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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_WQ_2.1.3.pdf
D4_HOW03_Appendix 54_ Aviation Assessments.pdf
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D4_HOW03_Appendix 58_Indicative Array Layout.pdf
D4_HOW03_Appendix 59_FCLP_rev3.pdf
D4_HOW03_Appendix 60_Draft CfD Budget Notice.pdf
D4_HOW03_Appendix 62_Q2.2.34.pdf
D4_HOW03_Appendix 63_Q2.2.7_Q2.2.44.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

[redacted]

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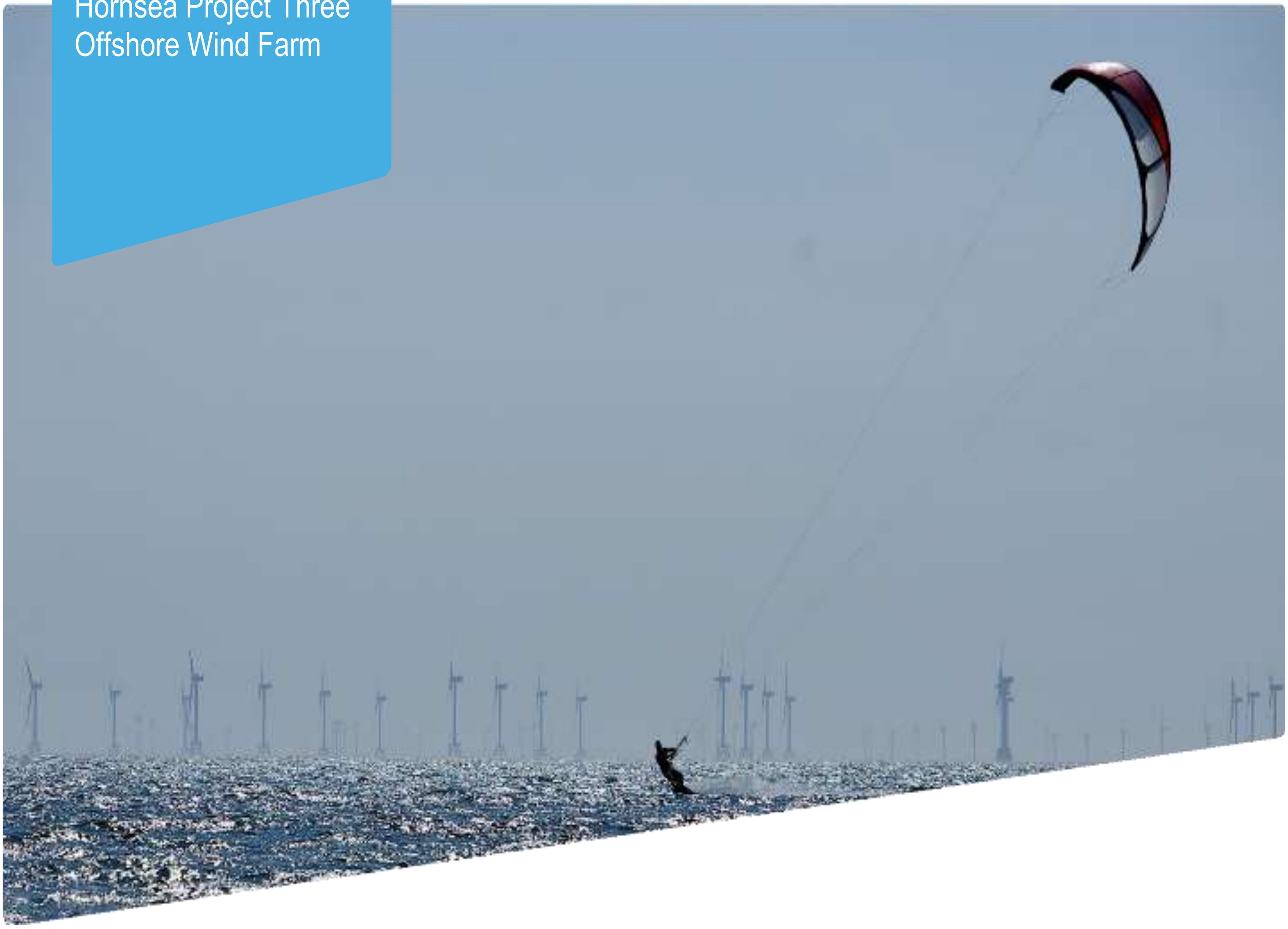

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Appendix 50 to Deadline 4 Submission – Roulund et al., 2019b

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

Scour and Erosion IX – Keh-Chia (Ed.)
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Scour and seabed changes at cable protection rock berms—field observations

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ABSTRACT: United Kingdom waters have morphologically dynamic bays and estuaries through which offshore windfarm export cables are laid. The export cables must cross existing cable and pipeline infrastructure before making landfall. Rock berms have traditionally been installed at such crossings and at locations of shallow cable burial for cable separation and protection. In some instances, the rock berms have caused scour and been affected by general seabed changes. Recent field observations of scour and seabed change at cable protection rock berms is presented.

In one location two separate rock berms are exposed to 1.0 m to 1.5 m general seabed lowering. One berm is aligned oblique to the current and has experienced excessive scour, while the other berm is aligned more parallel with the current flow direction and has experienced only minor scour.

A second location comprise a cable crossing with double rock berms aligned oblique to the current direction. The current speed was asymmetric being largest during flood and smaller during ebb tide. Excessive scour was observed in-between the two berms and on the in-shore side, while only limited scour was observed at the off-shore side of the berms. The asymmetry in scour is linked to the asymmetry in current speed indicating a strong scour dependence on the currents speed. In non-dimensional form, this dependence is linked to the so-called Shields parameter governing magnitude and mode of sediment transport.

1 INTRODUCTION

Figure 1 shows an observed scour incident that resulted in cable exposure and cable free-spanning. The scour between two parallel cable crossing rock berms caused exposure of the crossed cable. At the berm end, head scour exposed the crossing cable.

Published data and observations of rock berm scour is limited. Awareness of this phenomenon is increasing, even if only sparsely described and understood.

Scour from rock berms is typically observed in areas of strong currents, scour susceptible soils, and either where the rock berm is aligned oblique or perpendicular to the prevailing current. The latter is demonstrated in Whitehouse et al. (2006).

A rock berm aligned parallel to the prevailing current will cause comparatively little or no scour. This observation is of high interest for engineering design and cable routing and is supported by the field observations described in this paper.

A rock berm is a shallow structure placed on the seabed to stabilize or protect a cable or pipeline.

Traditionally, rock berms have been "sharp crested" having a triangular cross section with a narrow crest and gentle side slopes approximately 1:3.

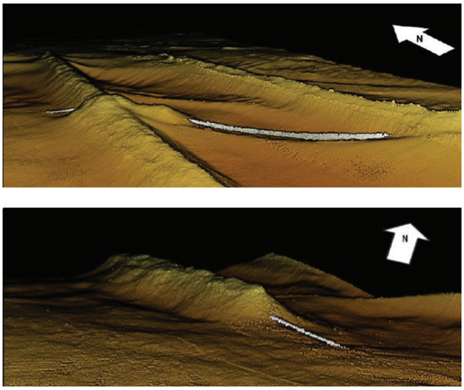

Figure 1. Scour at cable crossing rock berms resulting in fixed free span cable exposure. Two 250 m long rock berms 40 m apart. Morecambe Bay, UK.

Rock berm heights typically range from 1.0–2.0 m giving a cross-sectional seabed footprint of 7 to 13 m.

A candidate for an alternative berm profile is the "wide crested" berm. This type of berm is characterized by a wider crest but lower height than the sharp crested berm.

The wide crested berm and its hydraulic stability is described in detail in Roulund et al. (2017).

General seabed lowering around a rock berm effectively increases the berm height. Roulund et al. (2018) found that rock berm scour scales with the berm height. Thus, general seabed lowering around a rock berm will increase its scour potential.

Seabed lowering away from rock berms can also pose a cable integrity issue, simply by exposing initially buried cables. As discussed in section 10, such cable exposure may be of a temporary nature and less critical if the cable is capable of following the seabed down as the seabed lowers further.

If the cable is held in place by a rock berm, the cable just outside the berm is prevented from following the seabed down. Then a so-called fixed free span can develop as seen in Figure 1.

Seabed lowering can be assessed through morphological classification and analysis. A general classification of morphological features can be found in Knaapen (2005).

Fields observations of sand wave migration in the Outer Wash off the UK North Sea east coast is presented in Larsen et al. (2016). While typical sand wave migration speed was in the order of a few meters per year, local conditions was observed to see sand waves migrate at an order of magnitude faster.

The morphodynamics of tidal estuaries are often more chaotic than the regular sand wave fields found further offshore. Tidal estuaries may comprise interacting tidal channels, sand banks and mud flats exhibiting various degrees of mobility. This is illustrated for a number of UK sites in Burningham and French (2018).

2 SEABED SURVEYS, MODELLING AND MEASUREMENTS

Fields observations of scour are obtained primarily through multi beam echo sounding (MBES). Applied vertical datum in this paper is LAT VORF, in which LAT refers to Lowest Astronomical Tide, and VORF (Turner et al., 2010) is a modelled surface representing the variation in LAT in UK waters.

Point clouds of ungridded MBES data can be analysed to present three-dimensional objects. Examples of free spanning cables in this paper are based on ungridded MBES data.

Soil conditions at the observed scour locations are based on grab samples of surface sediments, supported by geotechnical investigations in the vicinity.

Wave, current and water levels conditions have been determined from hydrodynamic modelling by HR Wallingford using the Telemac2D and SWAN models and validated against tidal stations and measured currents and waves within the Morecambe Bay area.

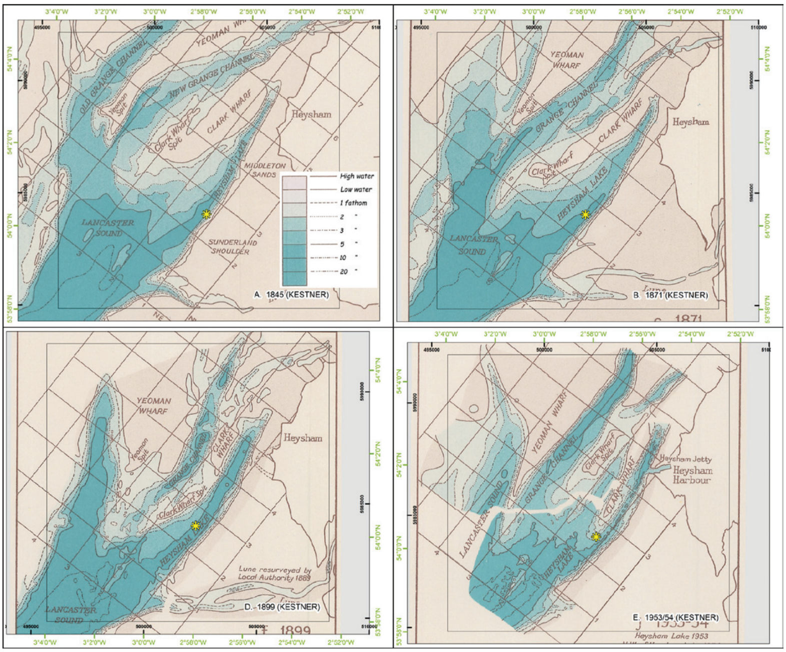

Figure 2. Cyclic tidal channel and bank migration. Example of large scale estuary morphodynamic in Morecambe Bay, Uk. Re-analyzed from Kestner (1970).

3 MORECAMBE BAY LARGE SCALE MORPHODYNAMICS

The presented scour and seabed change observations are located in Morecambe Bay on the UK west coast facing the Irish Sea. The Morecambe Bay continuously undergoes large scale estuary morphodynamic changes as presented by Kestner (1970). Kestner suggests a 40 year cyclic behaviour of tidal flats and channels. The georeferenced sea charts modified from Kestner (1970) in Figure 2 show the pronounced long term morphological dynamics within the inner part of Morecambe Bay.

While the main channels and banks remain identifiable, pronounced location shifts and planform undulations can be observed. The recent seabed surveys indicate that these changes in tidal channels and flats remains ongoing.

4 THE SCOUR INCIDENTS

Two scour incidents shown in Figure 3 are described in the following. Berm geometry details are given in Table 1.

At the Cable Splice, two short, 40 m long sharp crested single type rock berms were installed in March 2014. The berms were placed on top of shallow buried cables for both a northern and a southern export cable. The berms differed only in terms of orientation.

Excessive scour was observed only at the southern berm, while only very minor scouring took place at the geometrically identical northern rock. Both berms were installed on scour susceptible soils and both exposed to 1.0 to 1.5 m general seabed lowering developing within one year from installation. Only the orientation of the rock berms differed.

The scoured southern rock berm was aligned at 50 degrees to the prevailing current, while the non-scoured northern berm was aligned more parallel at only 17 degrees to the current.

Table 1. Berm geometry. Seabed level, length, height and orientation.

Location	$z_{sea,berm}$	L_{berm}	h_{berm}	Orientation
–	m LAT	m	m	deg N
1a, Splice, Northern	–15	40	1.4	25
1b, Splice, Southern	–17	40	1.4	–8
2a, Crossing, Northern	–11 to –7	250	1.7	85
2b, Crossing, Southern	–11 to –7	250	1.7	85

From the scour observation at the Cable Splice it is concluded that berm alignment is a key property for rock berm scour development.

At the Cable Crossing two berms were installed in March 2014. The berms were 250 m long, sharp crested and parallel, 40 m apart and placed on top of surface laid cables.

The berms were aligned at 32 degrees to the prevailing current direction. The current speed was asymmetric being largest during the flood tide towards north-east and smaller during ebb tide.

The cable crossing is located on a subtidal slope which from 2014 to 2016 experienced general seabed lowering due to tidal slope migration toward east-south-east.

On top of this seabed lowering, excessive scour was observed in-between the two berms and on the in-shore northern side, while only limited scour other than the general seabed lowering was observed at the off-shore southern side of the berms.

The asymmetry in scour is thought to be linked to the asymmetry in current speed. It is thus concluded that rock berm scour development is strongly dependent on current speed and current speed asymmetry.

In section 8, this current speed dependence is linked to the magnitude of the so-called Shields parameter.

5 SOIL CONDITIONS

Soil conditions are key properties for scour development. Rock bed and stiff clays may prevent or stop scour development. This effect is named "Geological control" and can from Figure 3 cross sections be observed within the scour holes at both the Splice and Crossing locations.

The Cable Splice is in an area of mobile marine sands bordered to the northeast and southeast by protrusions from the seabed surface of a non-erodible clay formation.

Two vibrocores, VIB15 1 km southwest and VIB06 1 km northeast of the location describe the upper soil layer as:

VIB15 – "Medium dense to dense olive grey, slightly clayey fine to medium SAND with few black, very soft clay lenses".

VIB06: "Hard, reddish brown, sandy CLAY with fine to coarse gravel" overlain by a thin veneer of "Very clayey, sandy medium to coarse GRAVEL with some shells".

Three grab samples were retrieved June 2018 within 100 m of the Cable Splice, see Figure 3. Average mean sediment grain size based on sieve analysis was XX mm.

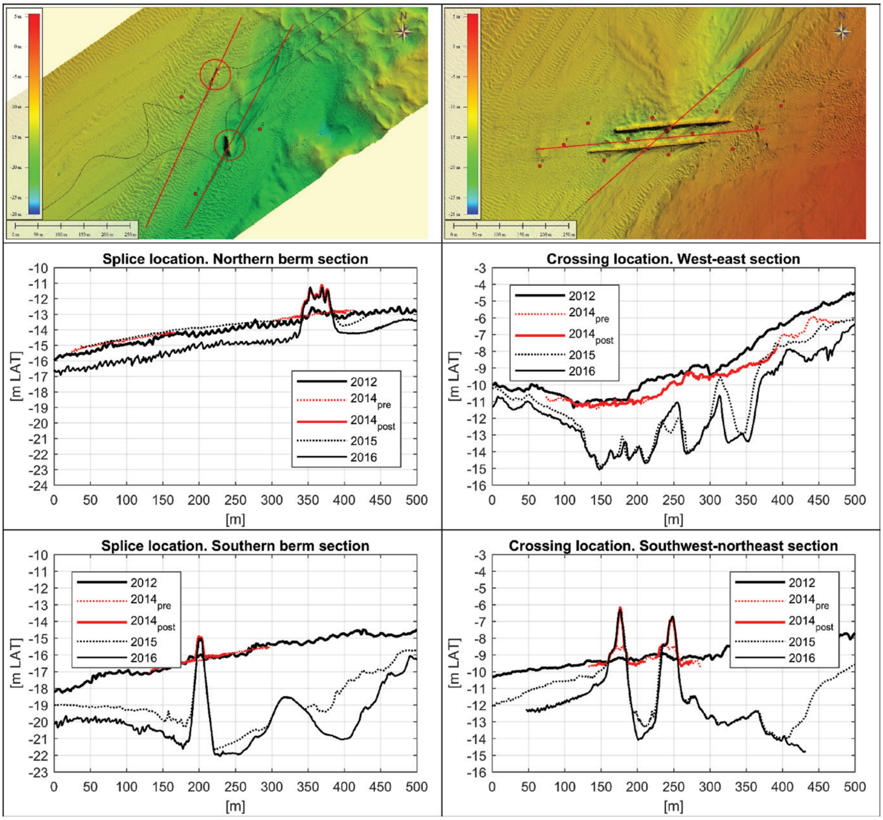

Figure 3. Fields observation of rock berm scour. Left: Cable Splice location. Right: Cable Crossing location. Top) June 2016 seabed bathymetry. Bottom sections: Nov.2012, March 2014 pre- and post rock berm as-built surveys, April 2015 and July 2016. Lines in top figure indicate section locations (start south, end north or start west, end east). Dots indicate locations of sediment grab samples.

The Cable Crossing is located on the slope of a tidal channel/-flat transition presently undergoing east-south-east migration. Most of the area comprises mobile marine SAND, with an isolated CLAY formation protruding northwest of the crossing.

Two vibro cores, 07A 600 m west and 08 A 2 km north-north-east of the location describe the upper soil layers as:

07A – "Light olive brown fine to medium clayey SAND with trace of shell fragments", "Dark grey fine SAND with dark grey/black, very soft clay bands" and "Greyish brown fine clayey SAND with many soft clay bands".

08A – "Very loose to loose, becoming medium dense to dense, light olive brown, fine to medium SAND with trace of shell fragments and occasional dark straining throughout".

Twelve grab samples were retrieved in April 2015 within and around the scoured seabed of the Cable Crossing as indicated in Figure 3.

Nine of the grab samples contained fine to medium sand with d_{50} of 0.18 to 0.31 mm with average d_{50} value of 0.23 mm. Two samples contained coarse gravel with d_{50} of 21 to 25 mm, while a single sample (5) contained fine sand with high silt content and d_{50} of 0.075 mm.

The two gravelly samples (2) and (6) were located within the scour pit. The material grading found here is thought to be a result of a winnowing process in which the finer material has been scoured away leaving coarse gravel at the bottom of the scour pit.

6 WAVE AND CURRENT CONDITIONS

The Morecambe Bay area experiences a very high tidal range, with a mean spring range of around 8.5 m and maximum spring range of 10.0 m. Depth averaged currents are routinely larger than 1.0 m/s.

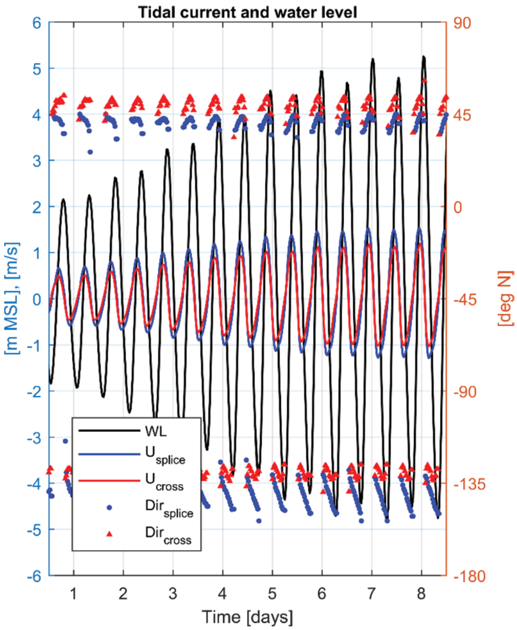

Figure 4. Tidal current and water level at Cable Splice and Cable Crossing. Neap to spring tide conditions. Water level (WL) relative to MSL (= 5.0 m LAT). Positive current velocity is applied for inshore directed flood flow, while negative current velocity is applied for offshore directed ebb flow. HR Wallingford hydrodynamic modelling.

Maximum spring and neap water levels and tidal currents modelled by HR Wallingford are shown in Figure 4 for the two scour locations. Maximum current speed occurs for water level around ±1.0 m Mean Sea Level (MSL).

Asymmetry in tidal current speeds are observed at both scour locations with the inward flood current being 15 to 20 percent larger than outward ebb current.

The entrance to Morecambe Bay faces southwest and is therefore exposed to the dominant south-westerly wind direction from the Irish Sea. The bay is partly sheltered by spits in the mouth of the bay. Waves are mostly relatively small within the bay, but can become large given certain combinations of wind direction and tidal phase.

7 SCOUR MECHANISMS

The mechanism of rock berm scour is to the authors knowledge not described in literature. Light may be shed on the scour process by seeking analogy to other scour/erosion phenomena.

The first analogy is to sediment interception seen in shoreline erosion by coastal structures such as shore perpendicular groynes and shore parallel breakwaters. The lee-side erosion at such structures is caused by their ability to intercept the littoral sediment transport and generate local flow circulation cells.

For rock berms, the berm alignment and berm height may similarly act to intercept the sediment transport on the seabed and in the near bed part of the water column, thus causing downstream scour.

Head scour at river groynes (Melville, 1992) or breakwater heads (Sumer and Fredsøe, 1997, 2002) is mainly driven by flow convergence and current induced vortex formation around the head or tip of the structure. Similar scour processes would likely also govern head scour at rock berms.

For large KC numbers Sumer and Fredsøe (2001) found that waves contribute to the scour development. Still, more likely waves should be considered as a mechanism for backfilling of current generated scour holes as reported in Sumer et al (2013). Wave dominated sites may therefore likely experience less rock berm scour than current dominated sites.

The 2 to 2½ dimensional flow across the rock berm crest may cause flow separation and vortex formation similar to flow over a back facing step if the berm is sufficiently sharp crested. When aligned oblique to the current, the generated vortex structure may roll up into a helical flow along the downstream side of the berm.

The increased turbulence generated downstream of the berm is a likely candidate for causing localised scour, while the helical flow structure may increase scour by driving sediment out away from the berm. Presence of such helical flow is observed in between the two Cable Crossing rock berms driving the formation of sandwaves in the scour pit.

Edge scour is described in Petersen et al. (2015a, 2015b) for stone covers and monopile scour protections. The edge scour can be attributed to local secondary flows and increased turbulence. Edge scour is found to scale with the rock cover height but results in only limited scour.

Edge scour is therefore considered a weaker mechanism compared to that of sediment transport interception, flow convergence and helical flow.

8 NON-DIMENSIONAL PROPERTIES

Roulund et al. 2018 demonstrated that rock berm scour scales with berm height, h_b. The berm scour, S, may therefore be expressed as:

$$\frac{S}{h_b} = S^* \cdot f(\alpha, B) \qquad (1)$$

where S^* is the non-dimensional scour depth and $f(\alpha, B)$ is an unknown functional dependence on the berm alignment, α, and width B.

The non-dimensional scour depth, S^*, will depend on a number non-dimensional flow and sediment parameters. A list of such parameters are described in the following as candidates to impact rock berm scour:

$$U_{cw}, KC, \theta, Fr, Re_h$$

Sumer and Fredsøe (2002) show that scour at pipelines and vertical piles are strongly dependent on the wave-current ratio, U_{cw}, and the Keulegan-Carpenter number, KC. In current dominated conditions the scour becomes independent of the KC number.

U_{cw} and KC impact vortex formation around the structures. Rock berm scour is possibly also dependent on these parameters, but likely to a lesser degree and with the expectation that current dominated sites will be KC independent and experience more scour than wave dominated sites. The KC number may still play an important role for back-filling of rock berm scour holes.

The observed scour at the Cable Splice and Cable Crossing locations have taken place in a current dominated area. The wave current ratio and KC number will therefore not be addressed in relation to the observed scour.

Current-only parameters addressed in the following are:

$$\theta, Fr, Re_h$$

The Shields parameter, θ, is known to govern the time scale of scour development. The rock berm scour described in Section 2 takes place in a high Shields parameter environment, making the Shields parameter a likely key property for rock berm scour.

The Froude number, Fr, describes the ratio between dynamic and hydrostatic pressure of the flow. Strong currents combined with shallow water depth increase the Froude number, making the flow increasingly responsive to local depth changes.

Sumer and Fredsøe (2002) shows $Fr > 0.2$ acts to increase pipeline scour depth. It is thus possible that increase of scour with the Froude number may also occur for rock berm scour.

The Reynolds number, Re_h, is defined relative to water depth. The Reynolds number describes the turbulence level of the approach flow. Scour processes are typically less sensitive to variations in the Reynolds number if the flow is fully turbulent.

The Froude number and the Reynolds numbers are wave independent defined as:

$$Fr = \frac{U_c}{\sqrt{gh}} \tag{2}$$

$$RE_h = \frac{U_c h}{\upsilon} \tag{3}$$

where g is acceleration of 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 Shields parameter is in the present context of current dominated conditions determined without contribution from wave bed shear stresses.

$$\theta = \frac{\tau_c}{g(\rho_s - \rho)D_{50}} \tag{5}$$

where τ_c is the current bed shear stress, ρ_s and ρ are sediment particle and water densities, and D_{50} is the mean sediment grain size.

$$\tau_c = \rho_w U_f^{\ 2} \tag{6}$$

and U_f is the friction velocity. Assuming a logarithmic velocity profile, the friction velocity can be calculated from the depth averaged current velocity:

$$U_f = \frac{U_c}{6.0 + 2.5\ln(h/k_s)} \tag{7}$$

where k_s is the grain roughness taken as:

$$k_s = 2.5D_{50} \tag{8}$$

9 FIELDS OBSERVATIONS OF NON-DIMENSIONAL PROPERTIES IN RELATION TO SCOUR DEVELOPMENT

The variation of θ, Fr, Re_h over a neap to spring tidal cycle is show in Figure 5 for the two scour locations.

Applied sediment and water characteristics are: D_{50} = 0.12 mm and 0.23 mm at respectively the Cable splice and Cable crossing locations, ρ_s = 2650 kg/m^3, ρ = 1025 kg/m^3 and $\nu = 1.4 \cdot 10^{-6}$ m^2/s. Representative seabed levels at Cable Splice and Cable Crossing are –15 and –9 m LAT, respectively with LAT being 5 m below MSL.

In the forthnightly tide, the Shields parameter is 4 to 5 times larger under spring than under neap tide. This large difference is due the non-linearity of the Shields parameter scaling with the square of the current speed.

In the daily tide, the inward flood flow gives rise to higher values of the Shields parameter than outward ebb flow. A net inward sediment transport therefore takes place at both scour locations.

As sediment transport scales non-linearly to the Shields parameter this further makes the flood, spring tide conditions dominate the scour process.

The variation in ebb and flood peak Sheilds parameter values is thus suggested as the main cause of the observed assymetry in the scour development.

A quantitative interpretation of the field observation indicates that for Shields parameter $\theta > 0.4$ significant scour develops. This is observed both north and south of the Cable Splice and north of the Cable Crossing.

South out the Cable Crossing, no or only limited scour is observed. Here the scour would be controlled by the outward ebb flow conditions, which reach a maximum Shields parameter of $\theta = 0.3$ only. The field observations thus indicate that the risk of scour increases significantly for Shields parameter $\theta > 0.3$.

The Froude number scales directly with the current speed obtaining its maximum value for water level around mean sea level. Even for spring tide conditions the Froude number remains below 0.2.

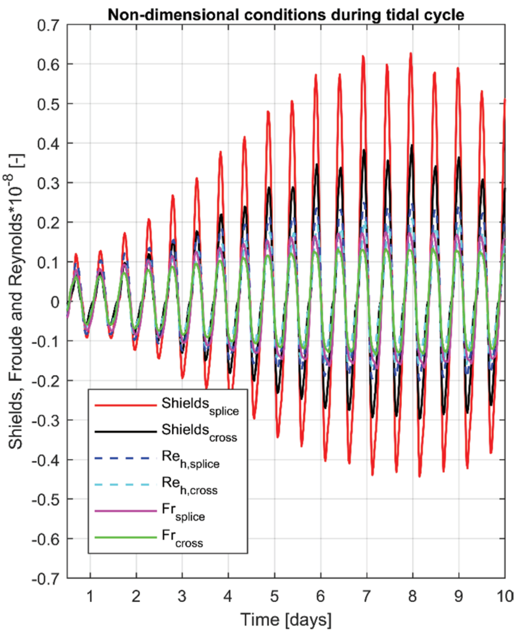

Figure 5. Shields parameter, Froude number and Reynolds number variation under neap and spring tide. Positive values are applied for inshore directed flood flow, while negative values indicate offshore directed ebb flow. Based on HR Wallingford hydrodynamic modelling.

The analogy to pipeline scour would thus indicate that for the observed magnitude of Froude number, this property is not a key cause of the scour incidents.

The Reynolds number also scales directly with current speed, and obtains its maximum slightly later for higher water levels. The Reynolds number is high O(10^7) under both neap and spring tide conditions, indicating fully turbulent flow. As such the influence of the Reynolds number cannot explain the assymetry of the scour development observed particular at the Cable Crossing location.

10 FIXED AND TEMPORARY EXPOSED CABLES

Exposure and free spanning of cables or pipelines are a typical outcome and main concern of rock berm scour. Pipeline and cable exposure also occurs due to natural seabed lowering. Cable free spans are suggested to be classified as either 1) Fixed or 2) Temporary, depending on the nature and expected duration of the free span.

Fixed cable free spans are typically seen in connection to scour and natural seabed lowering at mattress or rock covered cables. Figure 1 is an example of fixed free spanning cables. Reburial will normally not be possible. The most appropriate mitigation measure will often be rock dump coverage, if it can be designed to give limited scour impact.

Temporary free span and surface laying cables are typically observed in connection with natural seabed lowering and/or mobile bedforms. The cable follows the seabed down and can eventually self-bury. Figure 6 shows an example of temporary free spans.

Rock dumping or mattress coverage of temporary cable free spans are generally not recommended as the rock dump or mattress cover may cause creation of a permanent fixed free span in a situation of continued seabed lowering.

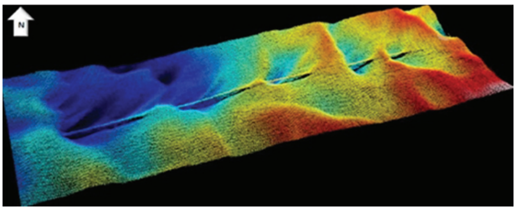

Figure 6. Image of temporary cable exposure and free span.

11 CONCLUSION

Field observations of rock berm scour have been presented for two locations. Both locations were in an area of strong tidal currents making the sites current dominated, but still occasionally exposed to large waves.

Scour and general seabed changes were observed both at a single berm, and at a double berm. The berms were in both cases aligned oblique to the prevailing current. A rock berm aligned more parallel to the current experienced no scour.

Rock berm alignment is proposed as a key property for rock berm scour.

Asymmetric scour development at the double berm Cable Crossing indicated a strong dependence of scour on the Shields parameter.

A quantitative assessment suggests that the risk of scour increases significantly for Shields parameter exceeding $\theta > 0.3$, with large scour being observed for $\theta > 0.4$.

The influence of the Froude number and Reynolds number was investigated, but no correlation to the scour development could be found.

Exposed and free spanning cables and pipelines are a typical outcome and main concern of rock berm scour. Classification of free spans as either 1) Fixed or 2) Temporary, is suggested to inform the most appropriate rectification response.

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