} , ratio B_{bottom}/h_{berm} .

Figure 6 includes a data point for the degraded rock berm from subtest F1_90deg subtest D having $B_{bottom}/h_{berm} = 9.2$ after being exposed to wave dominated conditions with Shields parameter of θ_{rock} 0.027. The theoretical smallest value of B_{bottom}/t is a berm with side slopes equal to angle of repose. This theoretical limit is included in Figure 6 using an angle of repose value of 40°.

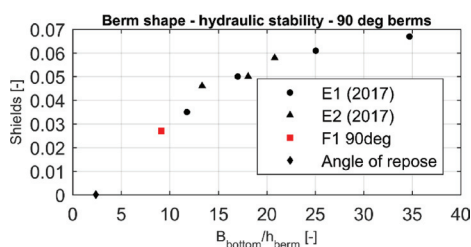


Figure 6. Rock berm hydraulic stability. Parabolic reshaped berm. Test E1 and E2 re-analysed from Roulund et al (2017).

13 CONCLUSION

Live bed scour physical model tests have been conducted to study trunk- and head section rock berm induced seabed scour and rock berm stability.

A comprehensive set of tests was carried out to identify key parameters influencing rock berm scour.

While the test series was very comprehensive, it was only scoped to interrogate the initial phase of scour development. Equilibrium scour was thus not attained. Conclusions drawn on the impact of various parameters are relative only, and do not describe the final magnitude of equilibrium scour depth.

Rock berm scour was shown to scale with berm height.

Maximum scour was found for oblique oriented berms, then followed by perpendicular berms. Only limited scour was observed for berms parallel or near parallel to the current direction.

Minor to moderate influence was observed from berm width and from single or double berm configuration.

The scour response was observed to increase significantly with increased current speed.

Flow regime change from current dominated to wave dominated conditions indicated the ability of waves to reduce or back fill scour developments.

Re-analysis of rock berm stability tests from Roulund et al (2017), showed that rock berms reshaped by wave action take on a stable parabolic profile uniquely defined by the $B_{\text{bottom}}/h_{\text{berm}}$ ratio as a function of the Shields parameter.

REFERENCES

- Escaramela, M., Roca, M. and Chellew, E. (2015). Towards better design of riprap bed sills – an experimental study. *Proceedings of the Institution of Civil Engineers – Water Management*, 170 (1). pp. 42–52.
- Roulund, A., Jensen, P.M., Marten, K.V. and Whitehouse, R.J.S. (2018). Scour and seabed changes at cable protection rock berms – Field observations. *ICSE 9th International Conference on Scour and Erosion*, Taipei, Taiwan, Nov. 2018.
- Roulund, A., Larsen, S.M., Whitehouse, R.J.S. and Crossouard, N. (2017). Hydraulic stability of cable crossing rock berms in combined waves and current. *SUT OSIG 2017*, UK, September 2017. <https://doi.org/10.3723/OSIG17.896>.
- Roulund, A., Sutherland, J., Todd, D. and Sterner, J. (2016). Parametric equations for Shields parameter and wave orbital velocity in combined current and irregular waves, *ICSE 2016 8th International Conference on Scour and Erosion*, Oxford, UK, September 2016.
- Soulsby, R.L. (2006). Simplified calculation of wave orbital velocities. *Report TR 155, Release 1.0*, HR Wallingford.
- Whitehouse, R.J.S., Damgaard, J.S. and Parkes, J. (2006). Field observations of scour around a rock berm over a subsea pipeline on a clay seabed. *ICSE 2006 3rd International Conference on Scour and Erosion*, 1–3 November 2006, Amsterdam, The Netherlands.
- Whitehouse, R.J.S., Sutherland, J., Powell, K. and Harris, J. (2014). Fast Flow Facility for sediment and morphology testing. *Coastlab14, Application of Physical Modelling to Port and Coastal Protection, Proc. of the 5th Int. Conf. 29 Sept – 2 Oct.*, Varna, Bulgaria, (eds.) Penchev, V and Pinto, FT, Vol. 2: 104–113.