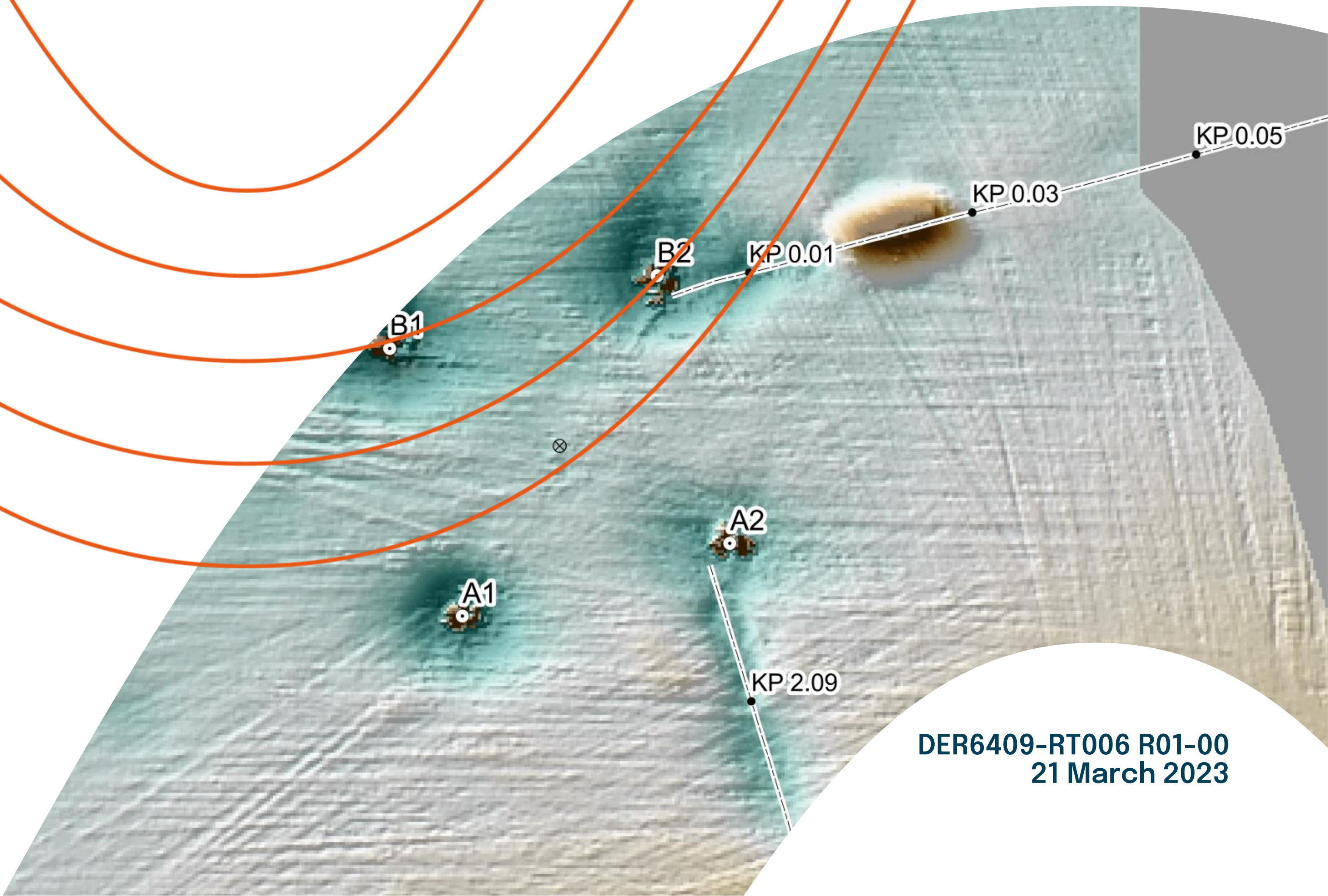
Beatrice Offshore Windfarm Seabed Change and Scour Monitoring

Technical Scour Assessment: Turbine Foundations



DER6409-RT006 R01-00
21 March 2023

Document information

Document permissions	Unrestricted
Project number	DER6409
Project name	Beatrice Offshore Windfarm Seabed Change and Scour Monitoring
Report title	Technical Scour Assessment: Turbine Foundations
Report number	RT006
Release number	01-00
Report date	21 March 2023
Client	Beatrice Offshore Windfarm Ltd

Summary

HR Wallingford were contracted by Beatrice Offshore Wind Ltd (BOWL) to prepare a scour and seabed change assessment to assist BOWL's asset management at the Beatrice Offshore Windfarm (BOWF) using the 2022 inter-array cable and foundation survey data. This report describes the outputs for the technical scour assessment at the wind turbine jacket foundations. Following on from site-wide asset management studies utilising the 2019, 2020 and 2021 post-installation survey data (HR Wallingford, 2021), the 2022 survey data are assessed at all 84 foundation locations to provide updated descriptive scour parameters to aid asset management.

Four pre-construction (2010, 2014, 2015 and 2016) and four post-construction (2019, 2020, 2021 and 2022) multibeam bathymetry surveys were made available for this study. The 2019 survey included 26 foundations, the 2020 survey 20 foundations, the 2021 survey 31 foundations and the 2022 survey 84 foundations. Thirty-one (31) foundations were common to both the 2021 and 2022 surveys, these are used to observe the evolution of the scour at the jackets.

From the review of the data quality and the vertical offsets between the 2022 and earlier surveys we recommend using an uncertainty of ±0.2 m when comparing any two bathymetric surfaces. When estimating scour depths, because the scour depth was relative (i.e. it is the difference between two different levels within the same dataset), a smaller uncertainty of ±0.1 m is appropriate.

We analysed the data using our in-house Automated Scour Analysis Tool (ASAT). From this tabulated scour parameters of local scour depth, extent and slope were generated for the 2.2 m diameter piled foundations.

On average in 2022 the mean local scour depth at the jacket legs was 0.3 m. A wide range of scour depths were observed from less than 0.1 m up to 1.2 m. The scour observed at all jacket legs surveyed in 2022 is smaller than the design scour allowance of 2.99 m.

For the twenty-one jacket legs for which we have data from the 2019, 2020, 2021 and 2022 surveys, from installation (2017) to the first post-installation survey in 2019 the average rate of scour was 0.09 m/yr. For the same locations from 2019 to 2020 the average rate of scour was 0.13 m/yr, from 2020 to 2021 the average rate of scour was 0.16 m/yr and from 2021 to 2022 the average rate of scour was -0.37 m/yr. At most locations the scour partially infilled between the 2021 and 2022 survey. It's thought that this may be an indication of a seasonal signal in the data, given that the 2022 data were collected much earlier in the year.

Scour is observed to form a relatively symmetrical circle around each pile. On average scour pit extents (from the pile wall) were 3.7 m in 2019, 4.5 m in 2020, 7.9 m in 2021 and 5.2 m in 2022. On average scour pit slopes were 3.1° in 2019, 5.8° in 2020, 5.6° in 2021 and 3.0° in 2022. Scour pits have a large range of extents and slopes, and differences observed between the 2019, 2020, 2021 and 2022 surveys may not be significant. The local scour pits at each jacket have not coalesced and global scouring within the footprint of the jacket is negligible.

Independent estimates of scour at jacket legs made in HR Wallingford (2021) indicated that without sediment backfilling (i.e. for currents only) the local scour depth could range from 2.8 to 4.4 m depending on the water depth and depth-averaged current speed. The local scour depth calculated with storm wave dominance indicates that wave-induced backfilling is likely, as the predicted scour depth is only between 0.2 and 0.4 m, considerably smaller than the current-only scour scenario.

We anticipate scour to continue to develop during storms where the surge current enhances the tidal currents flowing in a south / south-south-easterly direction, with episodes of sediment infilling due to storm waves from the east. If conditions at the site are particularly current-dominant due to tide and surge we anticipate scour to deepen. The surface soil type and

thickness is not expected to limit scour development within the design scour allowance at the majority of foundations.

Regarding the scheduled site monitoring, we recommend that the ten sample sites are selected to ensure that a small number of locations (minimum 2 – 3) are surveyed annually to track the progression of scour with time (i.e. we advise not surveying ten different locations each year).

We have identified unusually deep (>0.8 m) scour at WTG BE-B07, G08 and L07. These locations should be considered as a priority for future surveying.

It is predicted that the time of the year in which surveys are conducted will have large influence on the scour levels observed. In order to provide consistency surveys should be conducted at the same time of the year. Where possible observations of wave and current conditions should be utilised to determine if storm surge conditions or wave backfilling is likely to have occurred at the time of surveying.

Based on the current status of scour recorded in our analysis, at the present time no further geophysical survey work beyond the planned schedule (i.e. annual surveys) is required.

Figures and tables of results have been provided in a separate datapack.

Contents

Tables

Figures

1 Introduction

HR Wallingford were contracted by Beatrice Offshore Wind Ltd (BOWL) to prepare a scour and seabed change assessment to assist BOWL's asset management at the Beatrice Offshore Windfarm (BOWF) using the 2022 inter-array cable and foundation survey data. This report describes the outputs for the technical scour assessment at the wind turbine jacket foundations which were all installed in 2017. Following on from site-wide asset management studies utilising the 2019, 2020 and 2021 post-installation survey data (HR Wallingford, 2021), the 2022 survey data are assessed at all 84 foundation locations to provide updated scour parameters to aid asset management.

Figure 2.1 shows the boundaries of the wind farm lease site and the location of the 84 Wind Turbine Generators (WTGs). Each WTG is installed on a steel jacket substructure connected by four piled foundations driven into the seabed. The piles are identified in Figure 2.2 for reference. The WTGs are connected at a voltage of 33 kilovolts by a network of inter-array cables (IACs). There are a total of 91 IACs arranged in fourteen circuits (also referred to as strings) and six WTGs per string. The first WTG in a string is connected by an IAC to an Offshore Transmission Module (OTM). The circuits are cross-connected at the ends in pairs. The two OTMs in the centre of the array and their associated IAC form part of the Offshore Transmission Assets and are not included within this study.

2 Scope of works

The scope of works comprises:

- Identification and description of the data used in the study;
- Review data quality and comment accordingly;
- Review surveying positional measurement systems and comment on the overall positional accuracy of the pre-construction and post-construction survey data;
- Set-up and describe the data analysis process used;
- Produce tabulated scour parameters (including depths, local and global scour, as well as extent and slope angle of scour holes) within the *.pdf* report and as an electronic file in Excel *.xlsx* format);
- Provision of scour parameters including baseline seabed depth; general scour and local scour for the post-construction (2022) survey and difference comparison (for turbines where more than one post-construction survey is available);
- Describe the features of each individual scour hole, with justifications based on the soil profile and metocean conditions. Because the assessment is for jacket foundation structures the scour analysis will include the scour development at each leg of the structure and will identify both local scour due to the presence of the individual legs as well as any global scour due to the presence of the jacket as a whole[1];
- Provide visual images comprising the XYZ data as well as installation information and cross-sections in *.jpeg* (or equivalent) format;
- Comparison will be made with the scour predictions carried out in the pre-construction Environmental Statement;
- Empirical prediction based on scour surveys at a subset of foundations of potential scour across the site based on jacket parameters, soil conditions, water depth;

[1] Each jacket has four piles with labelling A1, A2, B1, B2, therefore there are up to four local scour holes per jacket. Jacket leg IDs are shown in Figure 2.2.

- Recommendations arising will advise on further monitoring and analysis where we consider this is required.

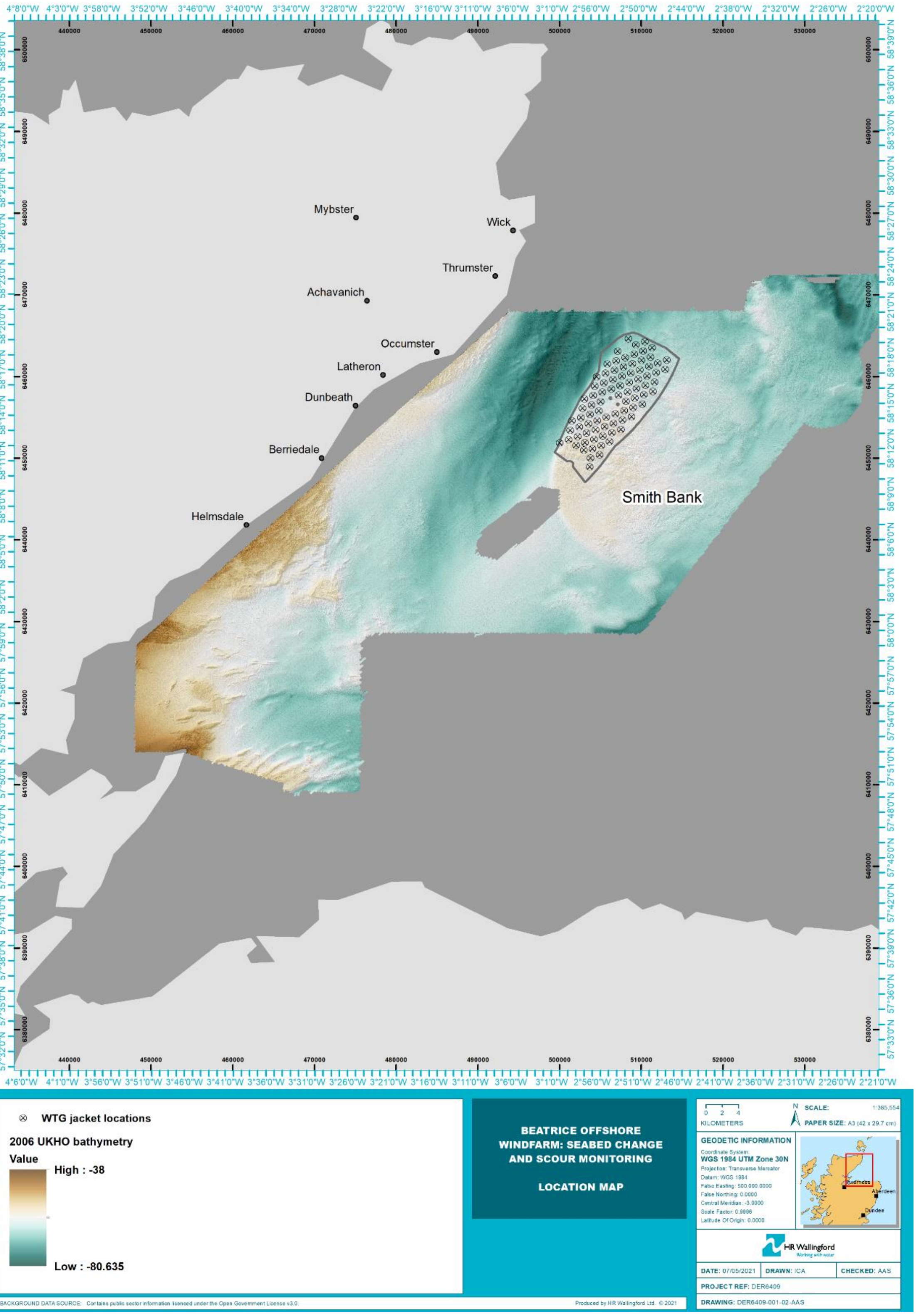


Figure 2.1: Beatrice Offshore Wind Farm location map

Source: HR Wallingford contains public sector information licensed under the Open Government Licence v3.0

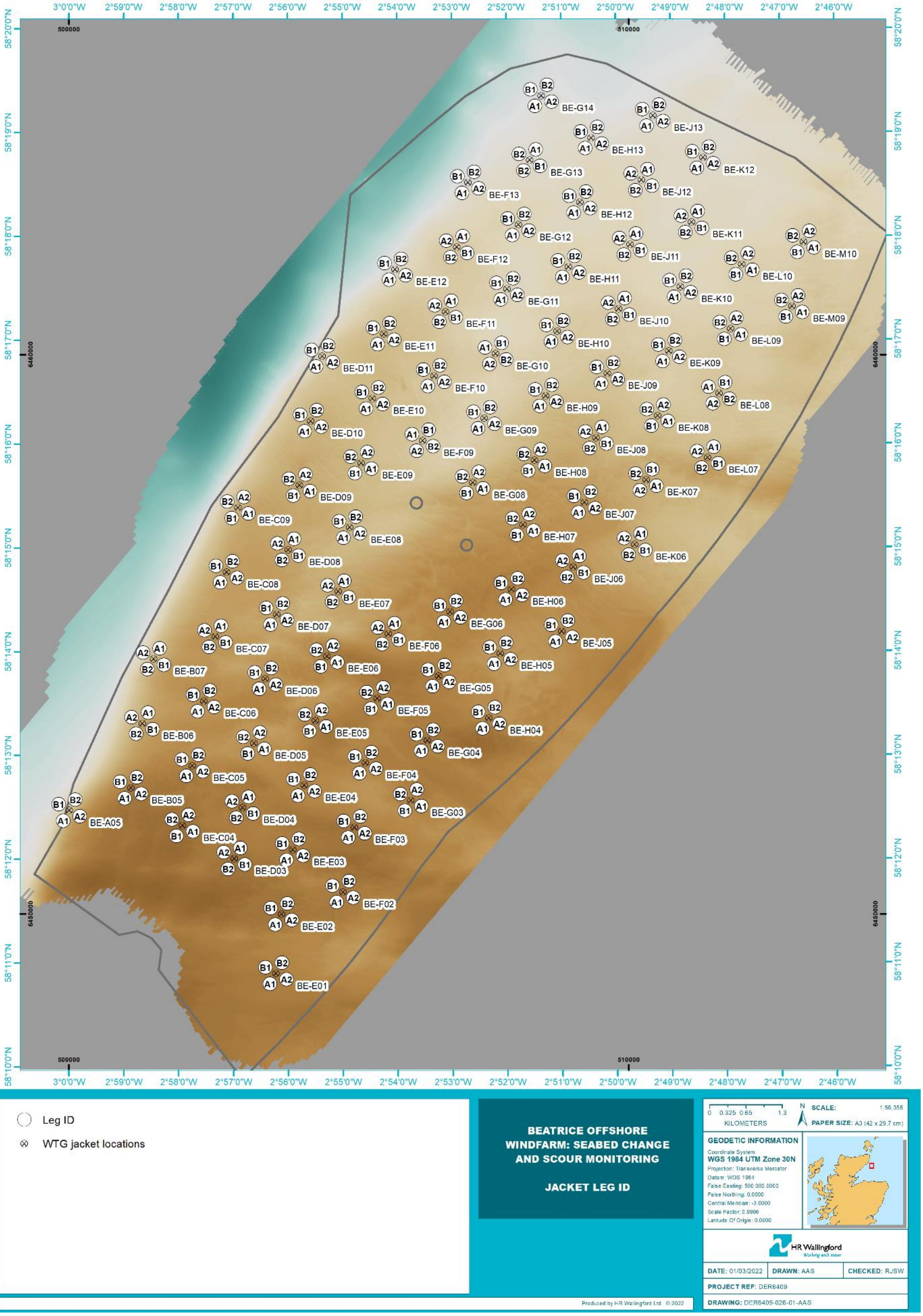


Figure 2.2: Jacket leg ID

Source: HR Wallingford

Notes: For clarity jacket leg IDs are offset from their actual positions

3 Site conditions

We recommend referring back to HR Wallingford (2021) for a full assessment of the site conditions.

4 Data review and quality check

4.1 Data availability

Table 4.1 summarises the bathymetric data made available for this scour assessment. Four pre-construction (2010, 2014, 2015 and 2016) and four post-construction (2019, 2020, 2021 and 2022) surveys have been provided. A bathymetric survey was conducted by Fugro at 45 planned WTG locations in 2013. This survey cannot be used in this study since the client was only able to provide depth contours and not the survey data.

Table 4.1: Summary of bathymetric data used in this study

Year	Month	Surveyor	Coverage	Geographical projection	Vertical datum	Resolution of data provided
2010	April - May	Osiris	Site-wide	WGS84 UTM 30N	Chart Datum, Wick	2 m
2014	December 2014 – January 2015	Fugro BV	200 m wide, 1 km spaced, lines	WGS84 UTM 30N	GNSS and DTU10 LAT. Fixed at 47.9 m	0.2 m
2015	July - September	MMT	Export and inter-array	WGS84 UTM 30N	GNSS and VORF LAT	1 m
2016		Fugro	Site wide	WGS84 UTM 30N	Not specified	0.5 m
2019	October	Fugro	10 WTG, 2 OTM, 13 inter-array cables, sections of export cables	WGS84 UTM 30N	VORF LAT	0.25 m
2020	October - November	RovCo	16 foundations, 14 inter-array cables, inter-connector, sections of export cable	WGS84 UTM 30N	LAT (method not specified)	Raw and 0.25 m*
2021	July	RovCo	10 foundations, 14 inter-array cables	WGS84 UTM 30N	VORF LAT	0.25 m
2022	April	RovCo	70 foundations, 65 inter-array cables	WGS84 UTM 30N	VORF LAT	0.25 m

Source: HR Wallingford

*Notes: *whilst these data were provided gridded to 0.25 m a grid resolution of 0.5 m is more appropriate for the spacing of the data (i.e the data are too sparse to create a 0.25 m grid)*

4.2 Data coverage

The spatial coverage of the 2022 bathymetric survey is shown in Figure 4.1, providing inputs to both the analysis of scour at WTG foundations and also for bed level change analysis along IACs (reported separately). The coverage of the other six surveys is presented in HR Wallingford (2021) and HR Wallingford (2022). Whilst 70 foundations were targeted in the 2022 survey, the additional coverage is provided by the IAC surveys, and that data is also analysed.

Figure 4.1 details the coverage at each foundation for the post-installation 2019, 2020, 2021 and 2022 surveys.

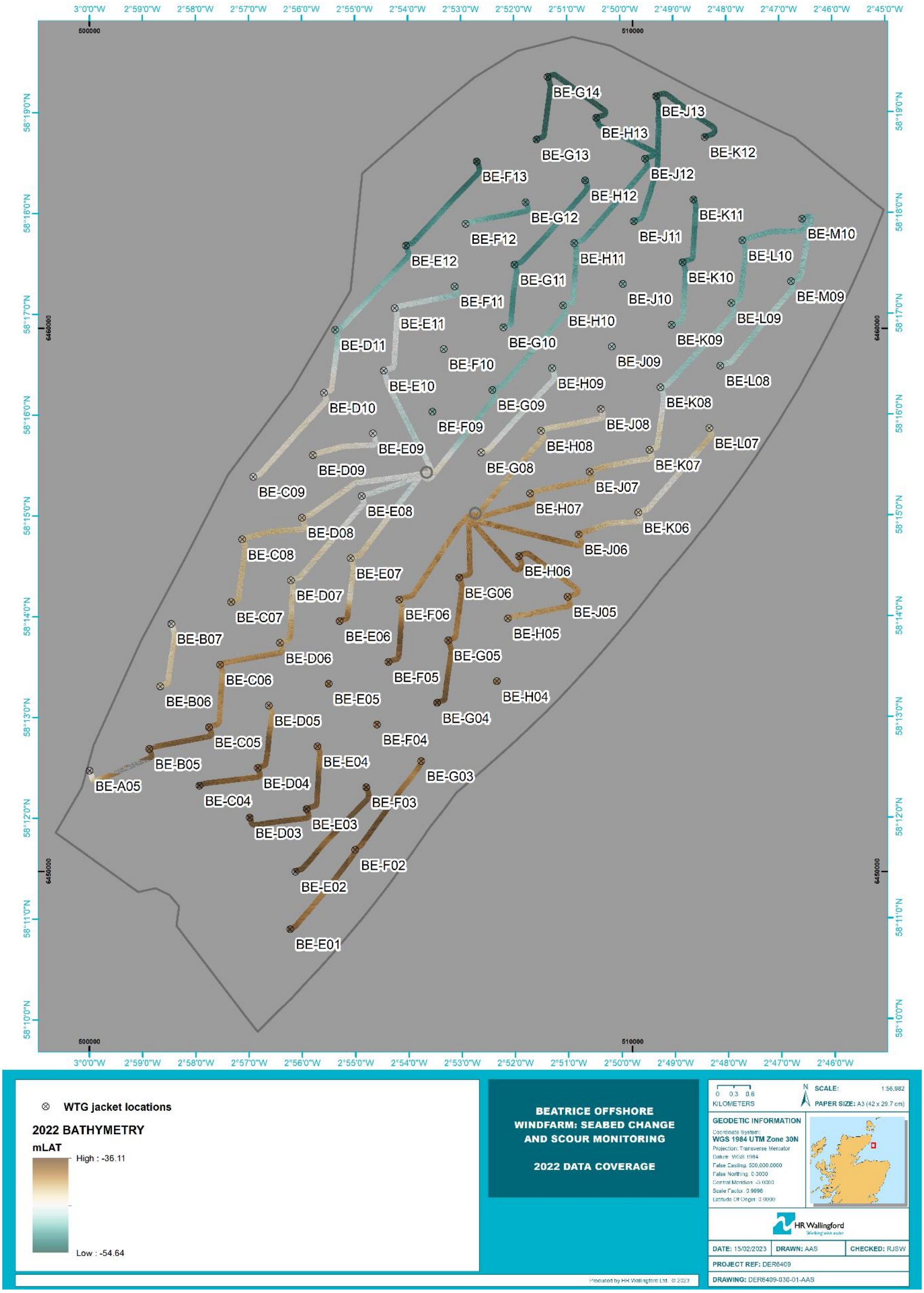


Figure 4.1: 2022 bathymetric data coverage

Source: HR Wallingford using RovCo data

Note: the two OTMs are located in the circles at the south end of the surveys for BE-F09 and BE-G08

Table 4.2: Data coverage for the 2019, 2020, 2021 and 2022 surveys

Jacket ID	2019	2020	2021	2022
BE-A05				Full
BE-B05				Full
BE-B06				Full
BE-B07		Full	Full	Full
BE-C04			A1 and B1	Full
BE-C05				Full
BE-C06				Full
BE-C07			Full	Full
BE-C08				Full
BE-C09				Full
BE-D03			Full	Full
BE-D04				Full
BE-D05		Full		Full
BE-D06	Full	Full	Full	Full
BE-D07				Full
BE-D08				Full
BE-D09		A1 and B1		Full
BE-D10				Full
BE-D11	Full	Full	Full	Full
BE-E01		A1, A2 and B2		Full
BE-E02	Full	Full	Full	Full
BE-E03				Full
BE-E04			A2 and B2	Full
BE-E05		A1, A2 and B1	Full	Full
BE-E06			A2, A2 and B1	Full
BE-E07				Full
BE-E08				Full
BE-E09		A1 and A2		Full
BE-E10	Full	Full	Full	Full
BE-E11				Full
BE-E12		Full		Full
BE-F02				Full
BE-F03		B2		Full
BE-F04			Full	Full
BE-F05			Full	Full
BE-F06				Full
BE-F09			Full	Full
BE-F10				Full
BE-F11			A1, A2 and B1	Full
BE-F12			Full	Full
BE-F13				Full
BE-G03		Full	A1 and A2	Full
BE-G04				Full
BE-G05				Full
BE-G06	Full			Full
BE-G08			Full	Full
BE-G09				Full
BE-G10		Full		Full
BE-G11				Full

Jacket ID	2019	2020	2021	2022
BE-G12		A2, B1 and B2		Full
BE-G13			Full	Full
BE-G14	Full	Full	Full	Full
BE-H04		Full	Full	Full
BE-H05				Full
BE-H06	A1, A2 and B2			Full
BE-H07				Full
BE-H08	A1, A2 and B2			Full
BE-H09				Full
BE-H10		Full		Full
BE-H11	A2, B2			Full
BE-H12			Full	Full
BE-H13	A1 and A2			Full
BE-J05	Full			Full
BE-J06	Full	Full	Full	Full
BE-J07				Full
BE-J08	Full	Full	Full	Full
BE-J09	Full	A2	Full	Full
BE-J10				Full
BE-J11				Full
BE-J12	Full	Full	Full	Full
BE-J13	A2, B2			Full
BE-K06	Full			Full
BE-K07				Full
BE-K08	A1, A2			Full
BE-K09	A1, A2			Full
BE-K10				Full
BE-K11			Full	Full
BE-K12	Full	Full	Full	Full
BE-L07	B1 and B2		Full	Full
BE-L08	B1 and B2		Full	Full
BE-L09	Full			Full
BE-L10	Full			Full
BE-M09	A1 and B1			Full
BE-M10	Full	Full	Full	Full

Source: HR Wallingford

4.3 Vertical datums

Cathie Associates performed a review of the bathymetry data and datums of the 2010, 2014 and 2015 surveys (Cathie Associates, 2015). In their review they established that a different vertical datum (Lowest Astronomical Tide, LAT; Ordnance Datum Newlyn, ODN; Chart Datum, CD and Vertical Offshore Reference Frame, VORF) had been used for each of the surveys. We have summarised these in Figure 4.2. Attempts were made by Cathie Associates at unifying the data through applying offsets. However, some large offsets still remained that could not be accounted for.

We have compared the differences in bathymetric surface across the site using the 2016 (the most recent site-wide survey) as a baseline (Table 4.3). In each case the distribution of values is relatively tight about a mean and when visually inspecting the surfaces the offsets appear relatively homogenous across the site. For this reason we have applied the fixed offsets listed in

Table 4.3 to vertically align the surveys to the level of the 2016 pre-installation surface. No offset was applied to the 2022 data given its close agreement with the 2016 survey.

Seabed levels reported by HR Wallingford are provided relative to Vertical Offshore Reference Frame (VORF).

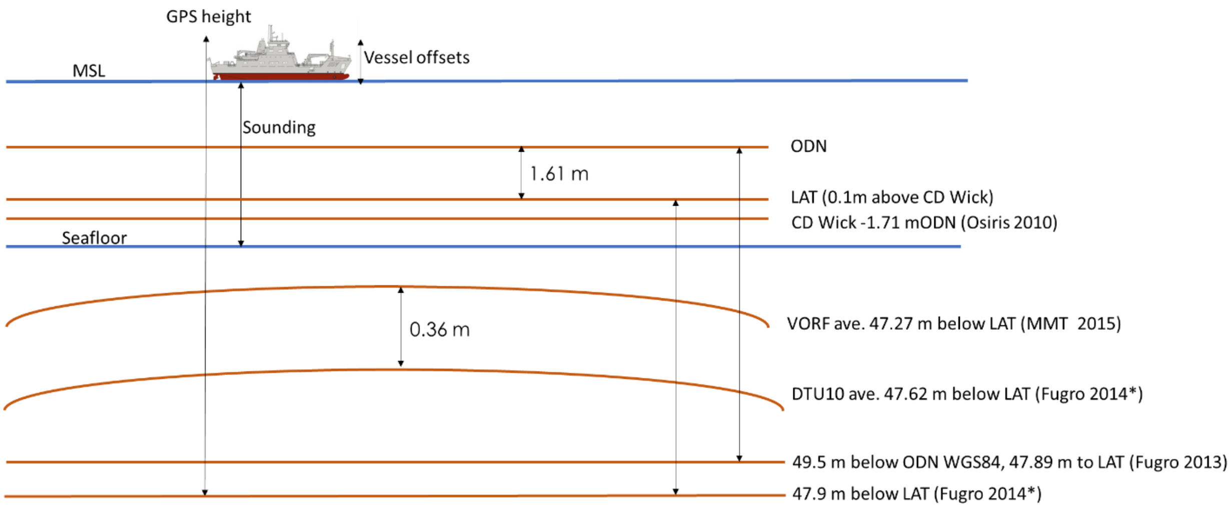


Figure 4.2: Vertical datum used for 2010, 2013, 2014 and 2015 surveys

Source: HR Wallingford

Notes: Fugro 2014 was provided using a fixed offset of 47.89 m, according to Cathie Associates (2015) this offset should have been 47.62 m

Table 4.3: Average difference between each bathymetric surface and the 2016 Fugro pre-construction bathymetric surface

	Average (m)	Standard deviation
Osiris 2010	0.61	0.12
Fugro 2014	0.54	0.12
MMT 2015	0.20	0.09
Fugro 2016	N/A	N/A
Fugro 2019	-0.07	0.12
RovCo 2020	-0.68	0.13
RovCo 2021	0.02	0.13
RovCo 2022	-0.02	0.12

Source: HR Wallingford

Note: N/A not applicable as this was used as baseline

4.4 Data quality

RovCo have not provided any estimates for the total propagated uncertainty of the multibeam bathymetry data. However, it is stated in the survey report (RovCo, 2023) that the survey was conducted to meet UKHO Special Order requirements. For a water depth of 40 m (representative of the depths found across the windfarm) UKHO special order specifications require a total horizontal uncertainty of less than 2 m and a total vertical uncertainty of less than 0.4 m.

The 2022 data were gridded by RovCo without the removal of the jacket structures data points. As a result any areas of seabed directly under the jacket bracing are obscured. For the purposes of scour assessment, it is best practice to clean out these datapoints before gridding such that the data shows only the bathymetry.

The cleaned xyz point files have been provided for each WTG. These data can be used to quantify the noisiness of the data. For each point the roughness has been calculated (example in

Figure 4.3). This value is equal to the distance between this point and the best fitting plane computed on its nearest neighbours. This value gives an estimate of variability between soundings. There will naturally be some roughness of the seafloor, but a higher value of roughness demonstrates that there is more noise within the data. Roughness doesn't give absolute accuracy (there could still be fixed vertical or horizontal offset), but does tell us about the spread of data, e.g. if tidal corrections or other time variables such as SVP correction, roll / pitch / heave correction have been correctly applied. Roughness is site specific, so only each pair of values for a given location should be compared. Typically the roughness for the 2022 survey was less than 0.05 m.

From our review of the data quality and the vertical offsets between the different surveys we recommend using an uncertainty of ±0.2 m when comparing any two bathymetric surfaces. When estimating scour depths, because the scour depth is relative (i.e. it is the difference between two different levels within the same dataset) a smaller uncertainty of ±0.1 m is appropriate.

At WTG H04 we observe a large area of 0.4 m accretion[2] when we compare the 2021 data with the 2022 data (Figure 4.4 – bathymetry in the 0.2 to 0.4 m band to the east of the jacket). This area is aligned with the vessel track and so it appears to be the result of survey error, rather than actual seabed lowering. Given that the 2022 data are in agreement with the 2020 data it appears that the 2021 data are offset. This appears to be the only survey line with this issue.

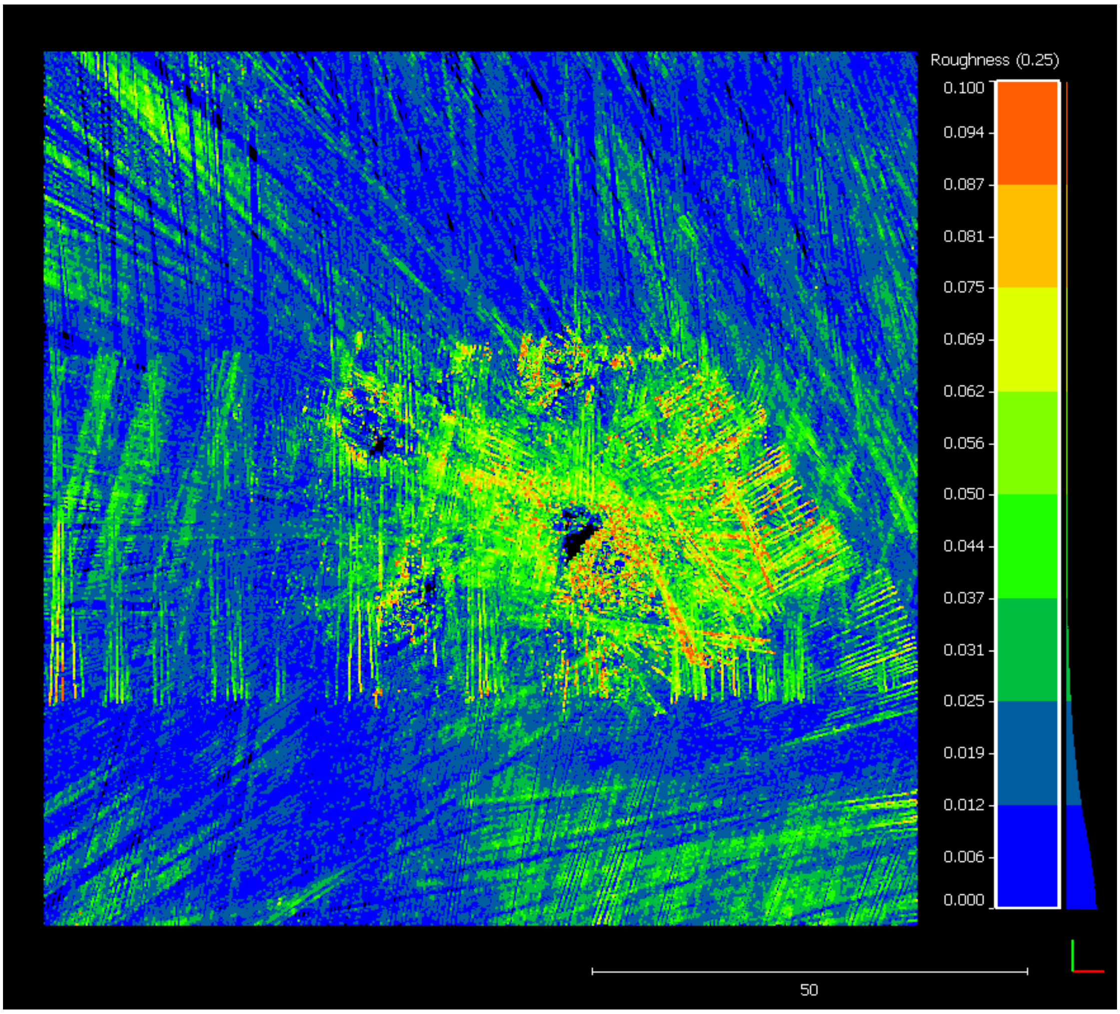


Figure 4.3: Roughness of 2022 survey data at G08

Source: HR Wallingford

[2] Accretion, i.e. positive values of seabed change between to surveys.

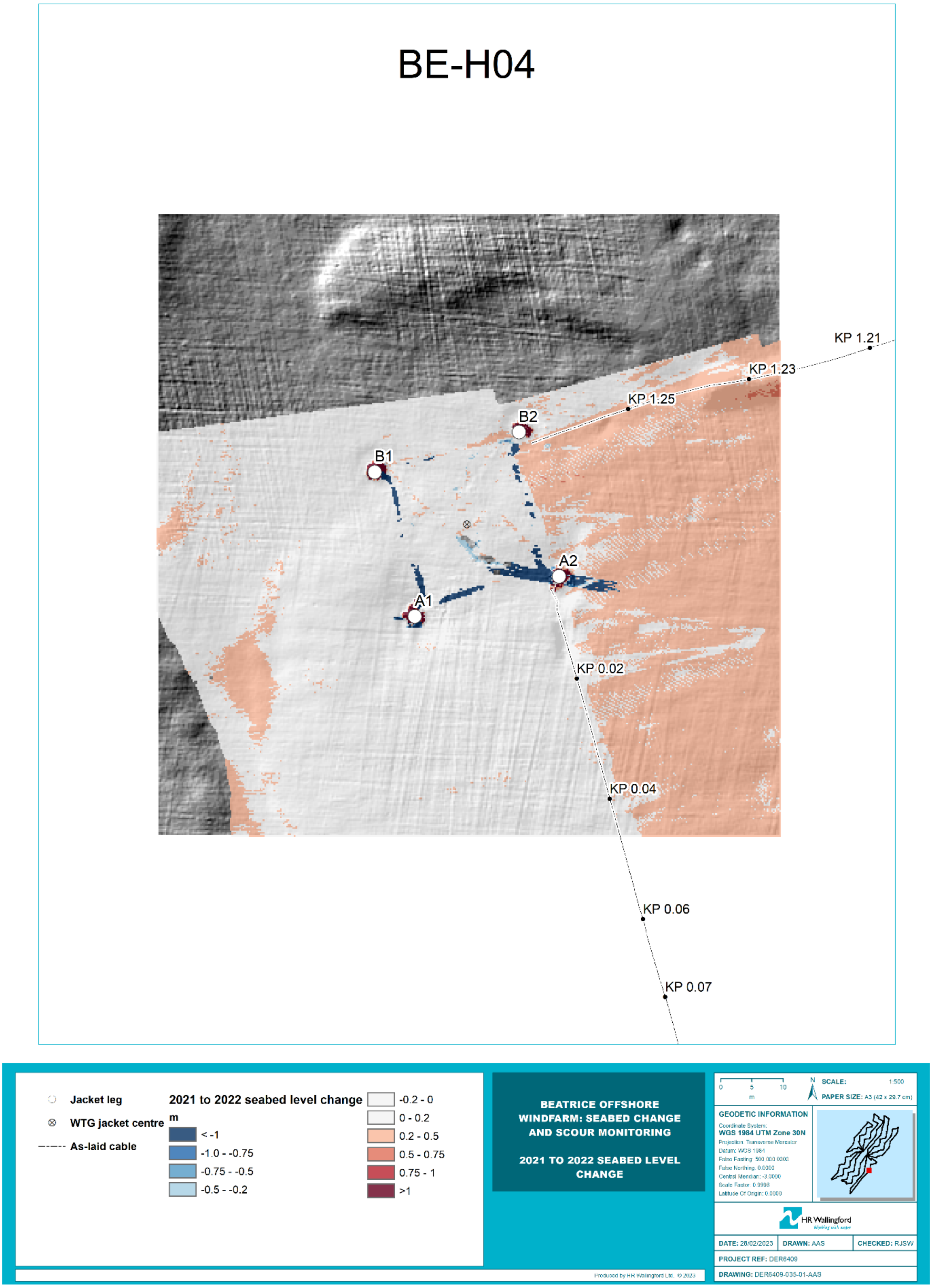


Figure 4.4: 2021 to 2022 seabed level change at H04

Source: HR Wallingford

5 Methods

Substantial processing and analysis of the xyz bathymetric data is required for the calculation of the observed local scour depth, scour hole extent, scour hole shape / orientation and scour hole slope angle at each jacket leg location. HR Wallingford uses its ASAT (Automated Scour Analysis Tool) to execute the required processing and analysis steps. These are summarised in flow-chart format in Figure 5.1, and provided on a step-by-step basis in Appendix A of HR Wallingford (2021).

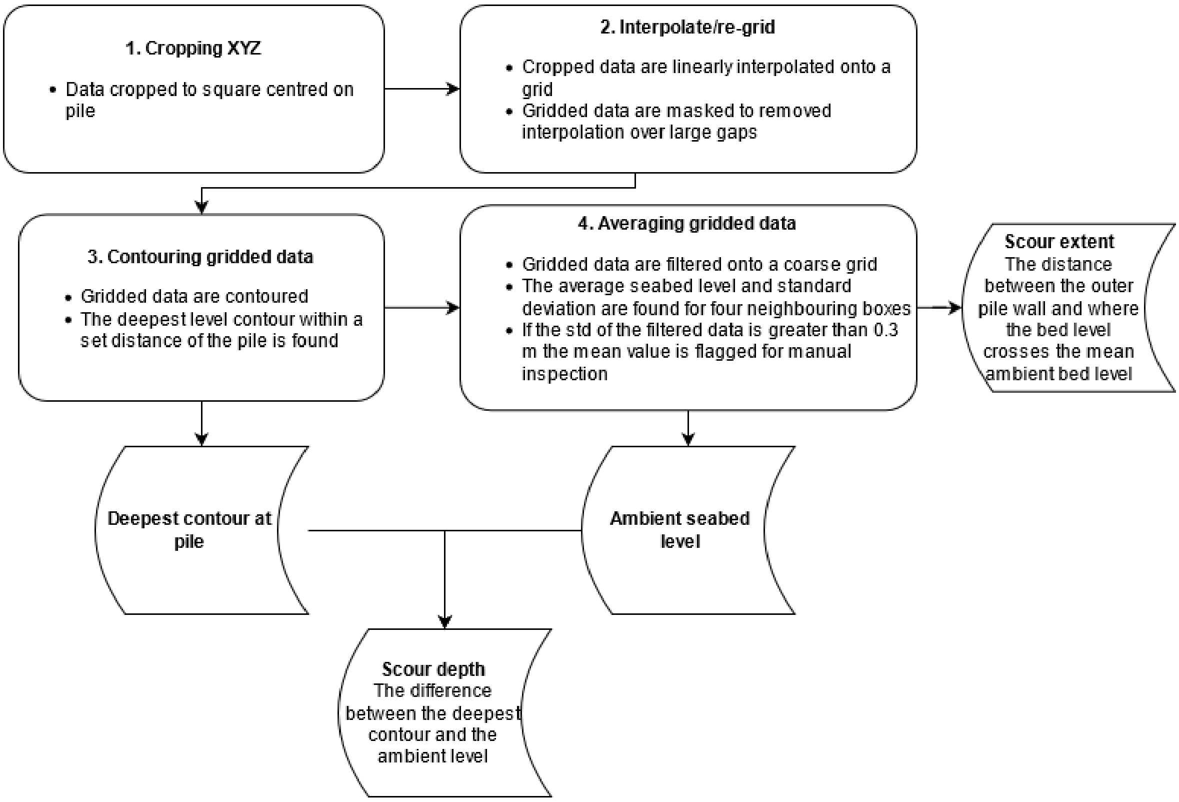


Figure 5.1: Flow chart describing main processing and analysis steps for obtaining key scour parameters using HR Wallingford's ASAT procedure

Source: HR Wallingford

Scour parameters are obtained using an automated process based on profiles taken through the gridded data at every 45° radial line around a given pile location. The extent of the scour hole from the pile wall is defined as the point at which the seabed profile crosses the representative average (ambient) bed level, resulting in scour hole extents in eight directions relative to the pile. If the profile line does not cross the average bed level, then no extent can be calculated. The extents, in combination with the lowest depth between calculated extent and pile wall, are then used to form right-angled triangles for calculating a representative scour hole slope. The result is up to eight measures of extent and corresponding averaged slope angle, thus providing comparative metrics describing the shape of each scour hole.

It is important to note that these comparative extent and slope metrics are calculated as an asset management tool to enable tracking and interpretation of scour at BOWF. They are not, however, directly comparable with traditional measures such as slope angle which is usually quoted for the steepest part of the scour hole.

Figure 5.2 shows the 2021 bathymetry for WTG L07. At this location there was good coverage around all four legs. Figures of the same format are provided for all surveyed locations in the datapack.

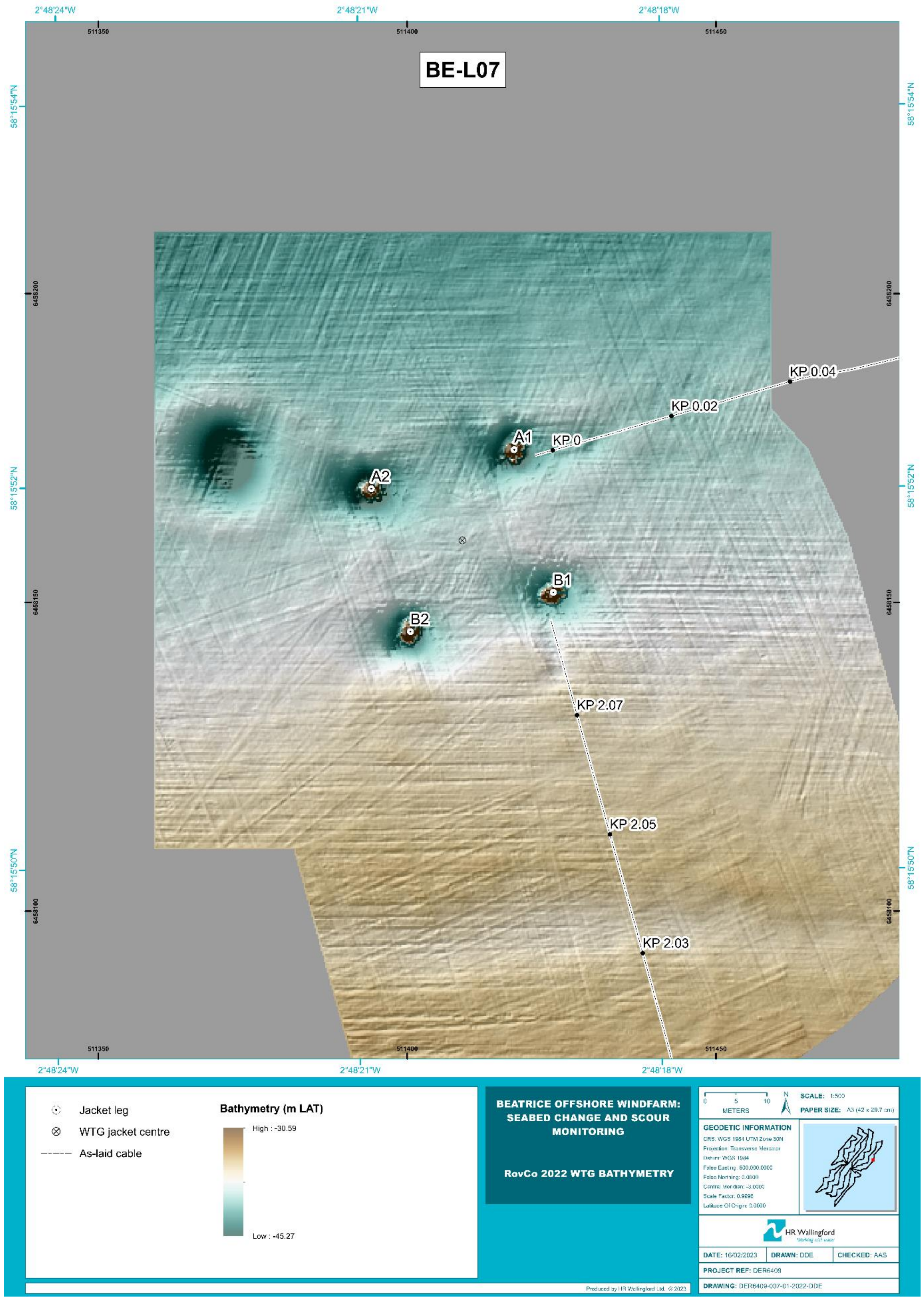


Figure 5.2: Example (L07 2022) of bathymetric data used as input to the Automated Scour Analysis Tool

Source: HR Wallingford using RovCo data

6 Analysis

As background to the analysis, each of the 4-legged pre-piled jackets have outer pile diameters of 2.2 m at mudline and pile-centre to pile-centre separation of 22.4 m on each side of jacket.

6.1 Local scour depth

Maximum local scour depths have been calculated at each jacket leg based on the Digital Elevation Models (DEMs) created from the survey data. The results for the 2022 survey are listed in Table 6.1. The results are also mapped in Figure 6.4, alongside the results for 2019 (Figure 6.1), 2020 (Figure 6.2) and 2021 (Figure 6.3). Care should be taken when comparing the results from the four (2019, 2020, 2021 and 2022) post-installation surveys as different foundations have been surveyed and they may not necessarily be representative populations.

It should be noted that because of the differing rotations of the jackets the leg naming is such that each label does not correspond to the same compass direction relative to the centre of the pile. For this reason it is not meaningful to compare each leg ID between locations. For reference the pile identifications are shown in Figure 2.2.

The summary statistics on scour are as follows:

- Maximum local scour depths range between <0.1 to 1.0 m and are on average 0.3 m for the 2019 survey;
- Maximum local scour depths range between <0.1 and 1.6 m and are on average 0.5 m for the 2020 survey;
- Maximum local scour depths range between <0.1 and 1.4 m and are on average 0.5 m for the 2021 survey;
- Maximum local scour depths range between <0.1 and 1.2 m and are on average 0.3 m for the 2022 survey.

It is of interest that at some locations no scour appears to have developed. The ambient metocean conditions across the site are expected to be relatively constant and so we would expect scour to develop relatively uniformly across the site. It seems likely that wave action may have resulted in the infilling of some scour pits. This could go towards explaining the large range of scour depths observed across the site. Alternatively, subtle changes in the soil conditions across the site might have an impact on the scour development. This theory is explored more in Section 6.1.2.

An example of the bed level transects produced is provided for BE-M10 leg A1 (Figure 6.5). The reported scour extent and angles are for the 2022 survey.

In terms of maximum scour depth there are a number of outliers in the 2022 dataset, these are discussed below.

Outliers

B07

Deep (of the order 1 m) scour has been observed at all four legs at B07 since the first post-installation survey in 2020. The maximum local scour depth decreased between 2020 and 2021 at leg B2. However, it is possible that the scour depth at this leg was overestimated in 2020. Between 2021 and 2022 the scour depth reduced at all four legs, but this may be due to a seasonal trend.

F09

The scour at leg B2 is twice as deep as the scour at the other three legs. It appears that this leg is close to the mound of sediment from where the array cable trenching began. It's possible that this activity caused some disturbance to the bed around this leg.

G08

Deep scour (>0.8 m) has formed at all four legs. The scour pits are all relatively symmetrical.

L07

Deep scour (of the order 1 m) has formed at all four legs. In the 2019 survey only B1 and B2 were covered, but with the 2021 and 2022 data we can confirm that scour is as deep at the other two legs. Although the scour is deep at B1 and B2 the scour depth did not change significantly between the 2019 and 2021 and 2021 and 2022 surveys.

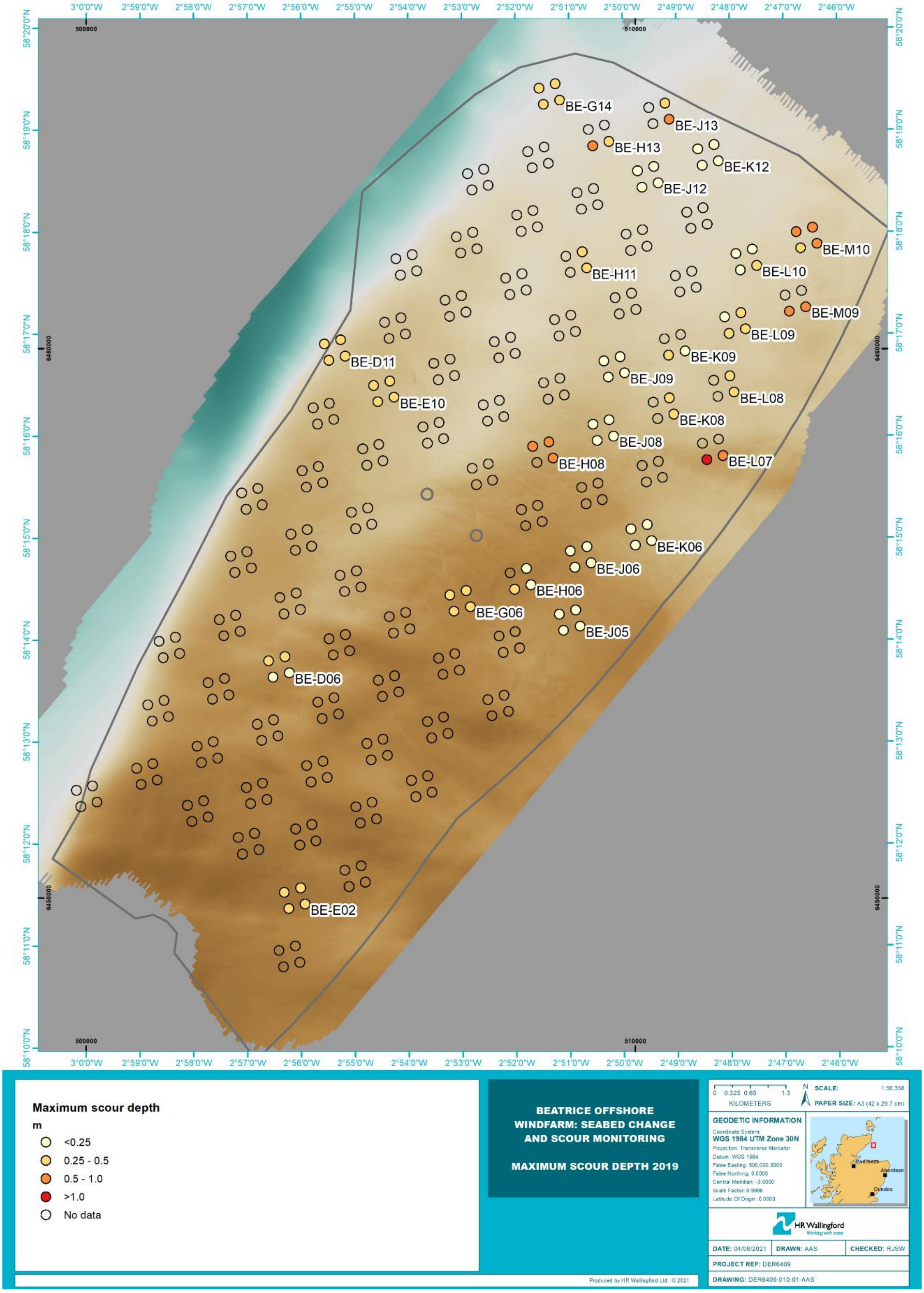


Figure 6.1: Maximum local scour depth at each jacket leg for the 2019 Fugro survey

Source: *HR Wallingford*

Note: *surveyed in October*

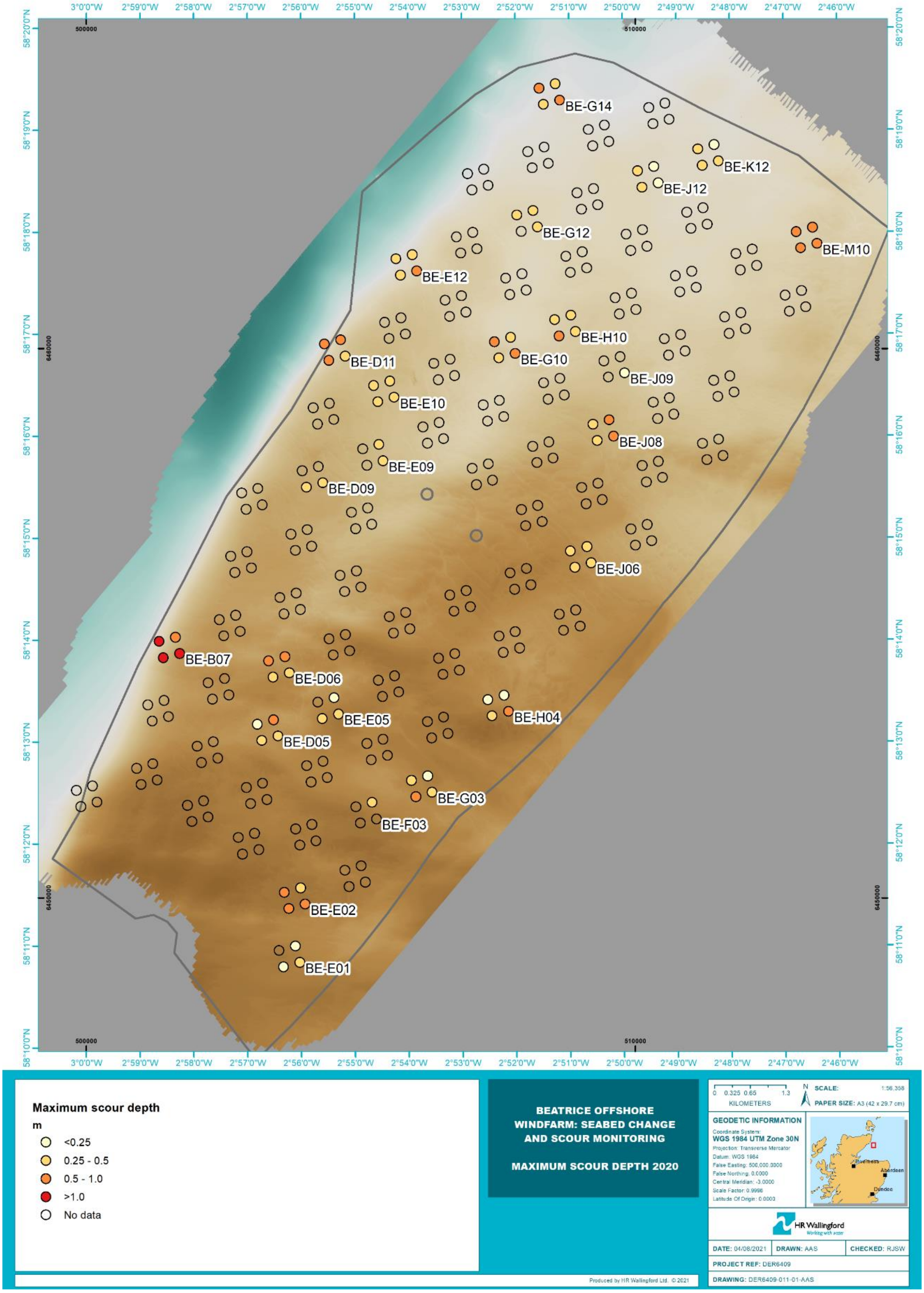


Figure 6.2: Maximum local scour depth at each jacket leg for the 2020 RovCo survey

Source: HR Wallingford

Note: surveyed in October-November

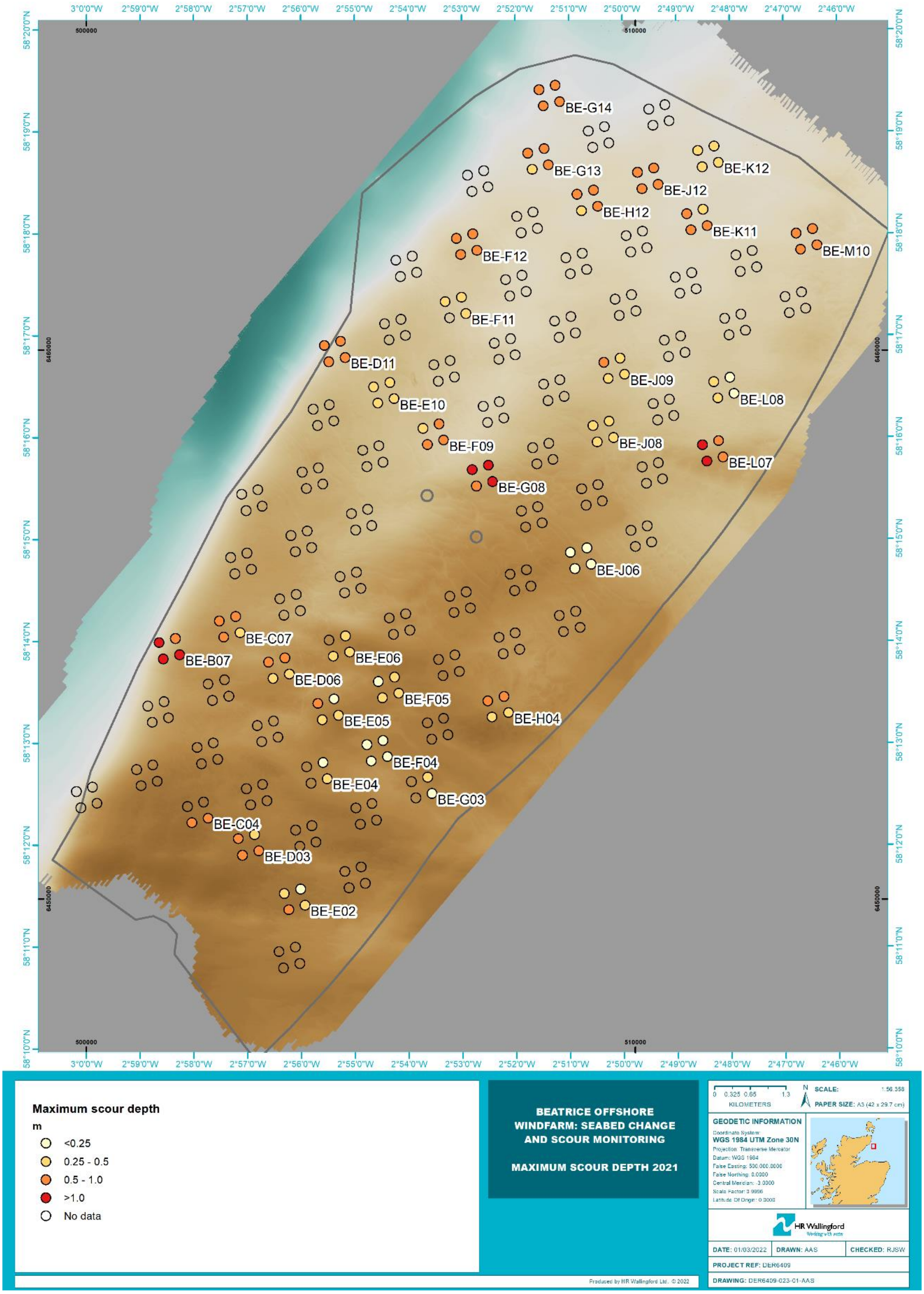


Figure 6.3: Maximum local scour depth at each jacket leg for the 2021 RovCo survey

Source: *HR Wallingford*

Note: *surveyed in July*

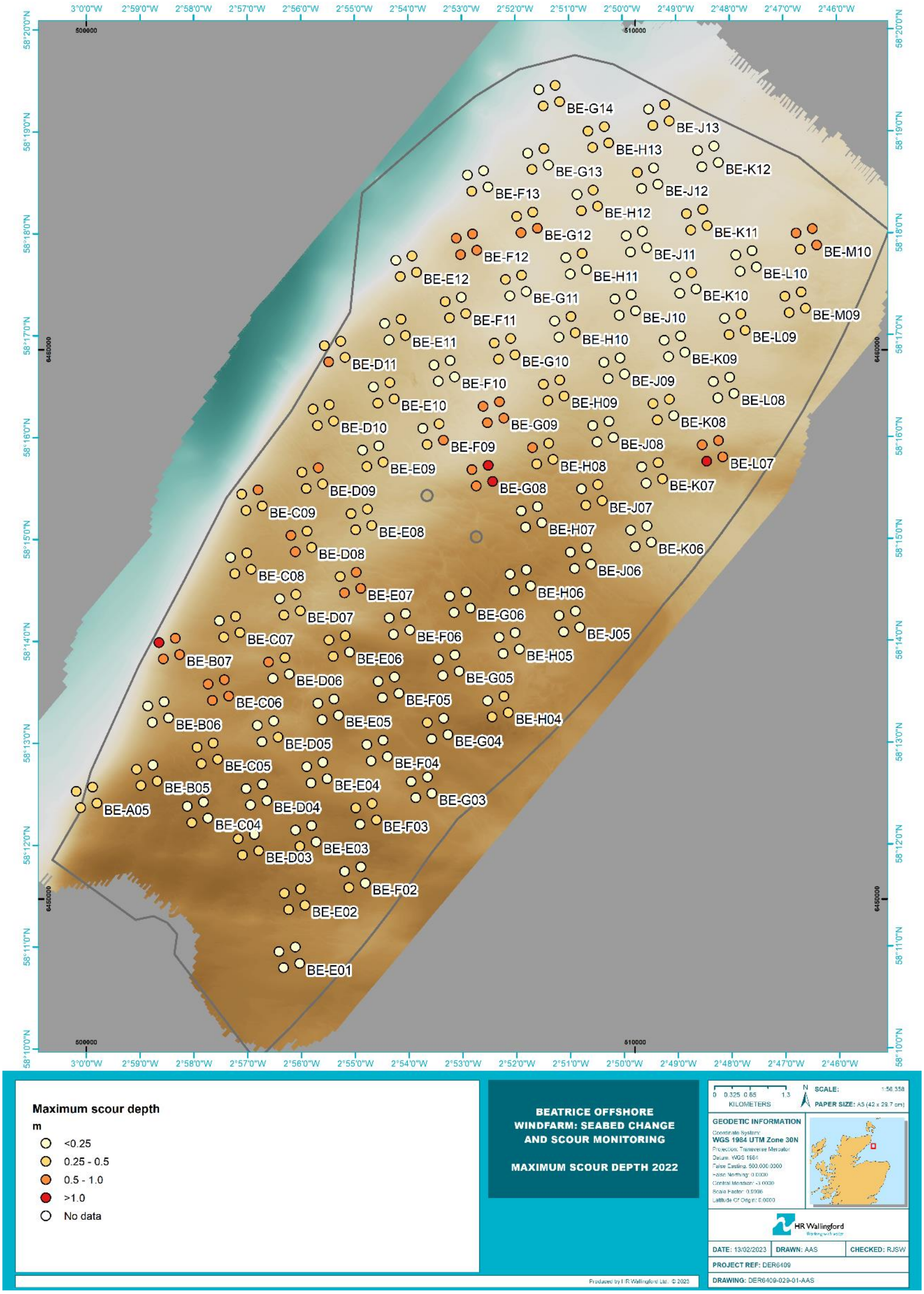


Figure 6.4: Maximum local scour depth at each jacket leg for the 2022 RovCo survey

Source: *HR Wallingford*

Note: *surveyed in April*

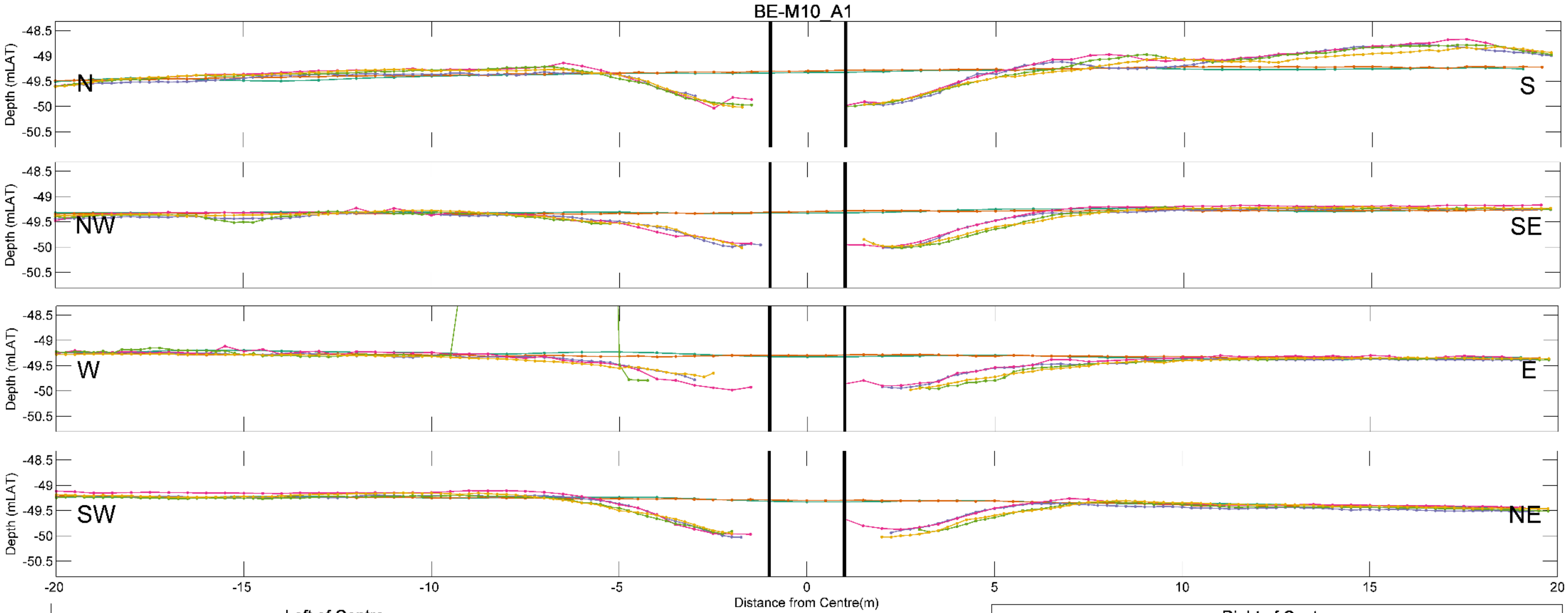
Table 6.1: 2022 maximum local scour pit depths

Foundation	Scour depth at A1 (m)	Scour depth at A2 (m)	Scour depth at B1 (m)	Scour depth at B2 (m)
BE-A05	0.5	0.5	0.5	0.4
BE-B05	0.3	0.3	0.3	0.2
BE-B06	0.2	0.2	0.2	0.1
BE-B07	0.6	1.2	0.8	0.9
BE-C04	0.2	0.2	0.3	0.2
BE-C05	0.3	0.4	0.3	0.4
BE-C06	0.7	0.5	0.6	0.7
BE-C07	0.4	0.2	0.4	0.4
BE-C08	0.4	0.3	0.2	0.4
BE-C09	0.4	0.5	0.4	0.3
BE-D03	0.2	0.5	0.4	0.5
BE-D04	0.1	0.0	0.2	0.1
BE-D05	0.3	0.2	0.2	0.1
BE-D06	0.2	0.2	0.5	0.3
BE-D07	0.4	0.4	0.2	0.3
BE-D08	0.5	0.6	0.4	0.5
BE-D09	0.4	0.5	0.3	0.3
BE-D10	0.3	0.3	0.3	0.4
BE-D11	0.5	0.3	0.3	0.3
BE-E01	0.0	0.2	0.0	0.1
BE-E02	0.4	0.3	0.4	0.3
BE-E03	0.3	0.2	0.2	0.2
BE-E04	0.1	0.2	0.0	0.2
BE-E05	0.1	0.1	0.1	0.1
BE-E06	0.2	0.4	0.3	0.3
BE-E07	0.5	0.5	0.5	0.6
BE-E08	0.4	0.3	0.3	0.4
BE-E09	0.4	0.2	0.5	0.2
BE-E10	0.3	0.3	0.1	0.3
BE-E11	0.2	0.3	0.2	0.4
BE-E12	0.3	0.3	0.2	0.4
BE-F02	0.3	0.1	0.2	0.2
BE-F03	0.2	0.4	0.3	0.4
BE-F04	0.0	0.1	0.1	0.2
BE-F05	0.1	0.2	0.0	0.0
BE-F06	0.0	0.0	0.1	0.0
BE-F09	0.2	0.3	0.4	0.7
BE-F10	0.2	0.2	0.2	0.2
BE-F11	0.1	0.3	0.3	0.3
BE-F12	0.6	0.6	0.5	0.6
BE-F13	0.3	0.2	0.1	0.2
BE-G03	0.1	0.0	0.1	0.1
BE-G04	0.2	0.2	0.3	0.2
BE-G05	0.1	0.1	0.0	0.1
BE-G06	0.0	0.1	0.1	0.2
BE-G08	1.1	1.1	0.9	0.8
BE-G09	0.7	0.7	0.6	0.8
BE-G10	0.3	0.3	0.5	0.4

Foundation	Scour depth at A1 (m)	Scour depth at A2 (m)	Scour depth at B1 (m)	Scour depth at B2 (m)
BE-G11	0.2	0.2	0.3	0.3
BE-G12	0.5	0.5	0.4	0.3
BE-G13	0.1	0.3	0.1	0.4
BE-G14	0.4	0.3	0.2	0.4
BE-H04	0.3	0.3	0.2	0.3
BE-H05	0.0	0.2	0.0	0.2
BE-H06	0.2	0.1	0.0	0.1
BE-H07	0.2	0.2	0.2	0.0
BE-H08	0.4	0.5	0.4	0.5
BE-H09	0.4	0.3	0.3	0.3
BE-H10	0.2	0.3	0.1	0.5
BE-H11	0.2	0.2	0.1	0.4
BE-H12	0.4	0.4	0.2	0.3
BE-H13	0.4	0.3	0.3	0.4
BE-J05	0.1	0.1	0.1	0.1
BE-J06	0.1	0.1	0.1	0.0
BE-J07	0.3	0.3	0.2	0.3
BE-J08	0.0	0.2	0.0	0.0
BE-J09	0.1	0.1	0.0	0.1
BE-J10	0.2	0.1	0.2	0.2
BE-J11	0.2	0.1	0.1	0.1
BE-J12	0.2	0.3	0.2	0.1
BE-J13	0.3	0.3	0.1	0.3
BE-K06	0.1	0.0	0.1	0.1
BE-K07	0.3	0.2	0.4	0.2
BE-K08	0.2	0.3	0.4	0.3
BE-K09	0.2	0.2	0.0	0.2
BE-K10	0.2	0.2	0.1	0.3
BE-K11	0.3	0.3	0.5	0.4
BE-K12	0.1	0.1	0.0	0.2
BE-L07	0.6	0.8	0.7	1.0
BE-L08	0.2	0.2	0.2	0.2
BE-L09	0.3	0.3	0.3	0.2
BE-L10	0.2	0.2	0.1	0.1
BE-M09	0.4	0.5	0.4	0.4
BE-M10	0.6	0.6	0.5	0.5
Min	**<0.1**			
Max	**1.2**			
Mean	**0.3**			
STD	**0.2**			

Source: HR Wallingford

Note: as mentioned in the text, the compass orientation of each leg is variable



Left of Centre	
N to S Extent = 3.95 m	N to S Slope Angle (Av) = 11.3°
NW to SE Extent = 6.05 m	NW to SE Slope Angle (Av) = 6.9°
W to E Extent = 6.55 m	W to E Slope Angle (Av) = 4.2°
SW to NE Extent = 4.55 m	SW to NE Slope Angle (Av) = 9.1°

Right of Centre	
N to S Extent = 4.15 m	N to S Slope Angle (Av) = 9.4°
NW to SE Extent = 5.70 m	NW to SE Slope Angle (Av) = 7.9°
W to E Extent = 7.75 m	W to E Slope Angle (Av) = 5.9°
SW to NE Extent = 5.95 m	SW to NE Slope Angle (Av) = 8.0°

Figure 6.5: Bathymetric transects for BE-M10 leg A1

Source: HR Wallingford

6.1.1 Rate of scour

In Figure 6.6 scour depth variations with time from installation are shown. Each point represents the maximum scour depth at one jacket leg (i.e. there can be up to four points per foundation). This figure shows that the rate of scour between installation and 2019, 2019 and 2020 and between 2020 and 2021 is relatively constant. Between 2021 and 2022 a reverse in the trend is observed and on average scour depths reduced over this period. The individual dates of installation in 2017 for each jacket are plotted as zero scour depth. An individual plot for each jacket is included in the datapack.

Table 6.2 includes the scour rates from installation to the 2019 survey, from the 2019 to the 2020 survey, from the 2020 to the 2021 survey and from the 2021 to 2022 survey. To allow for direct comparison only locations are included where data are available for all four surveys. From installation to the first post-installation survey in 2019 the average rate of scour was 0.09 m/yr. For the same locations from 2019 to 2020 the average rate of scour was 0.13 m/yr, from 2020 to 2021 the average rate of scour was 0.16 m/yr and from 2021 to 2022 the average rate of scour was -0.37 m/yr. A negative value for rate of scour implies a decrease in local scour depth i.e. the scour hole has got shallower over the considered period.

These estimates come from a relatively small sample size because of the limited number of jacket legs that have data available for all years.

It should be noted that these rates describe the net change in scour over a period of approximately one year. It is likely that there is variability in the scour depths and that the maximum rate of scour could be larger than that observed at the time of the surveys.

The time period between surveys is not even. For those repeated with a smaller time-gap a small change in scour (real or otherwise) results in a much higher rate of scour. If scour only occurs during a few months of the year then calculating the rate over this period will result in larger rates. Similarly, sampling the scour after a wave-induced backfilling even may result in a reduction in the scour depths and rate of scour, as was observed in the 2022 data.

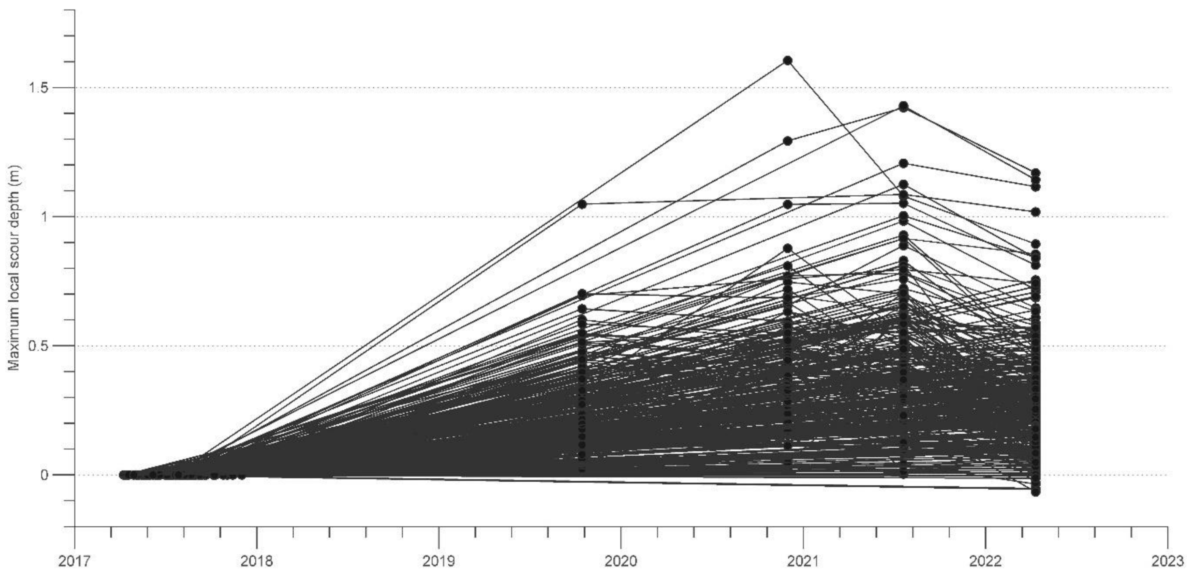


Figure 6.6: Maximum local scour depth at each jacket leg with time from installation

Source: *HR Wallingford*

Note: *this data is recorded in digital form in the datapack*

Table 6.2: Rate of change in maximum local scour pit depth from installation to 2019, 2019 to 2020, 2020 and 2021 and 2021 to 2022

	Installation to 2019 rate of scour (m/yr)	2019 to 2020 rate of scour (m/yr)	2020 to 2021 rate of scour (m/yr)	2021 to 2022 rate of scour (m/yr)
BE-D06_A1	0.09	0.18	0.12	-0.44
BE-D06_A2	0.07	0.14	0.22	-0.34
BE-D11_A1	0.21	0.27	0.01	-0.32
BE-D11_A2	0.12	0.12	0.24	-0.37
BE-D11_B2	0.17	0.14	0.04	-0.31
BE-E02_A1	0.13	0.20	0.06	-0.23
BE-E02_B2	0.12	0.10	-0.36	0.14
BE-E10_A1	0.13	0.09	0.04	-0.22
BE-G14_B1	0.19	0.12	0.21	-0.64
BE-G14_B2	0.18	0.04	0.37	-0.31
BE-J06_A2	0.03	0.34	-0.68	0.14
BE-J08_B2	0.07	0.11	0.16	-0.49
BE-J12_A1	0.09	0.04	0.43	-0.43
BE-J12_A2	0.10	0.16	0.35	-0.49
BE-J12_B1	0.07	0.01	0.71	-0.63
BE-J12_B2	0.08	0.19	0.50	-0.80
BE-K12_A1	0.07	0.16	0.13	-0.39
BE-K12_A2	0.07	0.12	0.18	-0.43
BE-K12_B1	0.08	0.20	0.08	-0.61
BE-K12_B2	0.04	0.03	0.28	-0.14
BE-M10_B1	0.17	0.13	0.15	-0.17
min	0.03	0.01	-0.68	-0.80
max	0.21	0.34	0.71	0.14
median	0.09	0.13	0.16	-0.37

Source: HR Wallingford

Note: only piles with 4 years of survey data are included

6.1.2 Impact of soil conditions

We notice that at BOWF there are a large range of scour depths across the site and even at individual jackets. To determine whether the soil type has a control on the maximum scour depth for each jacket the design soil profile has been plotted for the upper 3 m of the seabed and the maximum scour depth for the 2019, 2020, 2021 and 2022 surveys overlaid (Figure 6.8).

We note that typically scour depths are <0.5 m and are restricted to the surface layers of the Upper Quaternary gravels and sands (I-Gr). The only exception of this is at F09 where scour has occurred down to a depth of 1 m in 2021 at leg B2 penetrating the II-Gr soil layer. As noted in Section 6.1 it is hypothesised that the scour at this leg may have been caused by the cable installation processes.

At F02, F04, F05 and K06 where the surface layer comprises Quaternary gravels and sands (II-Gr) there has been minimal scour. However, as there has been minimal scour at locations where the surface comprises Upper Quaternary gravels and sands this does not necessary indicate that the soil is the limiting factor.

Whilst in the majority of locations the scour does not immediately appear to be controlled by the soil properties, it is noted that the profiles may be an oversimplification. For example, at G06 the nearest borehole (BHF-29) has an upper 0.55 m thick layer of sands, whilst the 0.55 to 1.55 m layer comprises gravel. At this location a maximum scour depth of 0.2 m was observed in 2022. This could indicate that the scour is limited by the presence of gravels not resolved by the design soil profiles.

Figure 6.7 shows a still from ROV footage captured at WTG L07 in June 2022. (We noted the local scour depth analysed from the survey data at this leg was 0.8 m in April 2022). This image shows that surrounding the foundation leg is a scour pit lined with shell fragments. It's possible that this material acts as an armour resisting the scouring of the sand beneath. Although this shelly material is visible at a large number of foundations it is not observed at all foundations.

Figure 6.7: Armouring of scour pit with shells

Source: RovCo 2022

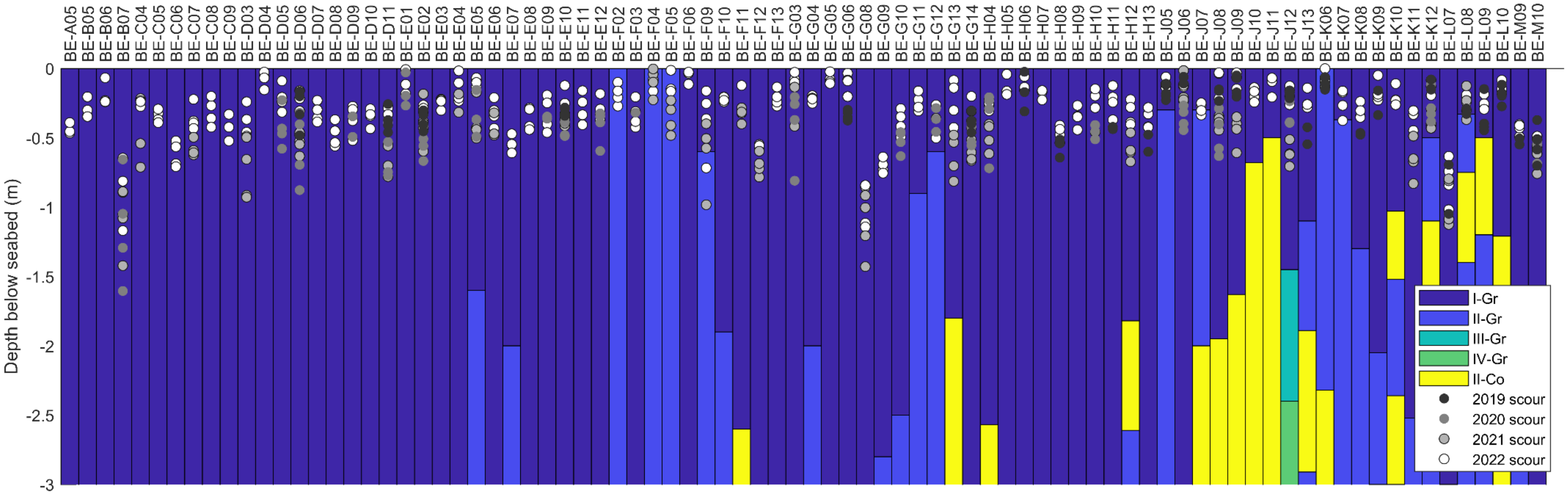


Figure 6.8: Design soil profiles (colour bars) and maximum scour depth at each leg for the 2019 (black), 2020 (dark grey), 2021 (light grey) and 2022 (white) surveys

Source: *HR Wallingford*

Note: *I-GR Upper Quaternary sands and gravels, II-Gr Quaternary non-cohesive, III-Gr Disturbed bedrock, IV-GR Largely intact bedrock, II-Co Quaternary cohesive (see HR Wallingford, 2021 for more details)*

6.2 Scour extent

Scour extent is calculated as the distance from the outer wall of the jacket pile out to where the seabed crosses the filtered mean (ambient) seabed level. Scour extents are estimated for each compass direction (provided in the datapack) and a mean is taken of all compass directions (Table 6.3). To avoid anomalous results scour extents were set as zero when the maximum scour depth at a given jacket pile was less than 0.2 m.

Between the 2019 and 2020 surveys the average scour extent increased on average by 0.8 m if the mean is taken or by 1.2 m if the median is taken. Between the 2020 and 2021 surveys the average scour extent increased on average by 3.4 m if the mean is taken or by 1.5 m if the median is taken. Between the 2021 and 2022 surveys the average scour extent decreased on average by 2.7 m if the mean is taken or by 1.6 m if the median is taken. The scour extent has a large standard deviation resulting in large differences between mean and median values.

Scour extent is largest to the east and southeast in 2019, west and northwest in 2020 and east and west in 2021 and 2022. Because different foundations are being compared between the surveys the difference in direction may not represent a true change in scour morphology. Equally, the large range of values suggest that the observed differences may not be significant.

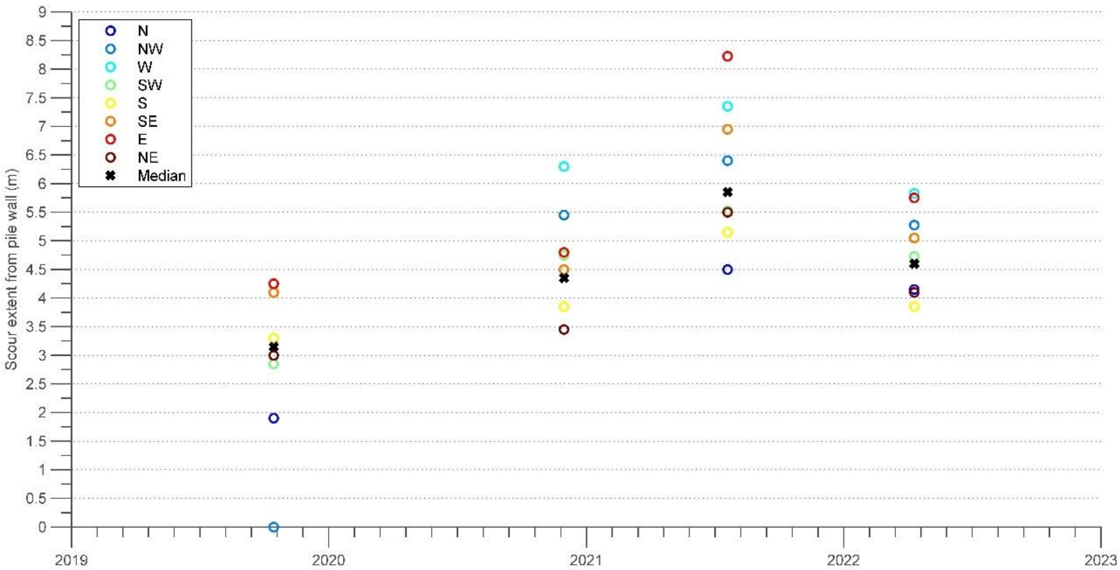


Figure 6.9: Median scour extent for the 2019, 2020, 2021 and 2022 surveys for each compass direction

Source: HR Wallingford

Table 6.3: Mean scour pit extents from 2022 survey

Foundation	Scour extent at A1 (m)	Scour extent at A2 (m)	Scour extent at B1 (m)	Scour extent at B2 (m)
BE-A05	3.3	4.8	3.2	3.8
BE-B05	8.4	8.2	4.7	7.4
BE-B06	10.0	9.0	7.8	0.0
BE-B07	4.7	4.4	5.6	4.5
BE-C04	10.8	5.8	6.0	4.0
BE-C05	10.6	6.1	4.1	10.8
BE-C06	6.2	7.8	5.5	7.7
BE-C07	7.6	4.9	11.8	9.7

Foundation	Scour extent at A1 (m)	Scour extent at A2 (m)	Scour extent at B1 (m)	Scour extent at B2 (m)
BE-C08	7.8	6.5	6.2	8.8
BE-C09	9.4	9.9	5.3	5.5
BE-D03	5.7	5.4	11.0	11.8
BE-D04	0.0	0.0	0.0	0.0
BE-D05	7.5	5.8	7.8	0.0
BE-D06	0.0	6.6	6.1	9.9
BE-D07	7.1	5.5	6.7	7.7
BE-D08	5.2	4.9	6.0	10.3
BE-D09	9.8	17.2	8.2	6.2
BE-D10	7.4	7.0	4.0	6.9
BE-D11	5.1	8.1	4.0	5.6
BE-E01	0.0	0.0	0.0	0.0
BE-E02	7.3	5.3	7.0	7.9
BE-E03	8.8	10.8	3.2	9.1
BE-E04	0.0	16.1	0.0	0.0
BE-E05	0.0	0.0	0.0	0.0
BE-E06	9.7	15.0	6.0	13.0
BE-E07	8.9	5.1	8.2	11.1
BE-E08	5.9	5.7	5.0	6.8
BE-E09	12.9	0.0	11.4	4.6
BE-E10	5.3	8.6	0.0	8.6
BE-E11	8.7	7.0	0.0	7.6
BE-E12	4.8	6.2	0.0	7.6
BE-F02	5.8	0.0	8.8	0.0
BE-F03	4.9	11.0	6.2	6.3
BE-F04	0.0	0.0	0.0	0.0
BE-F05	0.0	0.0	0.0	0.0
BE-F06	0.0	0.0	0.0	0.0
BE-F09	0.0	11.0	13.0	5.8
BE-F10	8.5	6.3	9.4	9.3
BE-F11	0.0	7.9	9.9	9.0
BE-F12	12.2	6.3	9.2	4.6
BE-F13	9.0	10.7	0.0	5.6
BE-G03	0.0	0.0	0.0	0.0
BE-G04	0.0	8.0	10.2	11.1
BE-G05	0.0	0.0	0.0	0.0
BE-G06	0.0	0.0	0.0	6.2
BE-G08	10.4	7.3	8.7	7.2
BE-G09	8.1	8.2	5.4	8.6
BE-G10	4.5	6.4	8.6	10.5
BE-G11	6.4	0.0	5.2	7.4
BE-G12	6.5	8.6	11.1	8.1
BE-G13	0.0	12.5	0.0	10.6
BE-G14	4.4	7.9	2.9	12.0
BE-H04	6.9	7.6	8.5	13.7
BE-H05	0.0	0.0	0.0	0.0
BE-H06	0.0	0.0	0.0	0.0
BE-H07	0.0	0.0	8.0	0.0

Foundation	Scour extent at A1 (m)	Scour extent at A2 (m)	Scour extent at B1 (m)	Scour extent at B2 (m)
BE-H08	6.2	5.8	12.2	7.1
BE-H09	8.3	10.9	5.5	6.5
BE-H10	0.0	7.9	0.0	9.5
BE-H11	5.8	4.9	0.0	6.4
BE-H12	9.0	17.0	4.8	5.6
BE-H13	9.6	8.3	5.4	8.9
BE-J05	0.0	0.0	0.0	0.0
BE-J06	0.0	0.0	0.0	0.0
BE-J07	7.3	8.8	8.0	7.6
BE-J08	0.0	0.0	0.0	0.0
BE-J09	0.0	0.0	0.0	0.0
BE-J10	7.3	0.0	0.0	8.4
BE-J11	12.0	0.0	0.0	0.0
BE-J12	0.0	10.0	0.0	0.0
BE-J13	9.5	9.8	0.0	11.2
BE-K06	0.0	0.0	0.0	0.0
BE-K07	5.2	0.0	8.0	0.0
BE-K08	5.8	14.5	5.5	5.3
BE-K09	5.7	5.0	0.0	0.0
BE-K10	8.5	7.8	0.0	10.5
BE-K11	6.1	5.3	9.5	11.2
BE-K12	0.0	0.0	0.0	0.0
BE-L07	5.4	6.3	11.1	8.7
BE-L08	2.2	5.8	8.6	0.0
BE-L09	10.7	7.4	10.9	0.0
BE-L10	0.0	0.0	0.0	0.0
BE-M09	5.4	10.7	4.9	6.1
BE-M10	5.6	13.1	3.5	4.3
Min	**0.0**			
Max	**17.2**			
Mean	**5.2**			
STD	**4.2**			

Source: HR Wallingford

Note: if scour depth less than 0.2 m no value for scour extent was calculated and it is set as 0.0 m

6.3 Scour slope

Average slope angles were estimated by taking the scour extent (as presented in the previous section) and the lowest seabed level in the profile line between the calculated extent and the pile wall. Slope angle was then calculated using the inverse tangent. If no extent was calculated, then no corresponding angle could be calculated. To avoid anomalous results scour slopes were set as zero when the maximum scour depth at a given jacket leg was less than 0.2 m. Average scour slopes for 2022 are presented in Table 6.4.

On average the scour slopes increased between the 2019 and 2020 surveys by 2.7° if the mean value is taken and 2.9° if the median is taken. On average scour slopes decreased between the 2020 and 2021 surveys by 0.2° if the mean value is taken and 0.4° if the median is taken. On average scour slopes decreased between the 2021 and 2022 surveys by 2.6° if the mean value is taken and 2.2° if the median is taken.

From 2021 to 2022 we observed a decrease in scour depths and extents combined with a decrease in scour pit slopes. This suggests that over this period the scour pits became smaller in all dimensions.

Scour slopes have a wide distribution and therefore the mean may be strongly impacted by one or two values. Figure 6.10 presents the median scour slopes for each compass direction. Slopes appeared steepest to the south and southeast in 2019, 2020 and 2022. Whilst slopes appeared steepest to the northeast and south in 2021.

In sandy sediments under unidirectional flow conditions the upstream slope of a scour hole can be approximated by the angle of repose (Harris and Whitehouse, 2015), whilst the downstream slope is about half this angle ±2°, approximately. Typical values for the angle of repose in sands are in the range of 26° to 45° (Hoffmans and Verheij, 1997). From the monitoring data obtained from built offshore wind farms, the scour extents for foundation structures placed in morphologically dynamic tidal areas within predominantly sandy environments indicate slope angles lower than those based on sediment angle of repose. This is not unexpected as under reversing tidal conditions the downstream / upstream positions will reverse and, therefore, the lower slope angles associated with the wake vortices are likely to prevail over the longer-term.

In our experience, the slope angles observed at BOWF are much less steep than observed at other wind farm sites where there are strong tidal currents. This may be partially due to the scour development still being ongoing, but also the generally weak tidal currents and potentially the periodic effect of wave action acting to (transiently) infill the scour.

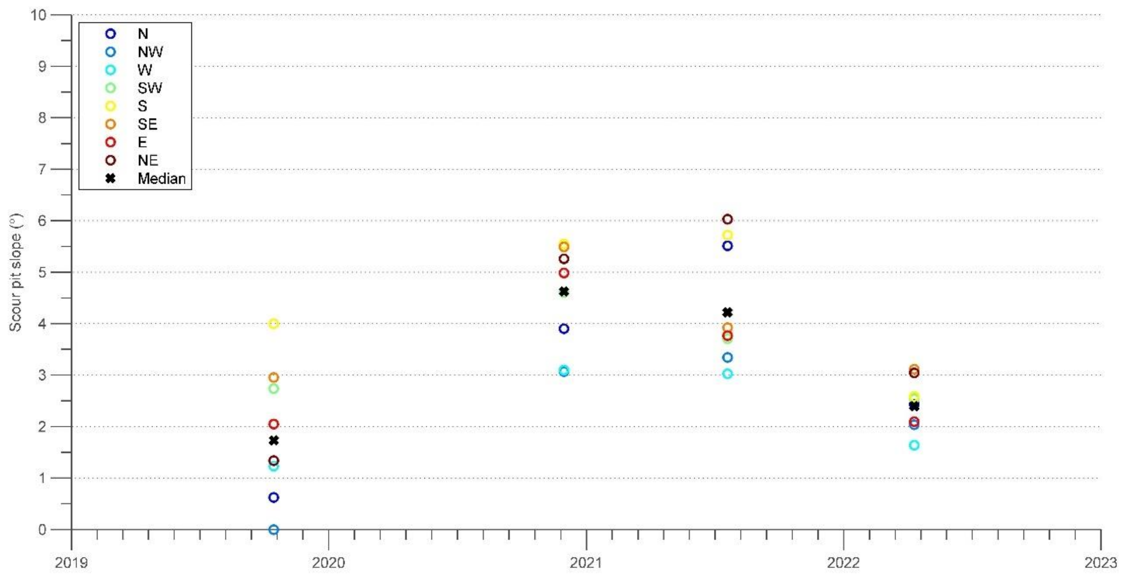


Figure 6.10: Average scour slopes for each compass direction for the 2019, 2020, 2021 and 2022 surveys

Source: HR Wallingford

Table 6.4: 2022 scour pit slopes

Foundation	Scour slope at A1 (°)	Scour slope at A2 (°)	Scour slope at B1 (°)	Scour slope at B2 (°)
BE-A05	10.3	7.7	12.4	8.5
BE-B05	3.1	2.8	4.0	3.1
BE-B06	1.8	2.7	2.8	0.0
BE-B07	11.7	16.2	10.3	14.2
BE-C04	2.3	3.7	3.5	4.9

Foundation	Scour slope at A1 (°)	Scour slope at A2 (°)	Scour slope at B1 (°)	Scour slope at B2 (°)
BE-C05	2.1	4.2	3.8	2.8
BE-C06	7.5	5.0	7.3	5.1
BE-C07	4.3	4.2	3.2	3.3
BE-C08	3.7	3.1	2.7	3.9
BE-C09	4.0	5.1	6.7	5.6
BE-D03	3.5	5.3	2.6	2.5
BE-D04	0.0	0.0	0.0	0.0
BE-D05	4.0	4.7	3.7	0.0
BE-D06	0.0	3.4	10.9	3.0
BE-D07	4.0	6.0	3.3	3.3
BE-D08	7.9	9.3	5.2	3.9
BE-D09	2.7	2.0	2.7	4.2
BE-D10	3.7	3.6	6.9	6.0
BE-D11	8.3	4.0	7.5	6.3
BE-E01	0.0	0.0	0.0	0.0
BE-E02	3.5	4.5	3.7	3.6
BE-E03	2.6	2.2	5.2	2.9
BE-E04	0.0	1.0	0.0	0.0
BE-E05	0.0	0.0	0.0	0.0
BE-E06	1.9	2.0	5.9	2.4
BE-E07	5.5	7.7	5.1	3.9
BE-E08	5.7	4.5	5.1	4.6
BE-E09	2.2	0.0	2.9	4.5
BE-E10	4.5	3.5	0.0	3.5
BE-E11	2.8	5.6	0.0	5.0
BE-E12	6.0	3.8	0.0	4.1
BE-F02	4.8	0.0	2.2	0.0
BE-F03	3.0	2.8	4.3	4.8
BE-F04	0.0	0.0	0.0	0.0
BE-F05	0.0	0.0	0.0	0.0
BE-F06	0.0	0.0	0.0	0.0
BE-F09	0.0	1.6	2.4	9.2
BE-F10	2.2	2.4	1.7	2.2
BE-F11	0.0	3.0	2.5	2.6
BE-F12	4.0	7.1	4.8	9.3
BE-F13	2.6	2.1	0.0	3.4
BE-G03	0.0	0.0	0.0	0.0
BE-G04	0.0	3.1	2.3	1.8
BE-G05	0.0	0.0	0.0	0.0
BE-G06	0.0	0.0	0.0	0.3
BE-G08	7.7	11.9	6.8	9.8
BE-G09	7.1	6.4	9.0	6.7
BE-G10	5.2	4.6	4.5	2.8
BE-G11	2.9	0.0	4.8	3.3
BE-G12	5.9	4.6	2.7	2.8
BE-G13	0.0	2.0	0.0	3.0
BE-G14	7.4	3.6	7.6	3.6

Foundation	Scour slope at A1 (°)	Scour slope at A2 (°)	Scour slope at B1 (°)	Scour slope at B2 (°)
BE-H04	3.5	2.9	2.3	1.6
BE-H05	0.0	0.0	0.0	0.0
BE-H06	0.0	0.0	0.0	0.0
BE-H07	0.0	0.0	2.1	0.0
BE-H08	4.6	7.2	3.1	6.5
BE-H09	4.0	2.5	4.4	3.5
BE-H10	0.0	2.7	0.0	3.7
BE-H11	4.0	3.5	0.0	4.9
BE-H12	3.3	1.7	4.3	4.0
BE-H13	2.9	3.4	4.3	3.8
BE-J05	0.0	0.0	0.0	0.0
BE-J06	0.0	0.0	0.0	0.0
BE-J07	3.1	3.2	2.9	4.1
BE-J08	0.0	0.0	0.0	0.0
BE-J09	0.0	0.0	0.0	0.0
BE-J10	2.6	0.0	0.0	2.5
BE-J11	1.6	0.0	0.0	0.0
BE-J12	0.0	1.7	0.0	0.0
BE-J13	2.4	2.1	0.0	2.3
BE-K06	0.0	0.0	0.0	0.0
BE-K07	4.6	0.0	4.1	0.0
BE-K08	3.9	1.7	5.0	5.3
BE-K09	3.7	1.2	0.0	0.0
BE-K10	2.0	3.0	0.0	2.4
BE-K11	4.1	4.7	3.8	2.7
BE-K12	0.0	0.0	0.0	0.0
BE-L07	10.0	10.1	4.8	8.6
BE-L08	2.7	4.0	3.0	0.0
BE-L09	2.4	3.4	2.0	0.0
BE-L10	0.0	0.0	0.0	0.0
BE-M09	6.7	3.3	7.2	4.9
BE-M10	7.8	3.5	10.8	9.4
Min	**0.0**			
Max	**16.2**			
Mean	**3.0**			
STD	**2.9**			

Source: HR Wallingford

Note: if scour depth less than 0.2 m no value for scour angle was calculated and it is set as 0.0 degrees

6.4 Global scour

Global scour refers to a lowering of the seabed surface over a wide area which is, in the case of jacket foundations, caused by the grouping effect of the multiple jacket legs and bracing. To measure the global scour the average seabed level for a 5 m radius centred on the centre of the jacket was extracted at each jacket for each survey (Table 6.5). At each jacket the average bed was then compared between surveys to determine whether there had been any systematic lowering (or deposition).

On average the bed level has not changed by a large amount (<0.1 m) since the jacket installation. The maximum lowering is 0.2 m. This lowering is potentially within the uncertainty of the survey data and is at this time not considered to be significant.

Although based on the 2019, 2020, 2021 and 2022 data the formation of global scour has not been observed it should still continue to be monitored as it may form in response to large storm wave action.

Table 6.5: Jacket centre seabed level and change in level for the 2016, 2019, 2020, 2021 and 2022 surveys

	Jacket level (mLAT)					Change in bed level 2016 to 2022 (m)
	2016	2019	2020	2021	2022	
BE-A05	-47.2				-47.1	0.0
BE-B05	-38.9				-39.0	0.0
BE-B06	-43.3				-43.3	0.0
BE-B07	-45.8		-45.8	-45.7	-45.8	0.0
BE-C04	-37.3			-37.1	-37.3	0.0
BE-C05	-39.5				-39.6	-0.1
BE-C06	-40.7				-40.7	-0.1
BE-C07	-41.8			-41.8	-41.8	0.0
BE-C08	-42.8				-42.7	0.0
BE-C09	-45.0				-44.9	0.1
BE-D03	-37.6			-37.5	-37.6	0.0
BE-D04	-38.6				-38.6	0.0
BE-D05	-41.1		-41.2		-41.1	0.0
BE-D06	-41.5	-41.5	-41.6	-41.4	-41.5	0.0
BE-D07	-43.3				-43.3	0.0
BE-D08	-43.2				-43.1	0.1
BE-D09	-43.9		-43.8		-43.8	0.0
BE-D10	-44.8				-44.8	0.0
BE-D11	-49.5	-49.5	-49.4	-49.5	-49.5	0.1
BE-E01	-38.3		-38.3		-38.3	0.1
BE-E02	-37.7	-37.6	-37.7	-37.6	-37.6	0.1
BE-E03	-37.9				-37.9	0.0
BE-E04	-40.0			-40.0	-40.0	0.0
BE-E05	-39.6		-39.8	-39.6	-39.7	0.0
BE-E06	-39.7			-39.8	-39.8	-0.1
BE-E07	-43.2				-43.2	0.0
BE-E08	-45.3				-45.4	-0.1
BE-E09	-45.3		-45.4		-45.3	0.0
BE-E10	-46.0	-45.9	-45.9	-46.0	-46.0	0.0
BE-E11	-46.1				-46.0	0.1
BE-E12	-52.3		-52.1		-52.2	0.0
BE-F02	-39.3				-39.2	0.1
BE-F03	-38.3				-38.2	0.1
BE-F04	-39.7			-39.6	-39.8	0.0
BE-F05	-39.1			-39.0	-39.2	-0.1
BE-F06	-40.9				-41.0	0.0
BE-F09	-48.3			-48.4	-48.4	-0.1
BE-F10	-47.6				-47.6	0.0
BE-F11	-48.2			-48.1	-48.1	0.1
BE-F12	-48.1			-48.1	-48.1	0.0
BE-F13	-53.6				-53.6	0.0
BE-G03	-40.0		-39.8	-39.9	-39.9	0.1
BE-G04	-38.1				-38.1	0.0
BE-G05	-39.1				-39.0	0.1
BE-G06	-39.4	-39.5			-39.6	-0.2
BE-G08	-44.6			-44.5	-44.6	-0.1
BE-G09	-49.3				-49.3	0.0
BE-G10	-48.7		-48.8		-48.8	0.0
BE-G11	-50.5				-50.5	0.0
BE-G12	-50.0		-49.9		-50.0	0.0
BE-G13	-52.9			-52.8	-52.9	-0.1

	Jacket level (mLAT)					Change in bed level 2016 to 2022 (m)
	2016	**2019**	**2020**	**2021**	**2022**	
BE-G14	-54.3	-54.3	-54.3	-54.4	-54.3	0.0
BE-H04	-40.4		-40.2	-40.4	-40.3	0.1
BE-H05	-41.3				-41.2	0.1
BE-H06	-39.2	-39.2			-39.4	-0.1
BE-H07	-41.9				-42.0	-0.1
BE-H08	-43.6	-43.6			-43.6	0.0
BE-H09	-47.0				-47.1	-0.1
BE-H10	-49.0		-48.9		-49.0	-0.1
BE-H11	-49.5	-49.5			-49.6	-0.1
BE-H12	-51.3			-51.2	-51.2	0.0
BE-H13	-52.9				-52.9	0.0
BE-J05	-40.8	-40.7			-40.8	0.1
BE-J06	-41.0	-40.8	-41.0	-40.9	-41.0	0.0
BE-J07	-42.0				-42.0	0.0
BE-J08	-44.9	-45.0	-44.9	-44.9	-44.9	0.0
BE-J09	-47.1	-47.2	-47.2	-47.1	-47.2	-0.1
BE-J10	-48.7				-48.8	-0.1
BE-J11	-50.1				-50.2	-0.1
BE-J12	-51.4	-51.6	-51.6	-51.6	-51.6	-0.2
BE-J13	-53.6	-53.5			-53.6	-0.1
BE-K06	-44.1	-44.0			-44.0	0.0
BE-K07	-43.7				-43.6	0.1
BE-K08	-46.9	-46.9			-46.9	0.0
BE-K09	-48.2	-48.3			-48.3	0.0
BE-K10	-50.8				-50.9	-0.1
BE-K11	-51.2			-51.3	-51.3	-0.1
BE-K12	-52.4	-52.4	-52.4	-52.4	-52.5	-0.1
BE-L07	-43.8	-43.7		-43.7	-43.8	0.0
BE-L08	-47.5	-47.4		-47.3	-47.3	0.2
BE-L09	-48.7	-48.7			-48.8	0.0
BE-L10	-49.2	-49.2			-49.3	-0.1
BE-M09	-48.6	-48.4			-48.5	0.1
BE-M10	-49.3	-49.4	-49.3	-49.3	-49.3	0.0
Min						**-0.2**
Max						**0.2**
Mean						**0.0**

Source: HR Wallingford

7 Empirical scour prediction

7.1 Maximum scour depth

In HR Wallingford (2021) estimates were made for the maximum scour depth at each of the jacket legs. Without backfilling (i.e. for currents only) these estimates resulted in scour ranging from 2.8 to 4.4 m depending on water depth and depth averaged current speed. With the inclusion of wave-induced backfilling the predicted scour depth is reduced to between 0.2 and 0.4 m. We anticipate scour to develop, with episodes of infilling. If conditions at the site are particularly benign, i.e. with low wave activity, for a long duration we anticipate scour to deepen.

7.2 Rate of scour

Relative to the 2022 survey the piles have been installed for a period between 4.3 and 5.0 years (depending on location). From experience HR Wallingford has observed that typically the equilibrium scour depth is met approximately 1 to 3 years after installation, however, this is strongly dependent on the site conditions and the structure type.

Between 2021 and 2022, at those foundations that were surveyed in both 2021 and 2022, the maximum scour depths on average reduced. This may be due in part to the time of year in which the two surveys were completed. The 2021 survey was conducted in July, whereas the 2022 survey was conducted in April. After a winter we would anticipate that storm action will have acted to infill some of the scour that has developed around the jacket legs. During the rest of the year this scour re-establishes under the tidal flow. Therefore, whilst we observe reduced scour in 2022 this may just be a result of seasonality and there may still be an annual trend towards increasing scour depths.

Given the average 2020 to 2021 scour rate of 0.17 m/yr the scour allowance (2.99 m) would not be exceeded until 9 years at the earliest (assuming a scour depth now of 1.4 m) and on average 15 years (assuming an average scour depth now of 0.5 m). This assumes that scour will continue at a similar rate and does not account for variability in the meteorological or soil conditions.

8 Recommendations for further monitoring

The monitoring strategy for BOWF was outlined in Section 4 of HR Wallingford (2021). Surveys are to be taken annually for five years commencing in 2020. For each survey ten locations will be surveyed. If significant scour is identified further geophysical survey work will be undertaken and / or the number of monitoring locations will be increased.

HR Wallingford have not identified scour close to or greater than the scour allowance of 2.99 m, therefore, no further geophysical survey work beyond the planned schedule (of annual surveys) is required.

Given that soil conditions and metocean conditions are relatively constant across the site predicted scour depths are also relatively constant. For this reason locations for further monitoring cannot be prioritised based on predicted scour.

HR Wallingford recommend that the ten sample sites are selected to ensure that a small number of locations (minimum 2 – 3) are surveyed annually to determine the time progression of scour. HR Wallingford advise not surveying ten different locations each year.

HR Wallingford have identified deep local scour (i.e. > 1 m) at WTG foundations BE-B07, G08 and L07. Some or all of these locations should be considered as a priority for future surveying to build up a continuous record of scouring.

It is advisable to request that surveyors remove any data points relating to the structure before gridding the data.

It is predicted that the time of the year in which surveys are conducted will have large influence on the scour levels observed. In order to remain consistent surveys should be conducted at the same time of the year. Where possible observations of wave and current conditions should be utilised to determine if backfilling by storms is likely to have occurred prior to the time of surveying.

9 Conclusions

At BOWF under tidal forcing alone the sands and gravels that make up the upper few metres of the bed are not mobile under normal conditions (i.e. away from the jacket structures founded on their 2.2 m diameter (D) piles). At the jacket structures the flow amplification is sufficient for scour to develop and on average in 2022 the mean local scour depth at the jacket legs was 0.3 m. Whilst a wide range of scour depths are observed in 2022, from less than 0.1 m up to 1.2 m, the local scour depths are well within the design allowance of 2.99 m (1.3*D). Observed (2019, 2020, 2021 and 2022) scour depths across the site range between 0 and 1.6 m.

Scour depths were observed to deepen from installation through to 2021. However, between 2021 and 2022 there was a reduction in the average scour depth. As there are no clear geological restraints in the upper 3 m of the seabed, at the majority of locations there is a sufficient thickness of non-cohesive sediment to allow the design scour depth to form. Therefore, we anticipate scour to continue to deepen in periods with the dominance of currents (i.e. tide and surge) and periodically there may be some infilling with sediment, caused by storm wave action. At the present time, no further geophysical survey work beyond the planned schedule (of annual surveys) is required.

10 References

1. Harris, J.M. and Whitehouse, R.J.S. (2015). Marine scour : Lessons from Nature's laboratory. 201(2014), 19–31.
2. Hoffmans, G.J.C.M. and Verheij, H.J. (1997). Scour Manual. Balkema, Netherlands.
3. HR Wallingford (2021). Beatrice Offshore Windfarm Seabed Change and Scour Monitoring: Technical Scour Assessment: Turbine Foundations. Report DER6409-RT001-R01-00.
4. HR Wallingford (2022). Beatrice Offshore Windfarm Seabed Change and Scour Monitoring: Technical Scour Assessment: Turbine Foundations. Report DER6409-RT003-R01-00.
5. RovCo (2023). ROV Inspection and Cable Survey Campaign 2022, ROVCO-22008-RP-002

We design smarter, more resilient solutions across both the natural and built environment to help everyone live and work more sustainably with water.

HR Wallingford
Howbery Park
Wallingford
Oxfordshire OX10 8BA
United Kingdom

+44 (0)1491 835381

info@hrwallingford.com

www.hrwallingford.com