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Norfolk Boreas Offshore Wind Farm

The Applicant's Response to the Request for Additional Information

Applicant: Norfolk Boreas Limited
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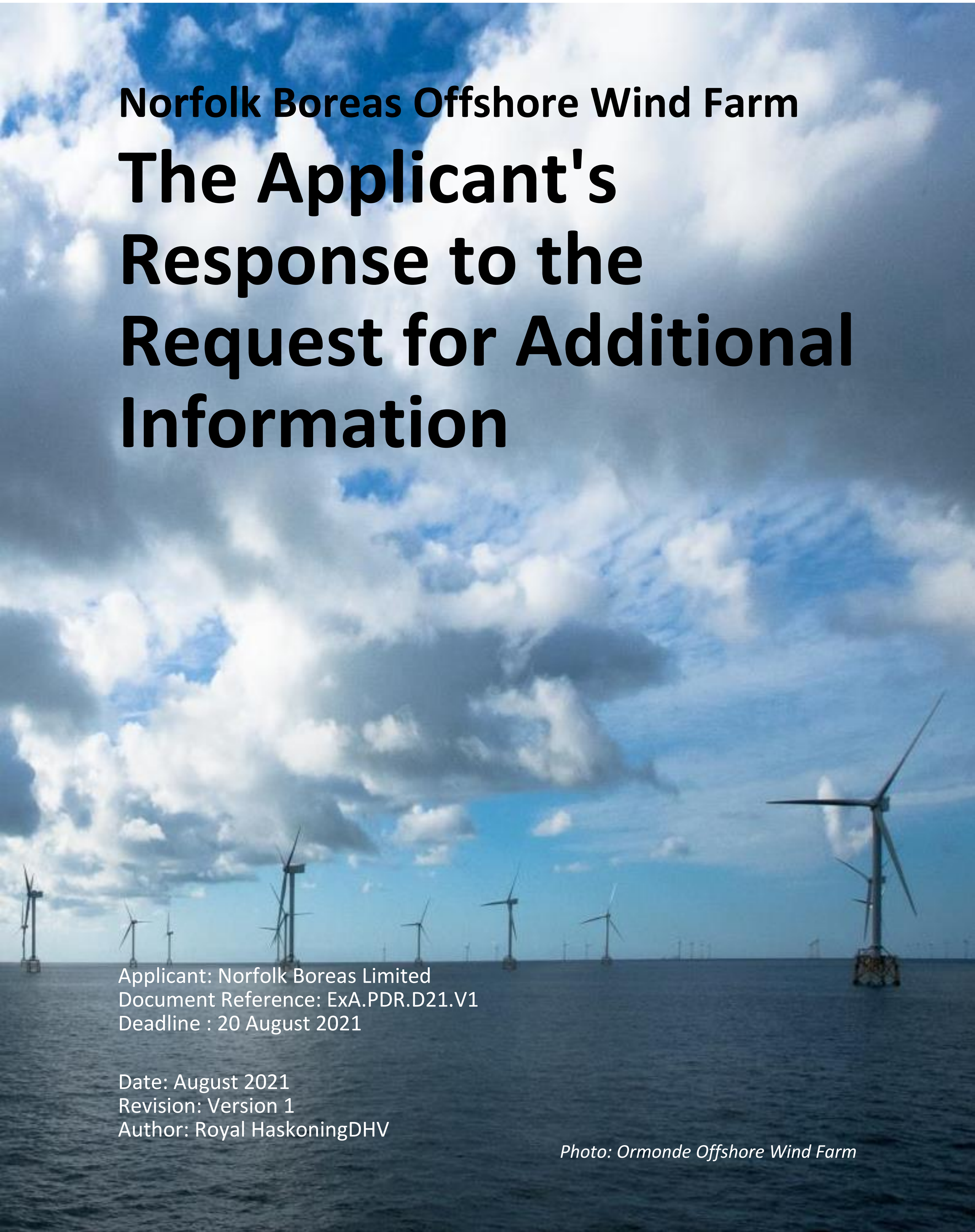

Photo: Ormonde Offshore Wind Farm

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Glossary of Acronyms

ExA	Examining Authority
HHW	Haisborough, Hammond and Winterton
HRA	Habitats Regulations Assessment
FFC	Flamborough and Filey Coast
NE	Natural England
PEIR	Preliminary Environmental Information Report
PVA	Population Viability Analysis
RSPB	Royal Society for the Protection of Birds
SAC	Special Area of Conservation
SIP	Site Integrity Plan
SoS	Secretary of State
SPA	Special Protection Area
TCE	The Crown Estate

1 Secretary of State's Requests for Additional Information

1. On the 9 July 2021 the Secretary of state published a letter requesting further information from Norfolk Boreas Limited (the Applicant) in relation to the Flamborough and Filey Coast Special Protection Area (SPA) and the Haisborough, Hammond and Winterton Special Area of Conservation (SAC). This document includes the Applicant's response to that request for further information, along with a Population Viability Analysis (PVA) report which is provided in a separate document [reference ExA.AS-2.D21.V1] that also forms part of this submission.

1.1 Flamborough and Filey Coast Special Protection Area

Paragraph number	Paragraph text:	Applicant's Response:
3	In relation to in-combination impacts on the kittiwake, razorbill, gannet, and guillemot features of the Flamborough and Filey Coast SPA, the **Applicant** is requested to provide the latest incombination assessments for collision and/or displacement effects, with and without Hornsea Project Four Offshore Wind Farm, including: • The predicted in-combination kittiwake collision mortalities, including the Hornsea Project Three Offshore Wind Farm in the assessment. • The results of updated PVA models for all of the above species and a comparison of the predicted SPA population sizes after 30 years, with and without the development.	The Applicant has provided the requested in-combination assessments for collision and displacement effects in the Updated Population Viability Analysis: Flamborough and Filey Coast SPA (document reference ExA.AS-2.D21.V1). This is summarised below. Updated tables of the cumulative and in-combination collision estimates (apportioned to the Flamborough and Filey coast SPA) for gannet and kittiwake, and of population abundance (as used to estimate displacement risk) for gannet, guillemot and razorbill have been provided. Following the advice from Natural England, these also now include the Dudgeon Extension and Sheringham Extension projects which have recently submitted preliminary environmental information reports (PEIR). The recently provided figures for the final Hornsea Project Three wind farm have also been included (these figures have also been accepted by Natural England). Totals are presented with and without the PEIR wind farms (i.e. including and excluding the preliminary figures for Hornsea Project Four, Dudgeon Extension and Sheringham Extension). Natural England has reviewed these tables (as presented in version 2 of Application document 8.26 In Principle Habitats Regulations Derogation Provision of Evidence Appendix 1 Flamborough and Filey Coast SPA In Principle Compensation) and agreed with the estimates used. As requested, for kittiwake the in-combination figures are also provided with and without the inclusion of Hornsea Project Three. The Natural England Population Viability Analysis (PVA) tool has been used for each species and the results are presented in the report (as well as the input log files to permit validation). The requested comparisons of each species' population size predicted after 30 years with and without Norfolk Boreas are provided, together with overall predictions for the in-combination effects. In addition, comparisons of the population growth rates are also provided which the Applicant considers to be a more appropriate metric for assessing potential impacts than population size based metrics. The reasons for this are related to how density dependent regulation is modelled in the Natural England PVA tool. This is explained in the report and is summarised below. Natural populations are subject to regulation through competition for limited resources and this process is referred to as density dependence, since the strength of the regulatory effect

Paragraph number	Paragraph text:	Applicant's Response:
		is determined by the size of the population. It is therefore appropriate to consider such effects when making predictions about future population sizes. However, it is difficult to collect data on the precise mechanisms involved. This has led Natural England to take a position that because of the uncertainty about the operation of density dependence, population predictions used for impact assessment (i.e. such as those obtained from PVA) should not include density dependence. However, density independent predictions of impact consequences over-estimate the likely effects since the models lack the realistic mechanisms by which increases in mortality (whether natural or anthropogenic) are offset by increases in, for example, productivity. The Applicant acknowledges the uncertainties in both the estimation of offshore wind farm impacts and seabird demography, and that it is therefore appropriate to apply precaution when predicting population consequences. However, the Applicant also considers that precaution has already been applied at several stages of the assessment, leading to over-precautionary impact estimates, and these are further compounded if the impact consequences are only assessed through the use of density independent PVA. Furthermore, there is ample evidence that seabird populations are subject to density dependent regulation. Therefore it is appropriate to apply a balanced approach in the PVA and give consideration to both density independent and density dependent PVA results in order to understand how assumptions on this matter affect predictions. The online version of the Natural England PVA tool, which the Applicant has been advised to use, provides one option for modelling density dependence and the mechanism used is not considered to represent realistic seabird population responses to competition. In simple terms, the NE PVA tool implements density dependent regulation in a very weak manner, the effect of which is outputs which are nearly indistinguishable from density independent ones. Therefore, it was apparent that very little additional insight would be gained into how the FFC SPA seabird populations may respond to impacts from running simulations using the NE PVA with the density dependent option selected. Thus, all models were run as density independent simulations, but the Applicant notes that the model does not properly account for key processes by which natural populations are regulated, particularly competition for resources such as prey and breeding space. In summary, the NE PVA tool effectively constrains users to undertake density independent simulations (or density dependent ones which do not adequately or realistically account for

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		important population regulating processes) and under most circumstances these predictions are the most precautionary that can be generated by a population model with the least theoretical and empirical support from seabird population studies. The above concerns about the PVA tool, and the results obtained notwithstanding, the Applicant has presented a full assessment of the consequences of predicted impacts as requested. These have demonstrated that for all species, even when the total in-combination impacts are modelled, there will only be small reductions in the population growth rates (the appropriate metric for considering density independent PVA outputs). The reductions in the growth rates will only slow the current rates of population growth, not cause population declines and the difference in the growth rates predicted with and without the Norfolk Boreas wind farm were extremely small. The maximum additional reductions in population growth rate attributable to Norfolk Boreas were: • Gannet 0.12%; • Kittiwake 0.017%; • Guillemot 0.010%; and • Razorbill 0.004%. The conclusions from the updated PVA and assessment are unchanged from those presented during the examination (REP2-035) and provide further support for the Applicant's position throughout the application and examination process that there will not be any Adverse Effects on Integrity for the Flamborough and Filey Coast SPA due to the Norfolk Boreas wind farm either alone or in-combination with other plans and projects.

1.2 Haisborough Hammond and Winterton Special Area of Conservation

Paragraph number	Paragraph text:	Applicant's Response:
4	In addition to the evidence submitted in the ABPMer Sandwave Study (2019), the **Applicant** and other **Interested Parties** are requested to provide details of any new evidence for the recovery of sandbanks/ sandwaves after levelling and cable installation, together with a commentary on its relevance to the proposed works at the SAC.	In the Information to support Habitats Regulations Assessment (HRA) [APP-201] the Applicant provided objective evidence which demonstrated that, due to the sandy nature of the seabed and the high sediment mobility experienced within the Haisborough, Hammond and Winterton (HHW) SAC, sandbanks and sandwaves are highly likely to exhibit recovery from any effects caused by pre-sweeping (seabed levelling) and export cable installation. The Information to Support HRA document (and specifically section 7.4.1.1.1) does draw heavily on modelling work and expert judgement presented in ABPMer (2018) [APP-206] and it also refers to relevant examples from existing wind farms where sandwave recovery in similar conditions to the HHW SAC has occurred. An example used is that of Race Bank offshore wind farm (DONG, 2017) where bathymetry monitoring provided evidence that sandwaves were showing signs of recovery within five months of export cable installation. However, at that point in time evidence of the continued recovery past five months had not yet been published. The Applicant acknowledges that, at the point of application submission, there was only a small number of examples from other offshore wind farm projects demonstrating sandwave or sandbank recovery from pre-sweeping (also referred to as seabed levelling or simply dredging). In the case of Race Bank, evidence demonstrated initial recovery but, at that stage, it was not known if recovery would continue and if full recovery would be achieved. Since then, further evidence of continued sandwave recovery has become available for Race Bank, and this is presented below. During the examination Natural England did acknowledge, in the Statement of Common Ground [REP16-010], that the mobile nature of the HHW SAC sandbank system would make it more likely to recover from changes in structure than less mobile sandbank systems, however through recent consultation with Natural England, the Applicant understands that they wish to see evidence of examples where <u>continued</u> recovery of sandwaves over longer timeframes has occurred. This request also aligns with the request from the SoS and therefore the Applicant has provided evidence to satisfy both Natural England and the SoS's requests. Included as Appendix 1 of this document is a paper published in 2019 by Larsen et al. The paper analyses data provided by Ørsted from 19 different surveys on the Race Bank offshore wind farm to assess the recovery of sandwaves from dredging (also known as pre-

Paragraph number	Paragraph text:	Applicant's Response:
		sweeping) as part of the cable installation. The Analysis shows that of the sandwaves observed, full recovery had occurred or was very well progressed within a single year of the impact occurring. One example showed recovery of a *3.5 metre high sandwave through which a 16m bottom width trench was dredged. Surveys covering 11 months show that the sandwaves almost fully regenerated*". Images of bathymetric data presented in Figure 2 of the paper show that the cable trench, which was clearly visible immediately following the cable installation, had become very faint four months after installation and had almost completely disappeared after 11 months. Furthermore, as part of an application to vary a marine licence to undertake remedial works to the array cables within the Race Bank offshore wind farm, the project was requested, by Natural England, to provide recent evidence of sandwave recovery. In response the images shown in Appendix 2 of this document were submitted. The first image shows processed bathymetric data from a survey in February 2019. In this image a 6m wide trench, which is a result of the cable installation, is clearly visible. The next image shows bathymetric data from a survey completed in March 2020. In this image the trench has completely disappeared and the sandwaves can be seen to have recovered. The final image shows the location of the cable beneath the sandwaves that have reformed over it. Race Bank offshore wind farm is located in the Race Bank-North Ridge-Dudgeon Shoal sandbank system which exhibits very similar environmental conditions to that experienced within the HHW SAC. As described in the Larsen et al (2019) paper the sediment type and Race Bank consists of *unconsolidated Holocene sediments of sand and gravel… "borehole data from across the site show a relatively uniform top sediment layer, consisting of fine to medium very well sorted sand with a negligible fines content*." *The majority of boreholes have a median grain size between 0.17 mm and 0.45mm*. This is very similar to sediment conditions evident within the HHW SAC which are described in the ABPmer sandwave study [APP-206] as being "*broadly characterised as coarse Holocene sediments, predominantly sand, with pockets of slightly gravelly sand and gravelly sand*". Furthermore, as stated in the ABPMer study, sediment samples are characterised as predominantly well-sorted with limited occurrences of poorly sorted sediment with a medium grain size in the range 250 to 500µm (0.25-0.50mm), corresponding to medium sand.

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		Due to the fact that Race Bank-North Ridge-Dudgeon Shoal sandbank system and the HHW system are both located in the Southern North Sea they also experience very similar hydrodynamic conditions. Current induced sediment transport at both sites aligns primarily with a North north-west to South south-east axis (see Figure 1 in Larsen et al (2018) paper and Figure 3 in the ABPmer report). Sandwave migration rates at both sites are also similar with the Larsen et al (2019) paper reporting migration rates between 3.6 and 36m/yr and the ABPmer study reporting rates between 5 and 30m/yr. Given the similarities in the approach to seabed preparation (i.e dredging and pre-sweeping), as well as the similarities in the environmental conditions which govern the two sandbank systems, the Larsen et al (2019) paper and the images presented in Appendix 2 provide additional support to the assumptions made in the Information to support HRA [APP-201] that recovery of sandwaves within the HHW SAC will occur following any sandwave levelling undertaken for the Norfolk Boreas project. Further to the evidence presented above, The Crown Estate (TCE) has published a review of cable installation, protection, and habitat recoverability (2019) undertaken by RPS. The TCE commissioned review is included as Appendix 3 of this document. The report reviews monitoring data from numerous offshore wind farms in UK waters and collates information on how the seabed has recovered from various different impacts in various different marine conditions. Under the section "reviewing physical impacts of cable installation", the report demonstrates that areas with sandy seabed types usually recover rapidly and in full following seabed levelling and trenching. The report finds that where evidence of sandwave levelling or cable trenching does remain following cable installation (i.e sandwaves have not recovered) this has occurred in areas with higher fine sediment content (muds and silts). The report concludes that, *"sandy sediments were generally shown to recover well following cable installation as evidenced by a lack of cable trenches observed at a number of offshore wind farms (e.g. Barrow, Burbo Bank, sand areas of Sheringham Shoal and Robin Rigg)."* The TCE commissioned review also demonstrates that where recovery had not occurred completely in sandy habitats and therefore signs of trenches were recorded in the years following cable installation, these examples were limited to areas with low levels of sediment transport (i.e. less dynamic areas with low seabed mobility). Therefore, in

Paragraph number	Paragraph text:	Applicant's Response:
		summary the findings demonstrate that sandy seabed types with high seabed mobility create the best conditions for sandwave recovery. As described above the HHW SAC sandbanks system is a very mobile, with high levels of sediment transport. This is acknowledged by Natural England in the statement of common ground [REP16-010]. The HHW SAC is also sand dominated (described as such on the JNCC's HHW SAC webpage[1] with further information on this is provided above and below) and therefore provides the ideal conditions for sandwave and sandbank recovery. The findings of the TCE review further support the conclusions made by the Applicant in its Information to Support HRA document [APP-201] that the sandbanks and sandwaves within the HHW SAC are very likely to fully and rapidly recover. The section of the Norfolk Boreas offshore cable corridor which crosses the HHW SAC is particularly dominated by sandy sediments, as shown in Figure 10.2 of the Environmental Statement [APP-291]. Therefore, the HHW SAC would be expected to largely follow the examples of recovery from Barrow, Burbo Bank, Sheringham Shoal and Robbin Rig wind farms as presented within the TCE commissioned review. Noting that the export cable routes for Sheringham Shoal and Norfolk Boreas are both located within the southern North Sea[2]. It should also be noted that the Applicant has committed to significant mitigation measures, which have not been employed by previous projects including those projects referenced within Appendix 1, 2 and 3, to aid sandbank and sandwave recovery. These include: 1. Limiting the amount of material dredged within the HHW SAC to 500,000m^3. 2. Reducing the number of export cables (and therefore the area of disturbance) from six to two. 3. Ensuring that all dredged sediment remains within the SAC.

[1] https://jncc.gov.uk/our-work/haisborough-hammond-and-winterton-mpa/

[2] Equinor have plans to extend the Sheringham Shoal offshore wind farm and have recently published their Preliminary Environmental Information Report. The Applicant has reviewed the information available and concluded that there is no potential for cumulative effects on seabed features as a result of the construction or operation of both projects.

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		4. Disposing of any dredged sediment close to the seabed using a fall pipe from the dredging vessel. 5. Disposing of sediment within a linear strip close to the cable route. 6. Disposing of material updrift of the cable route to allow infill of any dredged areas as soon as possible following cable installation. With these measures in place, it is anticipated that the speed and fullness of recovery would be increased dramatically. The Applicant recognises that it is not just the recovery of the physical form of the sandbanks that is important, but also the recovery of the associated biological communities. In [REP10-033] (in response to Natural England's comments on the Outline Norfolk Boreas Haisborough Hammond and Winterton Special Area of Conservation Site Integrity Plan and Cable Specification, Installation and Monitoring Plan) the Applicant provides evidence of how biological communities of the type found within the HHW SAC are likely to recover within 1 to 3 years of effects occurring. For example, in [REP10-033] the Applicant cites Newell & Woodcock (2013) who conclude that "*An overview of the literature confirmed that recovery of both substrate composition and associated biological resources is relatively fast in high energy environments characterised by sands that are colonised by mobile opportunistic species with a high rate of growth and reproduction*". Such communities are those which characterise the HHW SAC. The further evidence of sandwave recovery following cable installation which is now available (e.g., from Race Bank offshore wind farm and the TCE commissioned review) provides additional confidence in the evidence previously submitted to the Norfolk Boreas examination, that a full and rapid recovery will occur and therefore an Adverse Effect on Integrity can be ruled out. Furthermore, this evidence provides support for the use of pre-sweeping (also known as sandwave levelling) as the preferred option from an ecological perspective, to achieve deeper cable burial and reduce or remove the need for cable protection. It also increases the likelihood that the process of pre-sweeping will be permitted by the regulator (in consultation with the statutory nature conservation body), therefore increasing the confidence that cable protection will not be required within the HHW SAC.

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		In conclusion the additional evidence presented here, along with evidence submitted in the Information to support HRA [APP-201] and during the Norfolk Boreas examination, in addition to the comprehensive mitigation measures committed to by the Applicant are considered to provide the SoS with sufficient certainty that Adverse Effect on Integrity can be ruled out for the sandbank features of the HHW SAC for both temporary disturbance and long-term effects as a result of the Norfolk Boreas project. Furthermore, due to the increased certainty of sandwave recovery following pre-sweeping and the fact that with the use of pre-sweeping the Applicant is confident that cable protection due to adverse ground conditions is very unlikely to be required (see version 2 of document 8.25 of the Norfolk Boreas Application (In Principle Habitats Regulations Derogation, Provision of Evidence Appendix 3 Haisborough, Hammond and Winterton SAC In Principle Compensation) and Appendix 2 of the Applicant's response to request for information for the 25 June 2021 Deadline (ExA.PD.D19.V1)) the Applicant maintains that an AEoI can be ruled out for all features of the HHW SAC.

2 References

ABPMer (2018) Norfolk Vanguard and Norfolk Boreas Export Cable Route Sandwave bed levelling. APP-206 of the Norfolk Boreas Examination library. Available at: https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010087/EN010087-000379-5.3.7.1%20Information%20to%20Support%20HRA%20Appendix%207.1%20ABPmer%20Sandwave%20Study.pdf
DONG Energy, (2017). Race Bank Export Cable Dredge Areas, pre, dredged and post dredge images. Available to download from the MMO Public Register.
Larsen. S.M , Roulund. A and Mcintyre. D.L (2019). Regeneration of partially dredged sandwaves . Coastal Sediments 2019, *pp. 3026-3039* Available at: https://www.worldscientific.com/doi/pdf/10.1142/9789811204487_0260?download=true and included as Appendix 1 below.
RPS (2019). Review of Cable Installation, Protection Mitigation and Habitat recoverability. Commissioned by the Crown Estate. Available at: file:///C:/Users/303922/Box/PB5640%20Norfolk%20Projects/PB5640%20NP%20Exchange/01%20Post%20Examination/03%20Norfolk%20Boreas%20specific/03%2020th%20August%20Deadline/Evidence%20of%20sand%20wave%20leveling%20recovery/RPS%20review-of-cable-installation-protection-mitigation-and-habitat-recoverability.pdf and included as Appendix 3 below.

Appendix 1 Regeneration of partially dredged sandwaves Paper (Larsen et al 2019)

2. Provided in this Appendix is a paper written by Larsen et al (2019).

REGENERATION OF PARTIALLY DREDGED SANDWAVES*

SIGNE MIE LARSEN[1], ANDREAS ROULUND[2], DUNCAN LEE MCINTYRE[3]

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Abstract: Throughout the development and construction phases of Race Bank Offshore Windfarm in the United Kingdom several bathymetric surveys were undertaken to understand this morphologically complex site's seabed variability. A unique opportunity to study sandwaves response to dredging was identified. This paper focusses on how sandwaves having been partially dredged for offshore cable installation purposes respond to dredging activities and to what degree they regenerate and reform within the first year. One example shows a 3.5 metre high sandwave through which a 16 m bottom width trench was dredged. Surveys covering 11 months show that the sandwaves almost fully regenerated, while results from another location show bi-furcation in the re-generated sandwave. The bedform orientation and trench orientation relative to dominating current direction differs between the areas, which suggests either crest orientation or dredged trench orientation influencing the time scale and pattern of regeneration.

Introduction

The offshore wind industry is rapidly expanding and by 2030 The International Energy Agency (IEA) expect 30 % of energy in Europe to stem from wind energy, making this Europe's most important source of energy. With the growth comes an increase in offshore installed cables and structures. As these offshore installations cross various seabed types from surfzone through tidal flats all the way to deeper offshore waters interactions with a vast number of bedform types are inevitable requiring a better understanding of the seabed features encountered - understanding how they behave is crucial for building with nature.

Race Bank Offshore Windfarm (located in the southern North Sea, United Kingdom) has a high degree of morphological complexity (Larsen *et al.* 2016), including sandwaves of varying orientation, height and mobility. Sandwaves are large features with heights up to several metres and migration rates up to tens of metres per year (Knaapen 2005). To minimise lifetime risk of cable exposure or for installation tool performance it can be necessary to dredge or partly dredge away the sandwaves prior to cable installation. It is important to understand if and how fast sandwaves regenerate for two reasons; 1) to make sure the dredging activities do not permanently impact the original seabed features and 2) to find out how fast the sandwaves regenerate to optimise cable installation and dredge volume. Only few publications are available on this subject. This paper aims to add further field experience to existing knowledge and allow qualitative conclusions to be made on sandwave regeneration.

Background

For cable installation and to investigate the response of sandwaves to partial dredging, two 16 m bottom width trenches were dredged through two different areas, Area 1 and Area 2, within the Race Bank Offshore Wind Farm. Multiple high-resolution bathymetry data sets have been collected during the development and construction phases (see Table 1). The survey frequency in the period immediately after dredging is very high to insure the any initial regeneration is captured and the period where the trench remains open is determined. Within the first month Area 1 and Area 2 are surveyed 10 and 13 times, respectively. After the first month the survey frequency decreases and the focus is the long-term regeneration. The grid spacing for all surveys is 0.2 m, except the survey from April 1st 2017 in Area 1, where the resolution is 1.0 m.

Table 1. List of bathymetric survey dates and days after in-survey for Area 1 and 2.

Area 1		Area 2	
Survey date and time	**Days after in-survey**	**Survey date and time**	**Days after in-survey**
06.05.2016 10:50	-	05.05.2016 20:00	-
07.05.2016 17:30	1	06.05.2016 22:50	1
08.05.2016 06:54	2	07.05.2016 07:09	1
08.05.2016 09:02	2	07.05.2016 08:59	2
08.05.2016 11:04	2	07.05.2016 10:55	2
10.05.2016 07:50	4	07.05.2016 12:07	2
11.05.2016 10:00	5	08.05.2016 08:07	3
11.05.2016 14:05	5	08.05.2016 10:06	3
12.05.2016 10:40	6	08.05.2016 12:07	3
16.05.2016 12:35	10	10.05.2016 09:10	5
27.05.2016 08:25	20	11.05.2016 08:50	6

Table 1 (continued)

Area 1		Area 2	
Survey date and time	**Days after in-survey**	**Survey date and time**	**Days after in-survey**
06.06.2016 08:48	30	11.05.2016 12:30	6
25.06.2016 08:00	49	16.05.2016 11:35	11
01.08.2016 11:30	87	27.05.2016 09:48	22
19.09.2016	137	07.06.2016 09:13	33
01.04.2017	330	25.06.2016 09:08	51
-	-	01.08.2016 10:10	87
-	-	19.09.2016	136
-	-	08.03.2017	306

Method

From the bathymetry datasets the bedform characteristics such as seabed regeneration can be established. Regeneration of sandwaves is determined from identifying and comparing sandwaves in cross profiles covering the available bathymetry surveys as well as cut-and-fill analysis. Comparisons of the bathymetry to hydrodynamic conditions are used to analyse changes in regeneration patterns.

Sediment type and grain size

The seabed top layer at Race Bank consists of unconsolidated Holocene sediments of sand and gravel. No dedicated samples of the seabed sediment in Area 1 and Area 2 have been taken. However, borehole data from across the site show a relatively uniform top sediment layer, consisting of fine to medium very well sorted sand with a negligible fines content. The majority of boreholes have a median grain size between 0.17 mm and 0.45 mm. Soil data is based on results from geotechnical site investigations by Geo and Fugro.

Hydrodynamic Conditions

The southern North Sea is dominated by tidal current in the NW and SE directions. Fig. 1 show a depth averaged current rose with current velocity up to 1.2 m/s directed towards 180 degrees N and 335 degrees N. The largest waves are coming from a northern direction and reach significant wave heights, H_{m0}, up to 5.2 m. The tidal range is 6 m. Due to the close proximity of the two areas the hydrodynamic conditions in Fig. 1 is applicable for both areas.

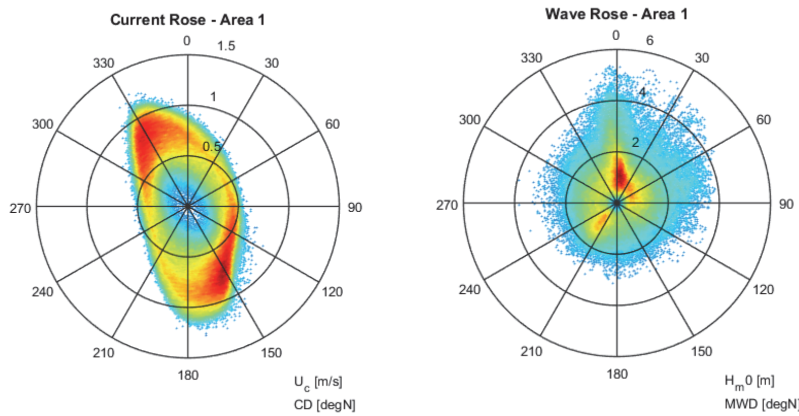

Fig. 1. Left: Depth-Averaged current rose for Area 1. Current direction is going towards [degrees N]. Right: Wave rose based on significant wave height. direction is coming from [degrees N]. Both are based on data from DHI Nemo model using data from 15.01.1979-28.02.2015.

Results - Area 1

Site Description

The seabed level in Area 1 varies between -10.0 m and -15.3 m relative to LAT. Area 1 is located in a highly morphologically dynamic area just south of the North Ridge, consisting of fast migrating sandwaves overlain with megaripples (designated as Zone 4, Larsen *et al.* 2016). In Area 1 two sandwaves are present, referred hereafter as Sandwave 1 and Sandwave 2 (see Fig. 2). Sandwave 1 has a height of 3.5 m whereas Sandwave 2 is 2.8 m high, both are approximately 90 m long. The migration direction of both sandwaves and megaripples is approximately 320°N, aligned with the prevailing current direction. In Larsen *et al.* 2016 the migration rate for Zone 4 is assessed to 31 m/yr, however, the individual rate for each of these two bedforms is slightly higher, around 36 m/yr in the period 2006 to 2016.

Available Survey Data

Over a 330-days long period from May 6, 2016 to April 1, 2017 16 surveys were performed over the two sandwaves in Area 1 along a 16 m bottom width trench dredged through the sandwaves. Figure 2 shows the In-survey and Out-survey, as well as the two last surveys 137 days and 330 days, respectively, after the In-survey.

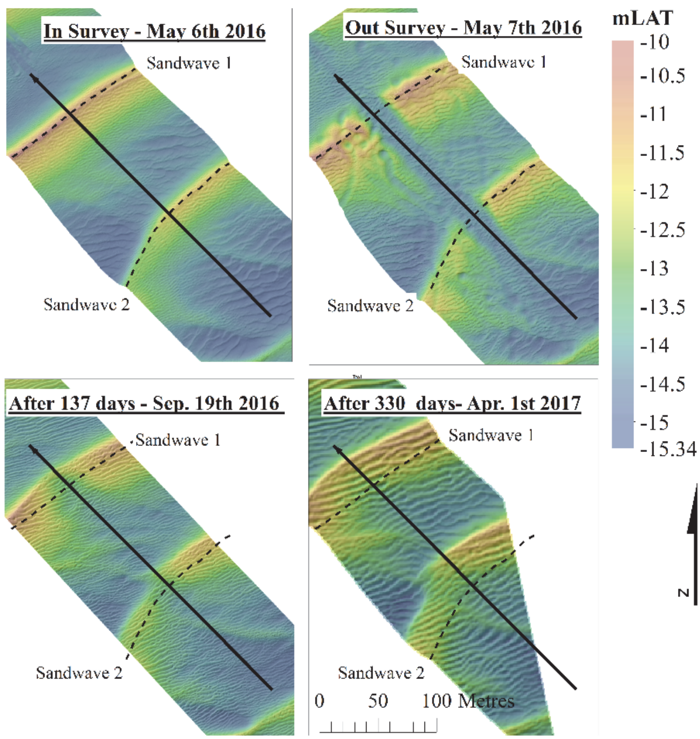

Fig. 2. Multibeam echo sounding surveys of Area 1. In-survey, out-survey, 4 and 11 months after dredging. Dashed lines are sandwave crests at time of in-survey, black arrows indicate the location and direction of profiles in Fig. 3. (Profile coordinates: From E: 352952.9 N: 5909201 to E: 352744.9 N: 5909410.2, UTM 31N).

In Fig. 3 profiles through the dredged trench are shown for the above mentioned 4 surveys. The profiles and the dredged trench are perpendicular to the sandwaves and to the prevailing current direction from Fig. 1. The orientation of the megaripples superimposed onto the sandwaves further confirms the local current direction. The data show backfill of the dredged trench and clear regeneration of the sandwaves reaching 74 % for Sandwave 1 and 67 % for Sandwave 2 of their original height within the 11 month covered by survey data.

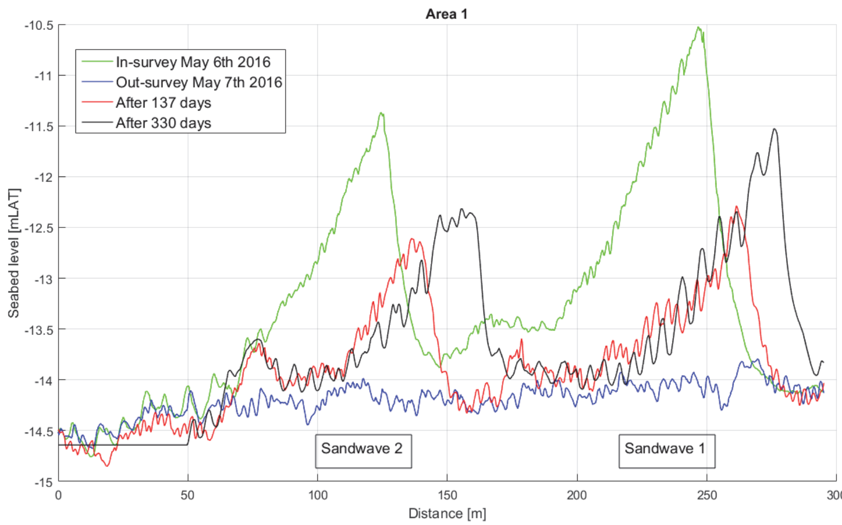

Fig. 3. Seabed profiles along line shown in Fig. 2 for Area 1. Data collected between 6, May 2016 and 1, April 2017.

Results - Area 2

Site Description

The seabed level in Area 2 varies between -12.2 m and -17.2 m relative to LAT. Area 2 is located in a transitional zone between the large slowly migrating Race Bank sandwaves to the south and the highly morphologically dynamic Zone 4 to the North (designated as Zone 2a, Larsen *et al.* 2016). In this area a tendency to bifurcation and convergence of the sandwaves exist.

One sandwave is found in Area 2 having a height of 2.3 m and a length of approximately 35 m (Fig. 4). The migration direction is 330°N for the sandwave, whereas the megaripples show a more complex pattern, which seems to be affected by the local morphology. In Larsen *et al.* (2016) the migration rate for Zone 2a was assessed to 27 m/yr, however, the migration rate of the dredged sandwave in Area 2 appears to be in a temporary state of stagnation. Throughout the 10 months of survey coverage the sandwave shows no migration, however in the period 2006 to 2016 the sandwave in Area 2 have migrated 3.6 m/yr in average. The sandwave is part of a bifurcation with the bedform to the south giving it a different orientation compared to the surrounding bedforms, which could explain the slow migration rate.

Available Survey Data

In a 306-day period from May 5, 2016 to March 8, 2017 Area 2 was surveyed 19 times; just before and in the 306 days following dredging of a 16 m wide trench through the sandwave. Fig. 4 shows the In-survey and Out-survey, as well as the two last surveys 136 days and 306 days, respectively, after the In-survey.

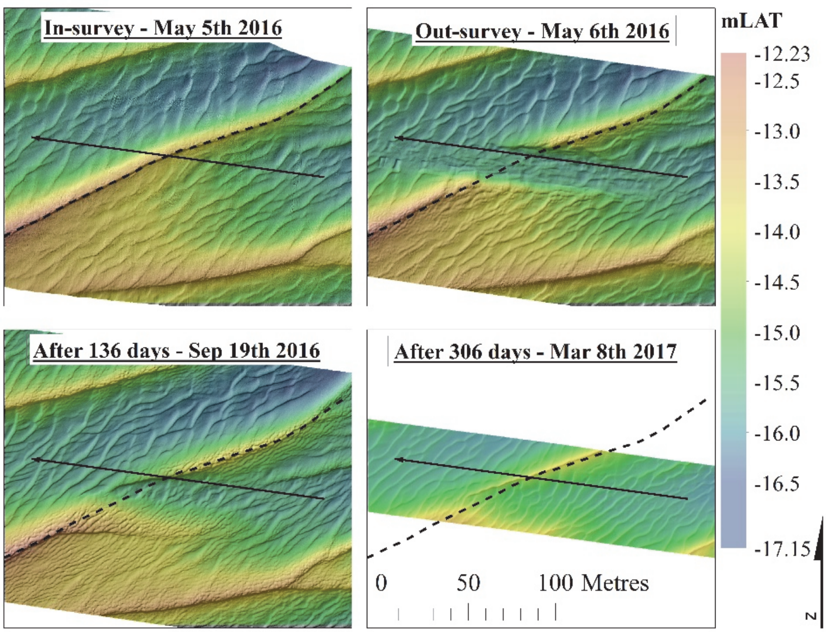

Fig. 4. Multibeam echo sounding surveys of Area 2. In-survey, out-survey, 4 and 10 months after dredging. Dashed line is sandwave crest at time of in-survey, black arrows indicate the location and direction of profiles from Fig. 6. (Profile coordinates: From E: 352860.9 N:5907503 to E:352692.4 N:5907526.3 UTM 31N).

Fig. 4 shows that the dredged sandwave tends to develop a bifurcation in the southern part of the trench, rather than the bedform regenerating to the original shape. The tendency is further highlighted by the difference plot in Fig. 5, where erosion is seen in the southern part of the trench, followed by deposition creating the new leg. This causes the trench to stay open in the southern part of the dredged channel, whereas the sandwave is regenerating in the northern part.

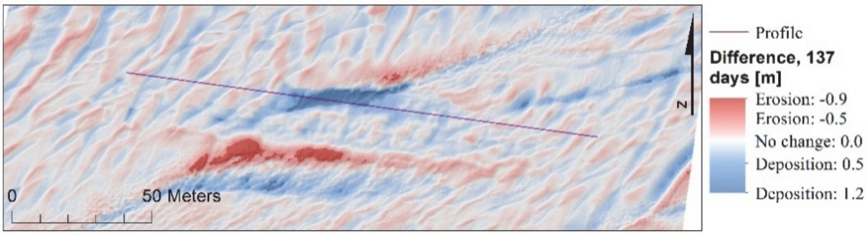

Fig. 5. Difference in seabed level (meters) between out-survey and after 137 days. Profile line corresponds to profile from Fig. 4 and Fig. 6.

The dredged trench is in an oblique angle to the sandwaves and to the dominating current direction. The orientation of the megaripples superimposed onto the sandwave show that the current pattern in the trough is complex and affected by the local morphology. This may also affect the regeneration process and may be responsible for development of the bifurcation.

Figure 6 shows a profile through the northern part of the dredged trench for the surveys shown in Fig. 4. From here it is clear that regeneration is taking place with the sandwave reaching 64 % of its full height within the first 10 months.

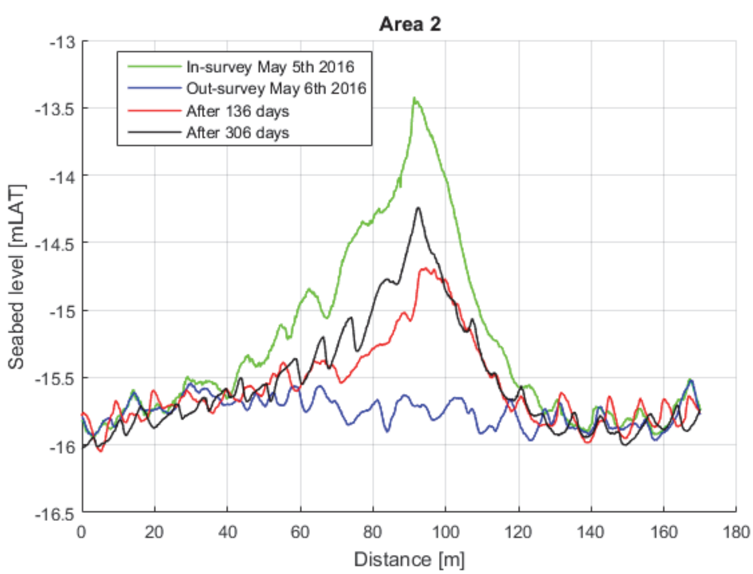

Fig. 6. Profile lines shown as black arrow in Fig. 4 showing survey data for Area 2 collected between May 5, 2016 and March 8, 2017.

Rate of volumetric regeneration

To investigate the volumetric regeneration a cut and fill analysis was performed. The analysis takes the difference between two surveys and defines a baseline, where volumes above the baseline are cut volume and volumes below are fill volumes. Cut volume corresponds to dredged/eroded volume and fill area corresponds to deposited volume. The net volume is found by subtracting cut and fill volumes. To remove disturbance from i.e. seabed mobility only the areas covering the bottom of the trenches only were used for the analysis.

The volumetric backfill over time is shown in Fig. 7. In the first period after the dredging both areas experience a net loss of sediment of up to 25 % of the dredged volume. After 30 days the backfill in Area 1 begins and by the end of the survey period 92 % of the dredged material is regained. The trench bottom width area in Area 2 begins to backfill 86 days after the dredging activity and reaches backfill of 54 % after 10 months.

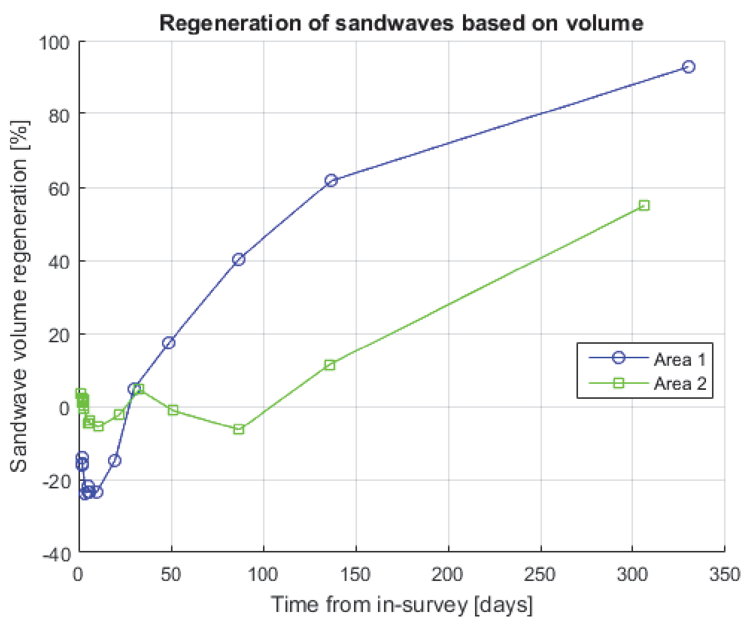

Fig. 7. Net volumetric sandwave regeneration in percent for Area 1 and Area 2.

Discussion

The sandwaves in Area 1 and 2 differ in respect to: Orientation relative to dominating current direction; Orientation of the dredged trench relative to sandwave crests; Migration speed of the sandwaves; and overall sandwave morphology (straight vs. bifurcating). Area 1 and 2 are in relative close proximity, such that regional wave, current and water level conditions are similar, even if the local bathymetry may influence mainly the local current patterns.

Fig. 8 shows the time development of the sandwave height regeneration within the first 10 to 11 months, whereas the volumetric calculations in Fig. 7 provides time development of volumetric regeneration. Even with the differences described above it is obvious that the sandwaves of Area 1 and northern part of the sandwave in Area 2 undergo similar regeneration in term of time scale.

From an analogy with time scale of scour development (Sumer *et al.* 1992), the regeneration time scale of a sandwave can be expressed in a similar asymptotic exponential form:

$$\frac{H_{sandwave,post-dregded}(t)}{H_{sandwave,pre-dredged}} = 1 - \exp\left(-\frac{t}{T}\right) \quad (1)$$

where $H_{sandwave,post\text{-}dredged(t)}$ is the height of the regenerating sandwave, $H_{sandwave,pre\text{-}dredged}$ is the height of the sandwave before dredging, t is time and T is the so-called time scale of the sandwave regeneration process.

For both Area 1 and 2 the sandwave height is seen to have regenerated to approximate 65 % after 300 days, corresponding to a time scale of $T = 285$ days or 0.75 years. With this timescale, the final regeneration can be forecasted, estimating that 90 % regeneration is reached after 1.8 years and full recovery (98 %) after 3 years.

A change in height of the superimposed megaripples is observed between the two sandwaves of Area 1 when comparing the latest 4 surveys (Table 2). From having megaripples of similar height after 49 days, the size of the megaripples superimposed onto Sandwave 1 increases compared to Sandwave 2. The larger megaripples at Sandwave 1 may be the result of non-linear bedform/sediment

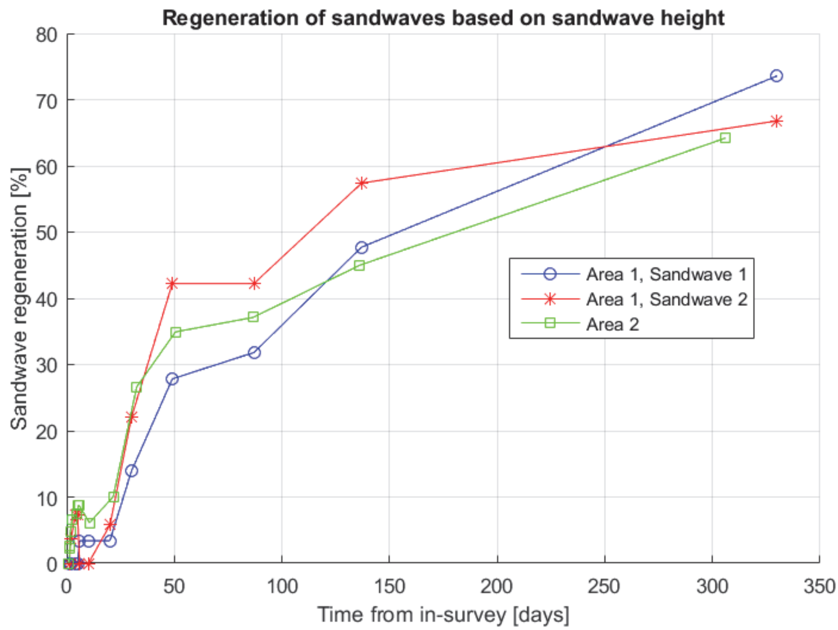

Fig. 8. Sandwave regeneration in percent based on sandwave heights for Area 1 and Area 2.

transport rate feedback, indicating larger sediment transport at Sandwave 1 compared to Sandwave 2. This could explain the increased backfill rate observed for Sandwave 1 after 137 days.

Table 2. Megaripple height for Area 1.

Days after In-survey	Sandwave 1 megaripple height [m]	Sandwave 2 megaripple height [m]
49	0.3	0.3
87	0.2	0.4
137	0.3	0.1
330	0.5	0.3

For installation purposes it is relevant to find out how long a trench stays open. To install a cable the trench needs to be wide enough to allow a trencher to pass through, including the cable lay tolerance. Figure 9 shows the change in seabed level within the trench bottom width area of Area 1 and Area 2. For Area 1 (top panel) a minimum of 8 m of the trench width is unaffected 30 days after the in-survey, and for most of the trench a wider corridor is available. The net deposited volume after 30 days of 5 % (Fig. 7) confirms that the trench backfill is limited at this time. The generally lower regeneration rate for Area 2 also affects how long the trench is open. Figure 9 (lower panel) shows the seabed change 87 days after the in-survey for Area 2. After 87 days the trench is still open for most of the dredged area, and only on a stretch of 20 m the trench width is affected by the regeneration of the sandwave. However, even here 13 m of the trenched width is unaffected. This is again supported by the net volumetric calculations, which after 87 days show a net erosion of 6 % of the dredged volume.

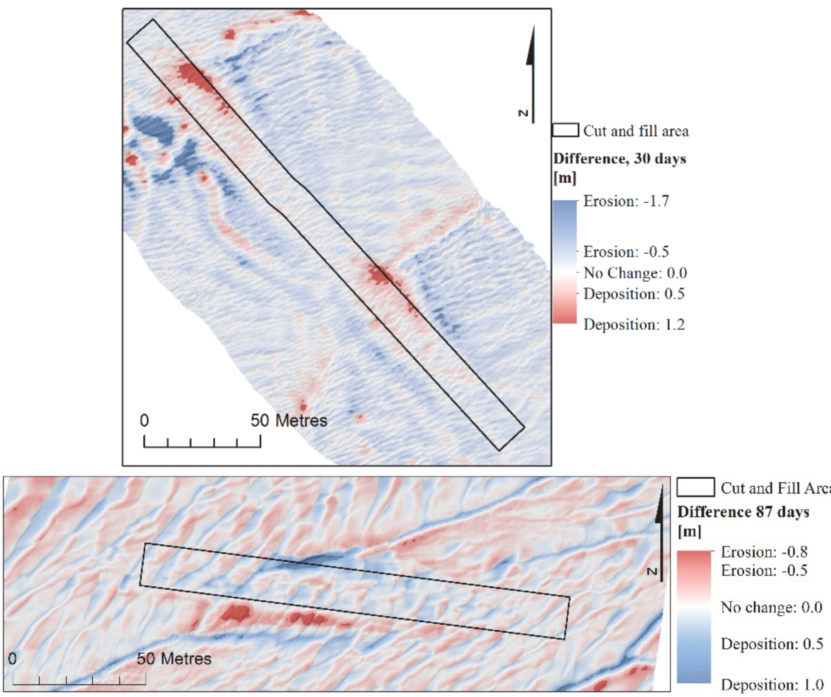

Fig. 9. Top: Difference plot for Area 1 between out-survey and after 30 days.
Bottom: Difference plot for Area 2 between out-survey and 87 days.

From Fig. 7 the surveyed period can be divided into two periods of different sandwave behavior. The first period is an adaption period, where the seabed reacts to dredging. Only limited regeneration is seen, megaripples are formed in the trenched area and the slopes of the dredged trench adjust slightly but leaves the trenched area relatively unaffected. The second period is the regeneration period, where the net volume of backfill increases and the sandwaves are regenerating.

The length of the adaption period is of particular interest for planning of cable installation. It may be worth considering doing relatively low-cost field experiments to gain site specific information of the regeneration time scale and the length of the adaption period prior to installation. Such information would enable pre-sweeping of all cables in a single vessel mobilisation, thus saving significant installation cost.

Van den Berg (2007) also studied sandwave regeneration and found partially dredged sandwaves to regenerate mostly within the first year and to be fully regenerated after 4 years. Small and Bean (2012) studied another sandwave location in the North Sea, which was partly dredged and surveyed 5 months after. Water depths were approximately 30 m and the dredged trench nearly perpendicular to the sandwave. Migration rate of the sandwave was in the order of 3 m/yr. 5 months after dredging only partial regeneration is observed with the trench still clearly visible. The backfill seemed to be controlled by megaripples migrating perpendicular to the dredged channel.

The result of the cut and fill analysis of Area 1 and 2 show a net backfill of the dredge volume. Sediment from elsewhere is transported into and deposited within both areas rather than reworking of the local sediment. This supports the assumption that dredged sandwaves will regenerate over time and cable installation impact is temporary.

Conclusion

Multiple bathymetrical surveys from 2016 and 2017 covering 10 and 11 months after trench dredging through two sandwave locations in the North Sea have been presented. For both location, megaripples and sandwaves responded immediately to the dredging. However, whereas the time scale for megaripple regeneration was days, the larger sandwaves required a timescale of months to years to fully regenerate, allowing time for engineering works such a cable installation or other in the temporary opened trench.

The regeneration of sandwaves was observed to follow an asymptotic exponential form. Even though the data coverage showed that the sandwaves were not yet fully reformed in height, it did show a clear regeneration indicating that sandwave will fully reform and that the dredging activities leave no trace on the seabed.

The seabed level in the trench bottom width area was mainly unaffected by backfill for 30 days and 87 days for Area 1 and Area 2, respectively. Sandwave migration speed in Area 1 was 36 m/yr in the observation period, while it was practically nil in Area 2. Hence areas of high bedform mobility is likely to experience shorter windows for engineering works. Field experience prior to installation, can enable forecasting of regeneration timescale and potential installation cost saving.

Cut and fill volume analysis showed a net backfill into the dredged area, further demonstrating the natural backfilling and regeneration of bedforms in the dredged trenched.

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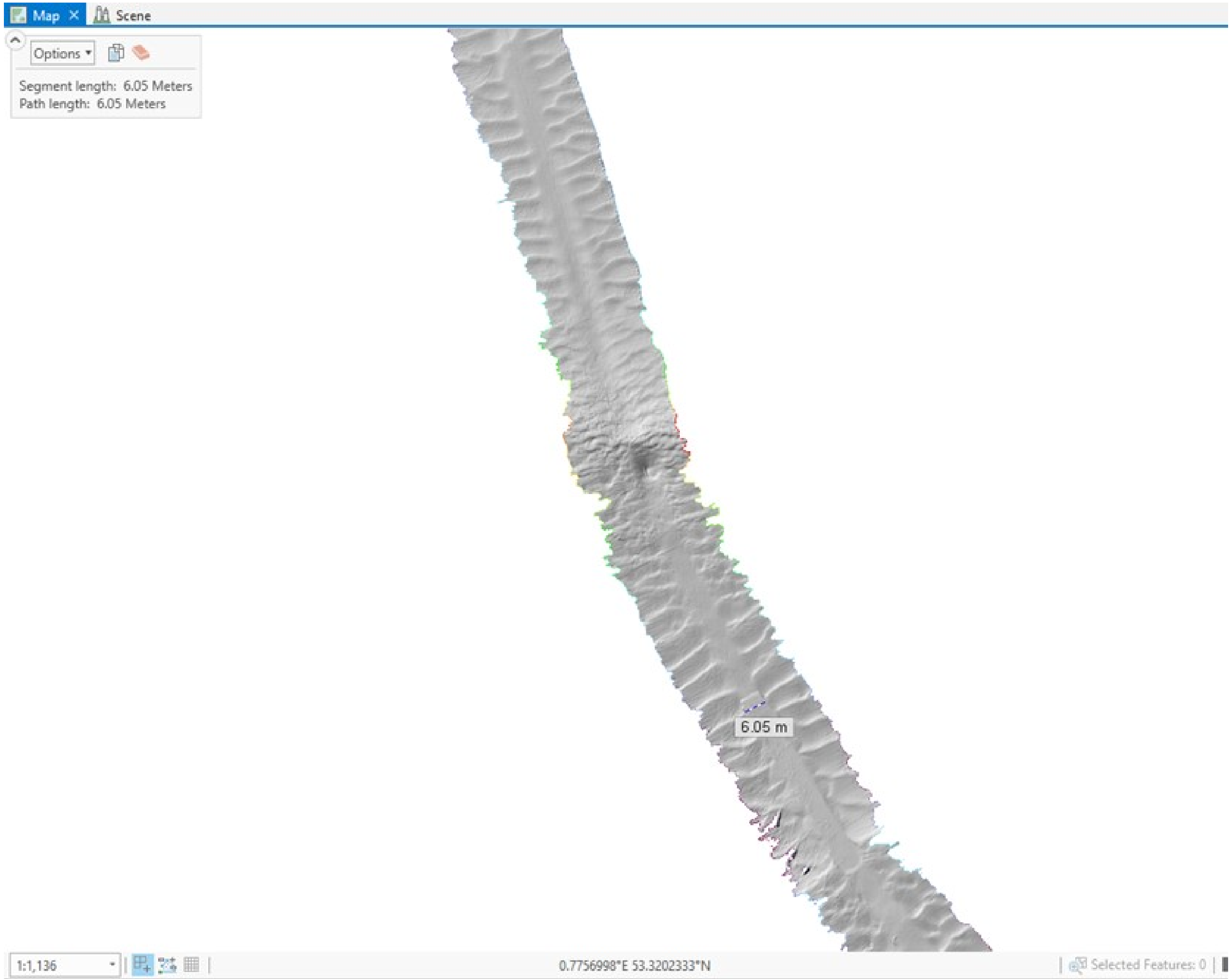
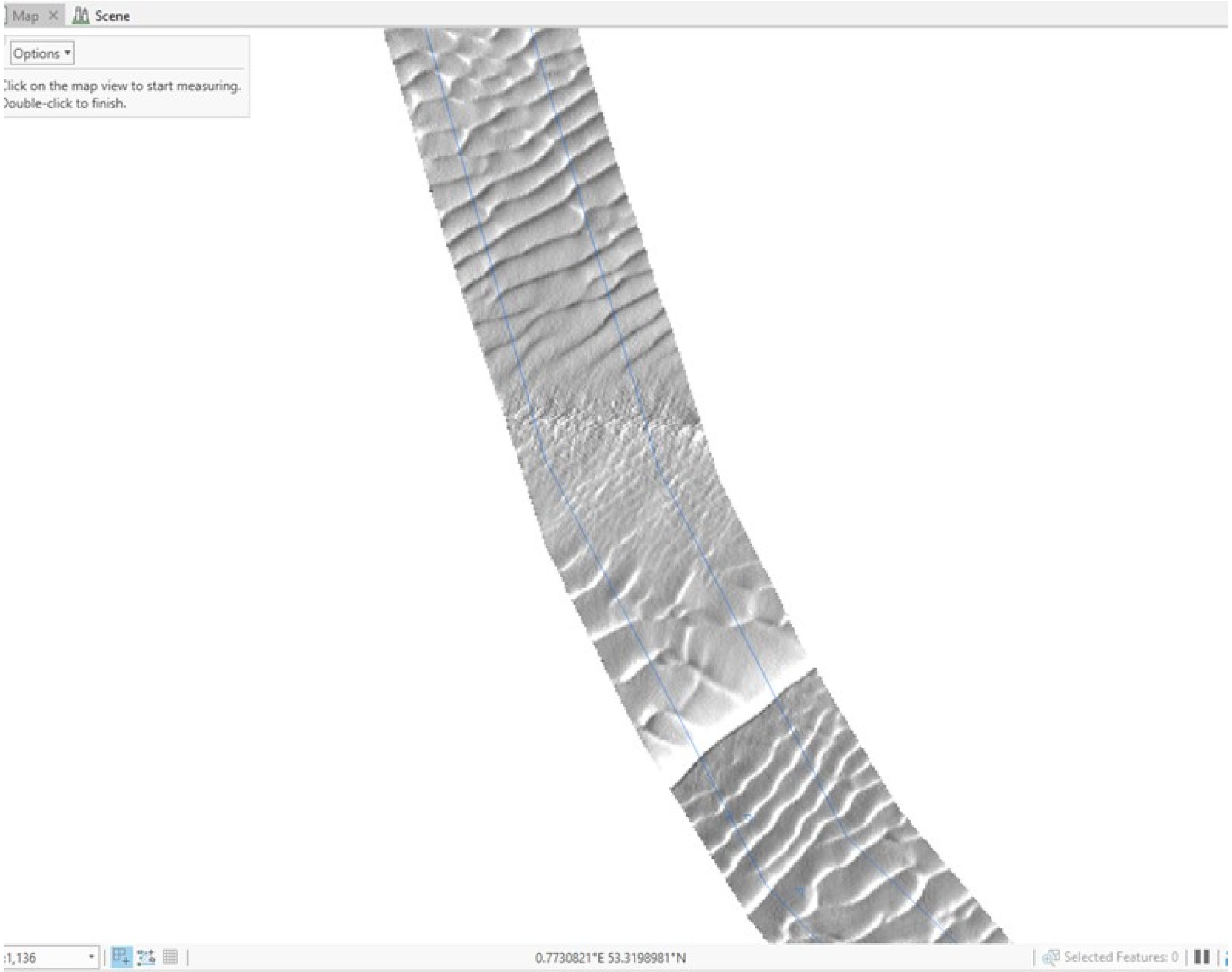
Appendix 2 Evidence of sand wave recovery from Race Bank array cable installation

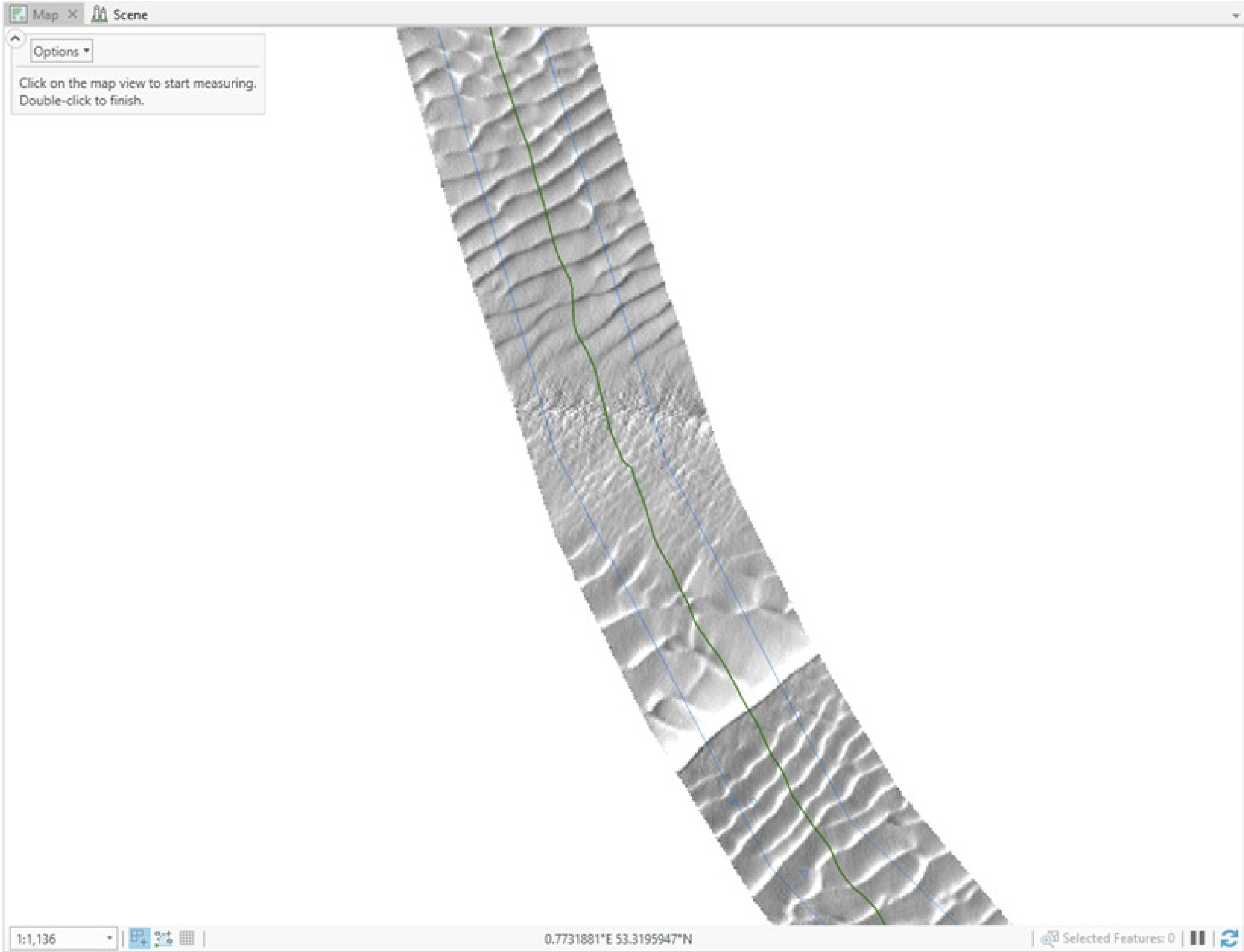
3. Provided in this appendix are images of bathymetric (Multibeam Echo Sounder) data which were submitted by Race Bank Limited as part of an application for a marine licence variation to undertake remedial works to the array cables within the Race Bank offshore wind farm.



String 8 – Feb 2019 post-installation data



String 8 – March 2020 (showing recovery over 1 year following full replacement)



String 8 – March 2020 overlaid with the location of the replaced cable)