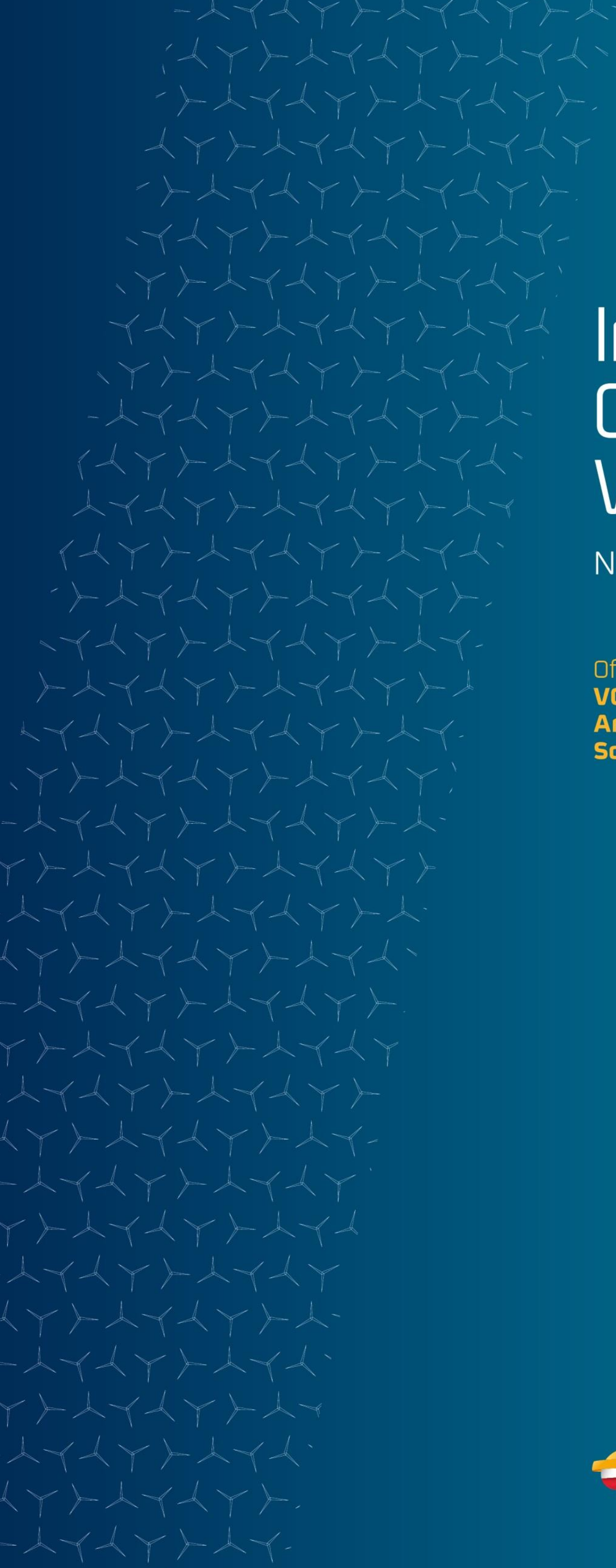

Inch Cape Offshore Wind Farm

New Energy for Scotland

Offshore Environmental Statement:

VOLUME 2B

Annex 10A.6: Development Area Scour Potential Assessment

REPSOL

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ANNEX 10A.6

DEVELOPMENT AREA SCOUR POTENTIAL ASSESSMENT:

Inch Cape Offshore Ltd

May 2013

DOCUMENT CONTROL

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GLOSSARY

AREG	Aberdeen Renewable Energy Group.
Bedform	Morphological features at the seabed (e.g. ripples, dunes) formed in response to sediment transport driven by wave-induced and/or tidal currents.
Current rose	A specific representation of tidal current data which shows magnitude, frequency and direction in a single plot.
Design Envelope	The Design Envelope describes a number of components and all permanent and temporary works required to generate or transmit electricity to the national grid including the Wind Farm and the Offshore Transmission Works (OfTW). The design envelope is detailed in Chapter 7: Description of Development.
EOWDC	European Offshore Wind Deployment Centre.
EIA	Environmental Impact Assessment.
Grain size	Reference to the physical size (diameter) of seabed sediments; specific metrics are often used e.g. median grain size (the size for which 50% of the deposit is finer, and 50% is coarser).
Gravel	Sediments which are greater than 2 mm in diameter.
Hm0	The significant wave height (the mean height of the highest one third of waves).
Mbsf	Metres beneath the seafloor.
Neap tide	A tide that occurs when the difference between high and low tide is least.
Tz	Zero crossing wave period.
Sand	Sediments which are greater than 0.062 mm in diameter but less than 2 mm in diameter.
Scour	The vertical excavation of sediments around a maritime foundation; “clear water” scour is where sediment transport occurs only in the vicinity of the structure following acceleration of flow around the piling base; “live-bed” scour is where flow everywhere on the bed is sufficient to mobilise and transport sediment at all times.
Shields value	$\theta_\infty = \frac{\tau_0}{(\rho_s - \rho) g d_{50}}$ The ratio of tractive force (shear stress, τ_o) to inertia (ρ_s - ρ)gd_{50} (where ρ_s and ρ are the density (specific gravity) of sediment and

	water (respectively), g is the acceleration due to gravity, and d_{50} is the median grain size) for a sediment particle.
Spring tide	A tide that occurs when the difference between high and low tide is greatest.
Shear (or bed) stress	τ_o The drag force per unit area over the seabed exerted by flows.
Critical bed stress	τ_{ocr} The value of τ_o at which sediments begin to move under flow.
Sediments	Granular deposits found on the seafloor, and generated by erosional process on the Earth's surface.
Till	Till or glacial till is unsorted deposited by glacial action.
Vortex streets	Regions of higher turbulence formed downstream as flow diverts around maritime structures.
Wake	A general term relating to regions of higher turbulence formed downstream as flow diverts around maritime structures.
Wee Bankie Formation	A stiff, variably matrix-dominated multiple grain size sedimentary deposit with containing sand, pebbly sand and silty clay with boulders. See Till.

10A.6.1 OVERVIEW

10A.6.1.1 Background

Inch Cape Offshore Limited (ICOL) is developing a Wind Farm and associated Offshore Transmission Works (OfTW). Definitions for the Wind Farm, OfTW, Development Area and Export Cable Corridor are as follows:

- Offshore Wind Farm/Wind Farm: Includes proposed Wind Turbine Generators (WTGs), inter-array cables, meteorological masts and other associated and ancillary elements and works (such as metocean buoys). This includes all permanent and temporary works required.
- Offshore Transmission Works (OfTW): The proposed Offshore Export Cable and Offshore Substation Platforms (OSPs). This includes all permanent and temporary works required.
- Development Area: The area which includes proposed WTGs, inter-array cables, OSPs and initial part of the Offshore Export Cable and any other associated works (see Chapter 7 Figure 7.1).
- Offshore Export Cable Corridor/Export Cable Corridor: The area within which the proposed Offshore Export Cables will be laid outside of the Development Area and up to Mean High Water Springs (see Chapter 7 Figure 7.1).

ICOL has commissioned Intertek Energy and Water Consultancy Services to undertake assessments of meteorological/oceanographic (metocean) and coastal processes relating to the Wind Farm and OfTW.

The Project has the potential to affect both the metocean and coastal processes regimes in and around the development areas. Effects may range from short to long term, and the assessment will consider timescales up to 50 years (The Crown Estate lease term for the Inch Cape Development Area). The OWF developers require an understanding of the magnitude and significance of these effects, with a view to implementing, where necessary, appropriate mitigation measures to minimise impacts.

The coastal processes study requires the delivery of a calibrated and validated coastal hydrodynamic (HD) and spectral wave (SW) model, and the delivery of a coastal processes assessment using the models and available information. The proposed assessment will provide the developers and other stakeholders with the regional and Project-specific characterisation of the metocean and physical geomarine environment. This will enable baseline environmental conditions to be determined, against which the effects of each individual project, and the cumulative effects of all projects, can be assessed. The study results will provide input into the Coastal Processes Impact Assessment Report and the required Environmental Impact Assessment (EIA) for each development. These will be considered in the ES Chapter 10: Metocean and Coastal Processes.

The technical issue of the potential for scour must be addressed for the sites. Scour frequently occurs around the foundations of maritime structures in tidal and wave exposed environments due to flow accelerations. Since scour gives rise to resuspension of sediment which might not ordinarily occur, there is the potential for change to the sediment regime. Therefore this aspect needs to be quantified.

10A.6.1.2 Scope of Work

The scope of this report is to deliver a general assessment of the likelihood of foundation scour at the Development Area, together with an overview of anticipated scour dimensions. The analysis has been performed for a single symmetrical jacket-type structure, as set out in the Design Envelope document, at a representative location within the Development Area boundaries.

The scour assessment considers:

- four discrete leg-leg spacings (20 m, 30 m, 40 m and 60 m) on a symmetrical jacket;
- Spring and Neap tidal current forcing;
- four return periods for extreme tidal current conditions (1:1, 1:10; 1:50; 1:50 years);
- the influence of waves (mean annual and typical maximum winter significant wave); and
- the influence of limiting-sub-surface geological conditions.

A review of scour potential along the proposed export cable route is presented in Section 10A.6.5.9, including estimation of the volume of scoured sediments. No scour assessment is undertaken for Offshore Substation Platforms (OSPs) or met masts. However in Chapter 10 assumptions are used to carry out a review of scour impacts from OSPs and met masts based on the conclusions of this study on WTGs.

The scope of work also included a review of principal scour protection/mitigation approaches.

It should be noted that this assessment will inform the EIA for the Inch Cape Project. The results are considered to be representative of potential worst case scour for the purpose of undertaking EIA, but are not intended for use in detailed engineering design.

10A.6.2 INTRODUCTION

The present distribution of sediments on the continental shelf reflects the balance between the supply of different grades of sediment (clay–silt–sand–gravel) and the reworking over millennia by the prevailing hydrodynamic conditions. When a WTG foundation is installed the tidal (and potentially wave-related) currents will be increased locally (Whitehouse, 1998) producing an associated increase in sediment transport and erosion. This is referred to as ‘scour’.

Marine scour is a complex phenomenon and the scour potential at a given location is a function of water depth (bathymetry), the wave-tide climate, the geological properties of the surface and sub-surface seabed sediment, and the type of foundation. In a typical offshore situation, differences in scour may arise due to differing water depths, variable waves and/or currents across the site, and spatially variable sediment type. An analysis of scour risk draws together the above elements into an integrated assessment process.

10A.6.3 INPUT DATA

Detailed information on the site conditions which govern scour potential (tidal range, water depth, wave-tide climate, geological properties of the surface and sub-surface seabed sediments) is provided inAppendix 10F -*Regional Baseline Assessment* for the outer Tay-Forth Firths area (Partrac, 2011) and in Annex 10A.1*Site Specific Baseline Assessment* for the Inch Cape development (Partrac, 2012). Figure 10A.6.1 shows the current velocity data measured at the site during the oceanographic monitoring campaign. Likely geometric and dimensional data have been provided for the jacket foundation structures (see Section 10A.6.4.3). Table 10A.6.1 provides a summary of the principal input data used in the scour analysis.

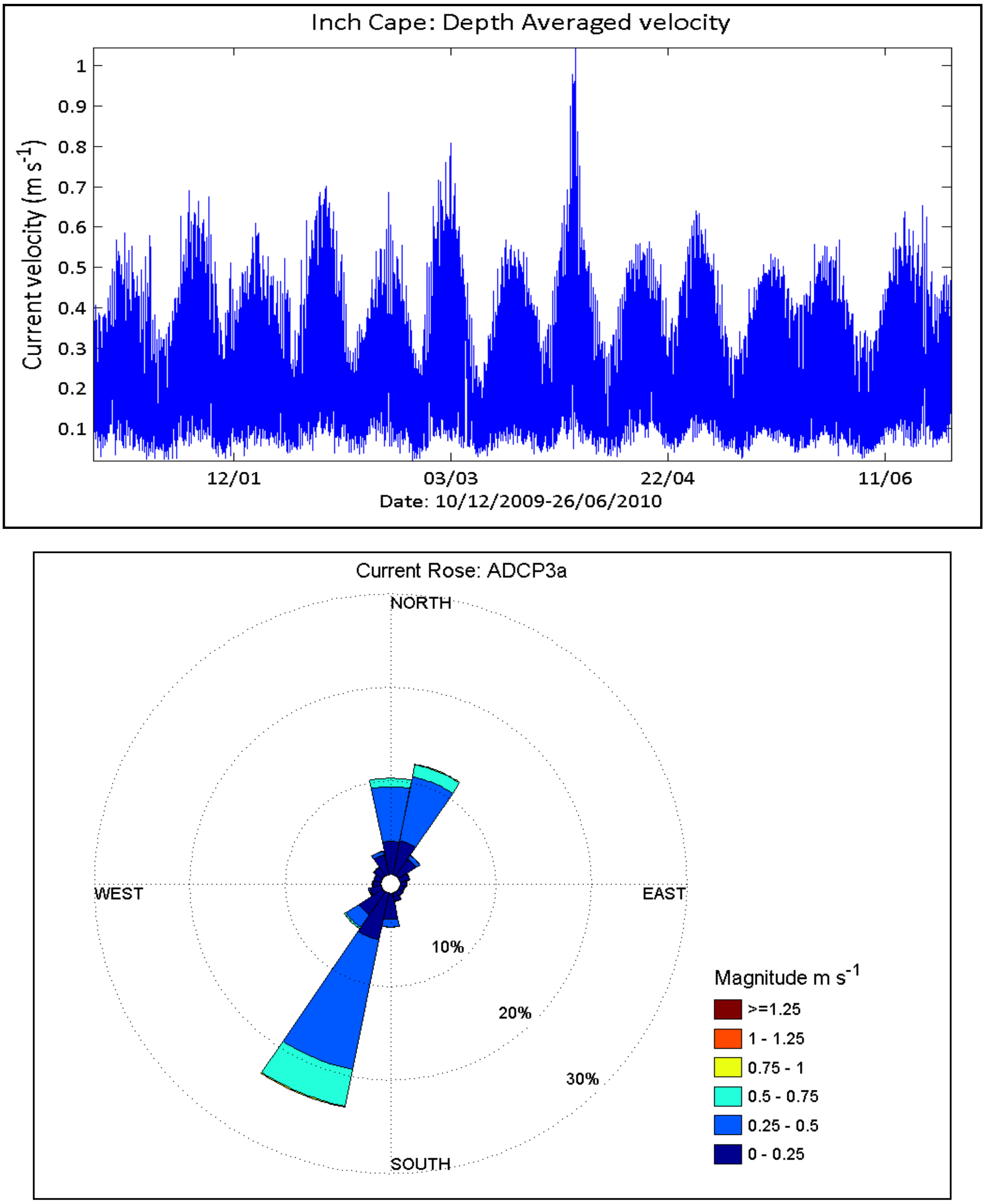
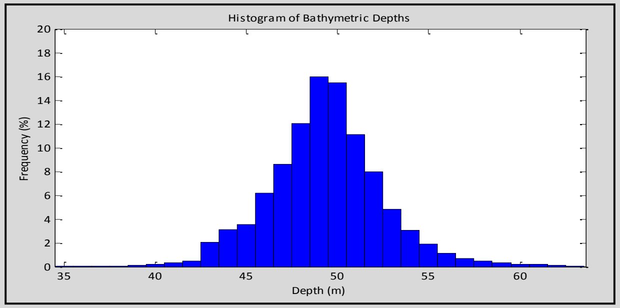


Figure 10A.6.1 Time series of depth averaged current velocity (upper panel) and current rose of velocity magnitude (m s^{-1}) and direction (º). Source: Inch Cape Metocean Campaign.

Table 10A.6.1 Input data for the scour assessment specific to the Inch Cape Development Area.

Metric	Data	
Location	Representative (on MEDIUM SAND seabed area; sand fraction > 90% of total)	
Tide range	~ 4.5 m	
Water depth  	Mean depth (h)	49.3 m
	Minimum depth	34.5 m
	Maximum depth	63.5 m
	Modal depth	49.3 m
	Median depth	49.3 m
Surficial grain size data	Largely MEDIUM sand, with generally a minor mud fraction and a variable gravel component. generally the sand is moderately sorted. d_{50} = 0.320 mm (σ = 0.067 mm)	
Sediment Vertical Profile	Beneath surficial sands/gravels, generally soft-sediments [Holocene + Forth formation] cover large areas of the site ranging from 0 to 20 m thick. This unit varies from muds and silty muds to interbedded sands and (stiff) clays with components of pebble and shell.	
Critical entrainment stress/Shields value (d_{50}= 0.320 mm used)	τ_{0crit} = 0.210 N m^{-2}; θ_{crit}=0.0410	
Wave data	Mean annual Hm0* = 1.18 m, T_z mean annual 4.8 s Maximum Hm0 = 6.24 m, T_z typically 8 – 9 s Modal direction NNE	

Extreme wave data (using the significant wave height parameter, Hm0)	1:1 year return wave Hm0 = 6.0 m; T_z = 7.8 s 1:10 year return wave Hm0 = 7.4 m; T_z = 8.7 s 1:50 year return wave Hm0 = 8.4 m; T_z =9.3 s 1:100 year return wave Hm0 = 8.8 m; T_z = 9.5 s
Current data (total) depth averaged	Peak Neap current 0.36 m s^{-1} (depth-averaged) Peak Spring current 1.05 m s^{-1} (depth-averaged) 1:1 year return current 0.88 m s^{-1} 1:10 year return current 0.95 m s^{-1} 1:50 year return current 1.00 m s^{-1} 1:100 year return current 1.02 m s^{-1} Principal current axis NNE/S-SSW (rectilinear)
Bed stress data (from metocean campaign)	Peak Neaps = 0.118 N m^{-2} Peak Springs = 0.384 N m^{-2} Mean annual wave (Hm0 = 1.18 m) 0 N m^{-2} Maximum Hm0 (Hm0 = 6.24 m) = 0.386 N m^{-2} 1:1 year return wave = 0. 206 N m^{-2} 1:10 year return wave = 0.567 N m^{-2} 1:50 year return wave = 0.956 N m^{-2} 1:100 year return wave = 1.198 N m^{-2}
Single symmetrical jacket structure; leg diameter	3 m
Distance between jacket legs (m)	20 - 60 m

*Hm0 is significant wave height

10A.6.4 PRELIMINARY CONSIDERATIONS

10A.6.4.1 Introduction

Some characteristics of the Development Area require definition prior to undertaking a scour risk assessment, and some procedural issues require mention. The following sections briefly address these.

10A.6.4.2 Clear Water versus Live Bed

First, seabed areas exposed to tidal currents can be classified as either '*clear water*' or '*live-bed'. Clear water* scour is where sediment transport occurs only in the vicinity of the structure following acceleration of flow around the piling base. *Live-bed* scour is where flow everywhere on the bed is sufficient to mobilise and transport sediment at all times. The regional and Development Area specific baseline assessments (Partrac, 2010; Partrac, 2011 Annex 10A.1) indicate that the tidal currents are capable of mobilising sand (but not gravel) at the Inch Cape Development Area only under upper phase Spring tides. This places the Development Area under the 'clear water – live bed' criterion as transitional. The importance of this is related principally to backfilling; if the local bed material is not mobile under native currents, post-scour backfilling of the scour pit is unlikely to occur and thus the computed equilibrium value (S_e) is unlikely to vary. At the Inch Cape Development Area, since sand is transported for only part of the time some backfilling might accompany active scouring but it is not envisaged to be at a high rate. This issue may also have a bearing on the design and implementation of any dynamic scour protection.

10A.6.4.3 Foundation Dimensions and Layout

Jacket structures may be regarded as a pile cluster (i.e. a group of piles). These are more complex structures in comparison to cylindrical monopiles and effects such as flow blockage, wake flow interference and turbulence generation between legs, or sheltering of piles, may occur. Further, the presence of a horizontal cross brace between the jacket legs (used in some jackets) may potentially generate scour depending on the brace width (D_b; i.e. vertically),the flow velocity (u), the nature of the bed material (sand, gravel etc.) and the distance to the bed (e_o). Diagonal braces will also block the flow and create turbulence but since they angle upward and away from the bed their impact on scour generation over and above that due to flow contraction at the bed surface due to the leg base is considered to be minimal.

The Design Envelope document describes a range of foundation options, including jackets and gravity base structures (GBS). It was determined that jackets represent a worse case for sediment scour and associated impacts, since scour protection will be built into any GBS foundation concept. There are various steel framed jacket substructures under consideration for the Project. For scour assessment purposes a four-legged jacket has been assessed as a representative arrangement for the purpose of identifying the worst case. The specification of a symmetric single jacket structure can be seen in Figure 10A.6.2 and is described below.

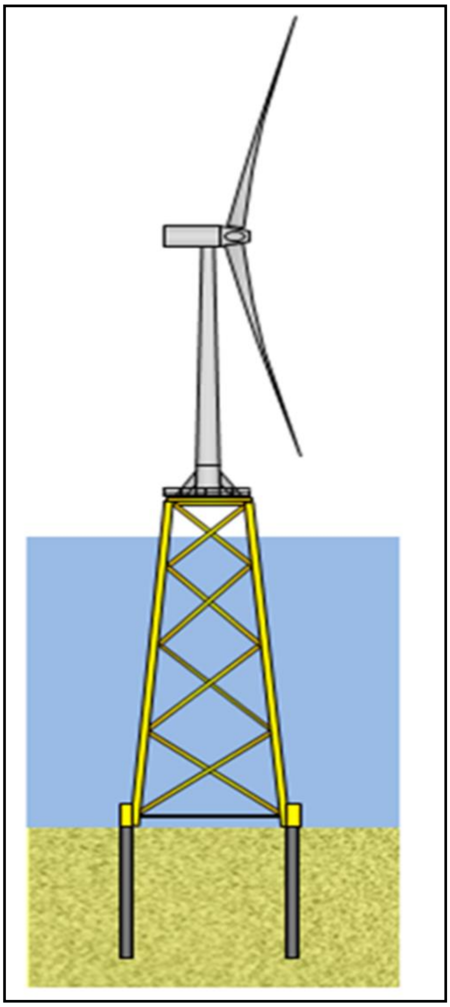


Figure 10A.6.2 Schematic of the specified jacket structure. Source ICOL Design Envelope

The jacket base comprises four legs of fixed diameter D = 3 m equidistant with a spacing (G [m]) of either 20 m, 30 m, 40 m or 60 m. It is possible there might be horizontal bracing at the bottom of the jacket. The presence of a horizontal cross brace between the jacket legs may potentially generate scour depending on the brace width (D_b; i.e. vertically), the flow velocity (u), the nature of the bed material (sand, gravel etc.) and the distance (clearance) to the bed (e_o). Hansen *et al.,* (1986) suggest that scour will not form where $e_o / D_b > 2$. It is anticipated that any structure design would aim to place a cross brace at a minimum height of $2D_b$ above the seabed so as to avoid scour.

Conventionally the minimum separation distance for jacket legs that is considered as non-interfering with adjacent legs is $G/D > 2 - 3$ (according to Sumer and Fredsoe, 2002) and >6 (according to Whitehouse, 1998). G/D is ≥ 6.6. Hence, *herein each leg can be considered for present purposes as a discrete cylindrical structure around which scour may develop fully and (notionally) independently*. This approach is consistent with that applied within the Ormonde offshore wind farm EIA (which constituted 33 WTGs on jackets) and also with the scour assessment undertaken for the Mainstream Neart na Gaoithe offshore wind farm EIA (Intertek METOC, 2011), and follows the general approach taken for similar oil and gas jacket scour problems (Sumer and Fredsoe, 2002). It is based, in part, on the logic that if scour is predicted to occur for a discrete cylindrical structure, then it would in reality also be expected for a jacket.

The ratio of pile diameter (D) to water depth (h) defines to an extent which equations should be used in any analysis. Clearly for this site $\frac{D}{h} < 0.5$ (see Table 10A.6), which indicates that the legs must be treated as a 'slender' cluster rather than 'wide' pile cluster (Whitehouse, 1998).

10A.6.4.3.1 Structure Orientation

With jacket type structures comprising symmetric but multiple legs, the orientation of the structure to the principal tidal axis should *not* lead to differences in scour extent around each leg. Since the current is rectilinear it is anticipated that scour will develop equally at and around each leg during both the flood and ebb tide phases. No wake interactions between legs are anticipated based upon the inter-leg spacing (see above), although this is considered in greater detail in this report (see Section 10A.6.4.2)

10A.6.4.4 Seabed Datum

Scour around foundations produces a vertical excavation of the sediment to generate a scour pit. The depth of this pit is conventionally referenced to the datum of the surrounding seabed level, which itself is known to change in coastal regions. Surrounding bed level changes are not anticipated to be significant at the Inch Cape Development Area as the seabed sediments are generally stable (except during the late phase Spring tides and during extreme storms). This issue is discussed more fully in the Annex 10A.1 *Development Area Baseline Conditions* .

10A.6.4.5 Scour Pit Alignment and Symmetry

Tidally generated scour pits are usually aligned with the principal tidal axis for rectilinear currents. This is the case at the Inch Cape Development Area and the axis is aligned NNE/S-SSW. Asymmetries in the tidal currents can also drive asymmetries in the scour pit dimensions. Flood currents at the site are stronger than the ebb currents (Annex 10A.1), with the difference being slightly more pronounced for Neap tides. The ratio of Spring flood to ebb tide current magnitude is 1.4 whereas that for the Neap tide is 1.6. Some degree of asymmetry is therefore expected but it is not anticipated to be pronounced.

10A.6.4.6 Stress Amplification

Scour occurs due to the amplification of bottom frictional stresses adjacent to structures. For a slender cylinder in deep water the usually accepted stress amplification magnitude is 4 (Whitehouse, 1998), although amplification factors up to 10 have been reported (Hjorth, 1975).

10A.6.4.7 Influence of Waves

It is necessary to consider if waves impact the bottom, and if they do whether they have the potential to mobilise sediments. The sediment transport analysis in the Inch Cape Development Area baseline summary description (Annex 10A.1) broadly indicates that during the summer months waves do not impact the seafloor, but that the worst of winter waves (significant waves in excess of 5.5 m and a zero crossing period in excess of 8 – 8.5 s) may generate sediment suspension.

10A.6.4.8 Sediment Size Influence

There are potential controls of scour through the ratio of structure geometry and size to sediment size. Melville and Sutherland (1988) showed that the effect of sediment size on the scour depth disappears when $D/d_{50} \geq 50$. Therefore, for the present study (sand), sediment size is not considered to be an important factor as this inequality is satisfied for the values of D and d_{50} (see Table 10A.6.1).

10A.6.4.9 Methodology

The quantitative assessment of scour is not an exact science and should not be regarded as such. Despite research over many years, and two prior rounds of offshore wind farm development in the UK, there remains a high level of uncertainty as to the potential depth and extent of scour at offshore foundations (Whitehouse *et al.*, 2011). Furthermore, there is at present no accepted method of assessing scour around multi-leg structures, apart from physical modelling (Wallingford, 2005). As such a conservative approach is taken which ensures that an appropriately conservative worst case assessment can be carried out.

The range of uncertainties is, to an extent, reflected in the range of technical approaches. This analysis is based upon the methodology of Whitehouse (1998) for clear water scour[1] and a quad pile cluster with non-interfering vortex streets (Equation 1). This method embodies research data from a range of studies and is based upon the ratio of bed stress to critical bed stress.

$$\frac{S_e}{D} = 1.3\left[2\sqrt{\frac{\theta}{\theta_{cr}}} - 1\right], \text{ when } 0.25 \leq \frac{\theta}{\theta_{cr}} < 1 \qquad 1.$$

and when $\theta < \theta_{cr}/\mathrm{M}$ (with M=4 for single pile situations). Here, S_e is the equilibrium scour depth, D is the jacket leg diameter, M is the stress amplification factor, and θ is the Shields parameter given by:

$$\theta_{\infty} = \frac{\tau_0}{(\rho_s - \rho) g d_{50}} \qquad 2.$$

where τ_0 is the bed shear stress, ρ_s and ρ are the density (specific gravity) of sediment and water (respectively), g is the acceleration due to gravity, and d_{50} is the median grain size. θ_{cr} is the value of θ at the threshold of sediment motion.

Medium sand is used (d_{50} = 0.320 mm) and this sand grade is found extensively across the Development Area. The effects of ambient currents (Spring and Neap tides) and extreme

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[1] See Section 4.2.

[2] Perhaps the only time when Neap scour dimensions might be relevant are during installation, and where placement of dynamic scour protection in the scour pit is entertained; a smaller scour volume would require less rocks (assuming

currents are investigated. Although the consensus which exists indicates that waves are of less importance in contributing to scour development, this is also explored. The principal scour metrics reported are the equilibrium scour depth (S_e), the horizontal extent or length-scale of scour (X_s), the scour volume (V_f) and scour footprint (α) for a single foundation. X_s is computed using a constant angle of repose (30°) which is only an approximation to the real-world situation. Cumulative scour volumes have not been computed and presented in this report. However, these generated using the total number of structures expected (see Chapter 10).

10A.6.4.9.1 Representative Location

The requirement of this study is for a generic scour risk analysis for a representative location within the Development Area. At this stage in project design, and prior to consent, a final wind farm layout will not be determined and as such there was no requirement to consider specific locations within the proposed Development Area.

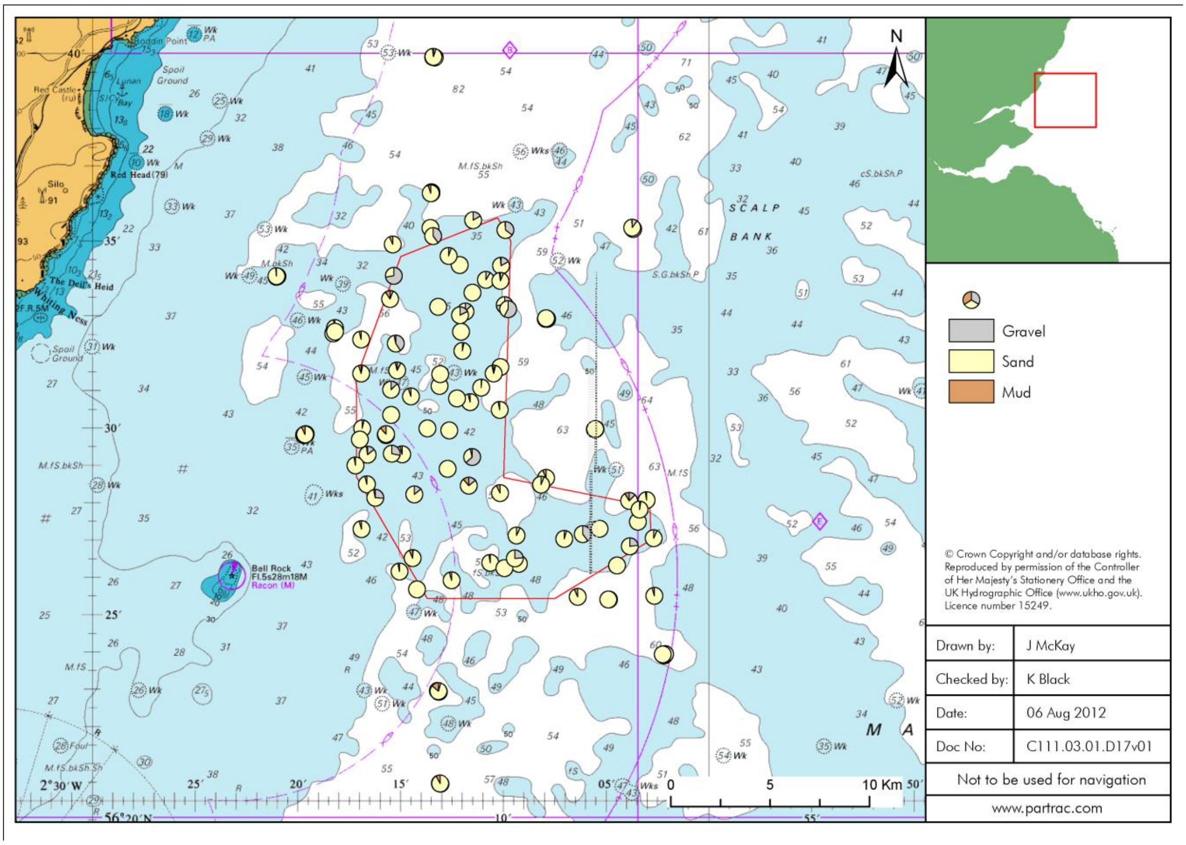
The geological characteristics of the 'representative' location are as follows: it is a dominantly sandy area of the seabed (>80 per cent sand, the case for >82 per cent of the site area), with a zero or very minor fines/gravel fraction, and at average depth (~49 - 50 m). Figure 10A.6.3 shows the seabed grain size data as a series of pie charts of gravel:sand:silt per cent, and it is immediately evident that sand is found widely across the site, and hence the notion of a 'representative' site applies to most of the Inch Cape Development Area. The sand present is dominantly medium in size (0.25 – 0.5 mm diameter), but note that if medium sand is entrained then any fine sand will also be mobilised. The analysis assumes a local depth of surficial sediment to 10 m below seabed, and therefore by default the representative site is a 'worst realistic case' i.e. the deepest expected scour pits may be formed. Note, however, shallow sub-surface geological conditions across the site may limit scour depths to less than this, and the importance of this is discussed in Section 10A.6.5.3.

Table 10A.6.2 Summary of particle size distribution data. Brown shading indicates samples where % sand is >80%. Source: Environmental Survey.

Sample	% Gravel	% Sand	% Silt	Median Grain Size (µm)	Folk Sediment Classification (Folk, 1954)
41	0.0%	100.0%	0.0%	352.3	Moderately Sorted Medium Sand
72	23.7%	76.3%	0.0%	384.0	Very Coarse Gravelly Medium Sand

Sample	% Gravel	% Sand	% Silt	Median Grain Size (μm)	Folk Sediment Classification (Folk, 1954)
66	13.9%	86.1%	0.0%	403.4	Coarse Gravelly Medium Sand
26	3.5%	96.5%	0.0%	337.2	Slightly Fine Gravelly Medium Sand
91	12.8%	87.2%	0.0%	300.8	Medium Gravelly Fine Sand
39	0.0%	99.2%	0.8%	286.2	Moderately Sorted Medium Sand
113	57.2%	42.2%	0.6%	4521.1	Sandy Medium Gravel
109	72.4%	27.6%	0.0%	38563.2	Sandy Very Coarse Gravel
105	0.0%	100.0%	0.0%	373.2	Moderately Well Sorted Medium Sand
64	17.4%	82.6%	0.0%	369.7	Medium Gravelly Medium Sand
107	0.0%	99.1%	0.9%	297.7	Moderately Sorted Medium Sand
25	12.2%	87.8%	0.0%	347.5	Fine Gravelly Medium Sand
63	5.6%	94.4%	0.0%	338.6	Fine Gravelly Medium Sand
24	0.0%	100.0%	0.0%	358.9	Moderately Well Sorted Medium Sand
53	8.8%	90.4%	0.8%	316.2	Medium Gravelly Medium Sand
79	17.3%	81.4%	1.2%	416.2	Fine Gravelly Medium Sand
80	6.6%	91.5%	1.9%	341.1	Fine Gravelly Medium Sand
58	74.4%	25.6%	0.0%	36022.2	Sandy Very Coarse Gravel
45	0.0%	100.0%	0.0%	312.6	Moderately Sorted Medium Sand
81	3.7%	93.1%	3.2%	314.5	Slightly Fine Gravelly Medium Sand
54	1.7%	98.3%	0.0%	322.7	Slightly Very Fine Gravelly Medium Sand
7	0.0%	96.6%	3.4%	256.2	Moderately Sorted Medium Sand
106	0.2%	99.8%	0.0%	309.5	Slightly Very Fine Gravelly Medium Sand
27	0.0%	99.2%	0.8%	285.1	Moderately Sorted Medium Sand
38	0.0%	100.0%	0.0%	380.6	Moderately Well Sorted Medium Sand
1	0.0%	100.0%	0.0%	317.0	Moderately Sorted Medium Sand
C7A	0.0%	88.7%	11.3%	116.6	Very Coarse Silty Very Fine Sand
C7B	0.0%	90.3%	9.7%	119.4	Moderately Sorted Fine Sand
C7C	0.0%	88.3%	11.7%	116.0	Very Coarse Silty Very Fine Sand
78	14.3%	83.8%	1.9%	328.2	Very Coarse Gravelly Medium Sand
28	4.1%	95.9%	0.0%	330.0	Slightly Fine Gravelly Medium Sand

Sample	% Gravel	% Sand	% Silt	Median Grain Size (μm)	Folk Sediment Classification (Folk, 1954)
44	5.4%	84.9%	9.7%	490.2	Coarse Gravelly Coarse Silty Coarse Sand
30	0.0%	99.1%	0.9%	342.7	Moderately Sorted Medium Sand
99	28.3%	71.7%	0.0%	354.3	Medium Gravelly Fine Sand
119	3.5%	91.2%	5.3%	246.2	Slightly Medium Gravelly Fine Sand
93	25.5%	71.3%	3.1%	347.2	Coarse Gravelly Medium Sand
22	0.0%	96.0%	4.0%	274.7	Moderately Sorted Medium Sand
71	62.6%	34.0%	3.4%	14402.8	Sandy Coarse Gravel
40	0.0%	96.0%	4.0%	288.4	Moderately Sorted Medium Sand
31	0.0%	100.0%	0.0%	377.6	Moderately Sorted Medium Sand
32	0.0%	99.3%	0.7%	322.0	Moderately Sorted Medium Sand
121	0.4%	94.1%	5.6%	287.4	Slightly Very Fine Gravelly Medium Sand
6	7.8%	88.5%	3.7%	285.7	Very Coarse Gravelly Medium Sand
21	40.8%	55.4%	3.8%	401.3	Sandy Very Coarse Gravel
8	0.0%	97.0%	3.0%	325.3	Moderately Sorted Medium Sand
11	0.0%	95.8%	4.2%	276.1	Moderately Sorted Medium Sand
55	7.0%	93.0%	0.0%	374.4	Coarse Gravelly Medium Sand
33	1.3%	92.3%	6.3%	280.1	Slightly Very Fine Gravelly Medium Sand
67	14.4%	74.0%	11.6%	292.7	Medium Gravelly Medium Silty Medium Sand
46	0.2%	93.1%	6.8%	197.3	Slightly Very Fine Gravelly Fine Sand
23	0.0%	96.9%	3.1%	308.2	Moderately Sorted Medium Sand
49	0.0%	97.0%	3.0%	283.2	Moderately Sorted Medium Sand
14	0.0%	92.7%	7.3%	278.2	Poorly Sorted Medium Sand
97	39.7%	60.3%	0.0%	968.7	Sandy Fine Gravel
83	4.5%	95.5%	0.0%	341.9	Slightly Very Fine Gravelly Medium Sand
68	0.0%	100.0%	0.0%	368.5	Moderately Sorted Medium Sand
69	0.0%	100.0%	0.0%	349.8	Moderately Well Sorted Medium Sand
82	2.8%	97.2%	0.0%	340.0	Slightly Fine Gravelly Medium Sand
34	0.0%	100.0%	0.0%	331.0	Moderately Well Sorted Medium Sand
57	23.0%	76.6%	0.4%	376.9	Very Coarse Gravelly Medium Sand



Drawn by: J McKay
Checked by: K Black
Date: 06 Aug 2012
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Figure 10A.6.3 Geospatial distribution of grain size (as gravel:sand:silt per cent) within the Inch Cape Development Area. Source: Data re-processed from the Environmental Survey.

10A.6.5 SCOUR ASSESSMENT

10A.6.5.1 Scour Assessment under Tidal Currents

Table 10A.6.3 summarises the results from the scour analysis. The following are presented: the anticipated equilibrium scour depth (S_e) and the horizontal extent or length-scale of scour (X_s) under the above tidal conditions (computed using Equation 1). In addition, the volume of sediment (V_s) liberated by scouring per leg and for the entire (single turbine) foundation (V_{TOT}), and the total scour footprint (α) are presented. Values of V_s are inherently conservative due to assumptions made on the scour pit shape.

Calculations have been performed for tidal currents corresponding to peak Neap and Spring current magnitudes, and for a series of extreme total current magnitudes of varying return periods (1, 10, 50 and 100 years).

Inspection of the data indicates during (peak) Neap tides limited or low rates of scour occur. Scour depths S_e of 2.0 m are expected, with corresponding lateral extent X_s of 3.6 m. Scour magnitudes are over three times greater under (peak) Spring tides (S_e = 6.7 m; X_s = 12 m). Given the tidal regime regular transitions between the Neap and Spring phases, in reality a scour pit excavated by a Neap tide will be deepened during the following Spring tides and therefore only the Spring tide data are of interest[2].

Higher currents, such as those resulting from additional meteorological forcing (surges), will also generate scour. A scour depth S_e in excess of 10 m is found for a 1:1 year return current, with a monotonically increasing scour depth for increasing return periods. Worst case (1:100 year) current-induced lateral extent is nearly 23 m.

Cumulative scour volumes have not been computed and presented in this report. However, these are considered in Chapter 10.

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[2] Perhaps the only time when Neap scour dimensions might be relevant are during installation, and where placement of dynamic scour protection in the scour pit is entertained; a smaller scour volume would require less rocks (assuming rock placement is adopted).

Table 10A.6.3 Summary of predicted equilibrium scour parameters.

Forcing		Scour Depth (S_e) m	Lateral extent x_s (m)	Volume of Scoured Sediment Per Leg V_s (m^3)	Volume of Scoured Sediment Per Foundation V_{TOT} (m^3)	Total Scour Footprint, α (m^2)
CURRENTS	**Peak Spring**	6.7	12	1230	4992	2261
	Peak Neap	2.0	3.6	40	161	298
	Return Period Total Currents (Yrs)[2]					
	1:1	10.5	18.8	4454	17817	5148
	1:10	11.6	20.8	5955	23820	6218
	1:50	12.4	22.3	7263	29053	7086
	1:100	12.7	22.9	7823	31292	7449
WAVES	**Mean annual wave**[1] **Hm0=1.18 m T_{zmodal}=5s**	Bed stress insufficient to generate scour				
	Typical maximum winter wave[1] **Hm0 = 6 m T_z=7s**	Bed stress insufficient to generate scour				

1 Data from oceanographic monitoring campaign, extreme value analysis by Physe (2011).

Note that if coarser sediments e.g. gravelly sediments are used in the analysis then the time period within each Spring tide during which scour can occur is less and therefore the rate of scour will be slower, but that the same equilibrium scour depth will eventually be attained.

Many previous scour (computation) studies have worked on the premise that the dimensions of the scour pits generally scale geometrically with the diameter D of the pile, and expressed the equilibrium (maximum) scour (S_e) depth as a multiple of the pile diameter (D). Similarly, the ratio of the horizontal extent of the scour pit (x_s) to D has received attention and generally the relation is found[3]: $x_s \cong 2.25 D$ (measured from the pile wall not the centre). For the above analysis for the non-extreme Spring/Neap tides s_e / D = 0.66 – 2.20 and x_s = 1.2 – 4D (assuming an unconstrained sediment thickness). These estimates are in generally good agreement with those reported in the literature:

- Sumer and Fredsoe (2002) found $s_e / D \cong 1.3$ (±0.7),
- Clark *et al*., (1982) quote values for s_e / D ranging from 1.0 to 2.3.
- den Boon *et al*., (2004) found $s_e / D \cong 1.75$,

In an examination of 115 datasets, Whitehouse *et al*., (2011) report only six of these were greater or equal to s_e / D =1.3. The maximum value for s_e / D found anywhere on the UK continental shelf since the inception of the development of offshore wind farms (i.e. encompassing the range of inshore water depths, tidal and wave conditions) is 1.77 (Carroll *et al*., 2010). It is essential to note the data of Sumer and Fredsoe (2002), which forms the basis of the DNV Guidance (2011), has a standard error term (0.7) due to variability in their results. Closer inspection of the Whitehouse (1998) approach for a clear water scour also shows scatter and variation in the estimate of s_e / D ranging from ~0.7 to 1.8 (due principally to uncertainties in bed stress values).

There is a dependency on absolute current magnitude (extreme currents create deeper, broader scour pits) in which the maximum value for s_e / D is 4.2, and that for x_s is 7.6 D.

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[3] DNV 2011. Design of Offshore Wind Turbine Structures. Offshore Standard DNV-OS-J101. 142pp.

10A.6.5.1.1 Scour Footprint

The values of x_s (Table 10A.6.4) can be used to judge whether scour pits merge to form part of a larger region of scour beneath and around the structure (so-called 'global' scour) or whether pits remain local to each leg. Table 10A.6.4 presents results for (peak) Spring tides and for the four current return periods. An assessment is made for four different leg – leg spacing distance (*G*; 20, 30 m, 40 m, and 60 m)

These show that for the a jacket with D = 3.0 m during normal tidal conditions of a (peak) Spring tide global scour is anticipated for only the smallest leg – leg spacing (*G* = 20 m); for larger foundations scour is expected to be confined to the immediate environ of each leg.

Since higher currents generate deeper and more extensive scour, the propensity for global scour to occur is greater, and global scour is expected around structures with *G* = 20 m and *G* = 30 m, and for *G*= 40 m for 1:50 and 1:100 return period currents. Global scour is not expected around the biggest proposed structures (i.e. those with the greatest leg spacing; *G* = 60 m), as the individual scour footprints at each leg never overlap.

This analysis assumes that there are no horizontal cross-brace beams that are close to the bed (ie less than $2D_b$) on jackets. The presence of these would modify the scour process and may promote global scour at lower current velocities and smaller values of *G*.

The values of x_s also indicate the footprint region outwith the foundation structure is affected by scour. These show that a typical Spring tide impacts an area extending ~4 - 8 m from the foundation, whereas the 1:25 year storm surge current impacts a length scale of just over three times this.

Table 10A.6.4 Comparison of predicted lateral scour extent (X_s [m]) with leg separation distance (G [m]).

Forcing	Leg Diameter *D* (m)	Lateral extent X_s (m)	Scour Pit Interaction? Leg Separation Distance *G* (m)			
			20 m	30 m	40 m	60 m
Peak Spring tide	3	12	Yes	No	No	No
Return Period Total Currents (Yrs)[1]						
1:1	3	18.8	Yes	Yes	No	No
1:10	3	20.8	Yes	Yes	Just	No
1:50	3	22.3	Yes	Yes	Yes	No
1:100	3	22.9	Yes	Yes	Yes	No

[1] Data from R485_Inch Cape Metocean Criteria Vo1 D1 (2). Report by PhysE to R485_Inch Cape Offshore Ltd. October 2011.

10A.6.5.1.2 Scour Timescales

The timescale over which scour occurs can be derived, although these are very approximate as no analytical solutions are available to predict scour timescale in temporally variable, reversing tidal environments with great accuracy. For a given set of environmental conditions the scouring of sediments at structures initially occurs rapidly but then approaches its ultimate (equilibrium) value (S_e) over time. From the foregoing analysis, scour at the Inch Cape Development Area would be expected to progress at a faster rate during Spring tides and at a lower rate during Neap tides, which is a complex situation in terms of estimating the timescales for scour.

Scour pit depth evolution S through time t at a fixed pile in a steady current is given by the expression (Whitehouse, 1998):

$$S(t) = S_s \left[1 - \exp(-\tfrac{t}{T})^p\right] \qquad 3.$$

where S_e is the equilibrium scour depth, T is the characteristic timescale for the scour and p is a fitting coefficient usually taken as unity. T is defined as the time after which the scour depth has developed to 68 per cent of the equilibrium value. T is obtained from

$$T^* = T[g(s-1)d_{50}^3]D^{-2} \qquad 4.$$

where g is the gravitational acceleration, s the sediment mineral specific gravity ρ_s/ρ (normally 2650 kg m^{-3} for sand), and d_{50} the median grain size of the sediment. This equation requires:

$$T^* = A\theta_\infty^B \qquad 5.$$

where

$$\theta_\infty = \frac{\tau_0}{(\rho_s - \rho) g d_{50}} \qquad 6.$$

A is 0.005 and B is -2.2 (these are constants for a given geometry) and τ_0 is the bed stress; θ_∞ is related to the ambient flow i.e. away from the structure.

For the Inch Cape Development Area T = 12 days for Spring tide conditions using this approach. Due to the temporally variable offshore current regime, and a lower scour rate for Neap tides, this estimate is conservative and actual *in situ* scour timescales would be expected to be longer. Caution is therefore advised if these data are used for design purposes, or to underpin scour mitigation implementation.

10A.6.5.2 Scour Assessment under Waves

The energy associated with mean annual wave conditions (*Hm0* = 1.3 m; T_z ~ 5 s) does not penetrate to the seabed (Table 10A.6.1) and therefore is not able to generate scour. The observed peak significant wave height observed during the oceanographic monitoring campaign (Hm0 = 6.24 m; Table 10A.6.1) will induce sediment transport (typical bed stress τ_0 = 386 N m^{-2};) but only when wave periods are > 8 s, which occur only infrequently (probability of occurring in any year is <10 per cent; Physe, 2011). Moreover, rare storm events are of relatively short duration (i.e. days) and therefore the severity of sediment transport events is limited. On this basis waves can effectively be ignored as an important scour-generating mechanism at the Inch Cape Development Area, and the Development Area can be classified as *tidally dominated*.

10A.6.5.3 Limiting Sub-Surface Conditions

Scour involves the amplification of near-bed flow velocity by the presence of a fixed structure and vertical excavation of the sediment mass. In unconstrained, non-cohesive and unconsolidated sediments scour is able to continue for as long as the amplified flow around the structure base is capable of transporting sediments. Whether scour can progress unabated depends essentially on the vertical down-core profile of grain size/sediment type to the equilibrium scour depth (S_e). If there are sub-surface horizons where substantially different[4] grain sizes occur, or if there is a highly limiting condition such as bedrock, then the actual scour depth will be less than that predicted. Limiting sub-surface issues are known from other UK OWF sites and Whitehouse *et al.*, (2011) present case studies from these with a range of differing limiting conditions.

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[4] i.e. different to the surficial grain sizes.

The foregoing analysis was undertaken using the assumption that the structure would be sited on at least 10 m thickness of medium sand. Detailed data on the nature of sub-surface sediments and sedimentary horizons are available from six boreholes drilled on the site. Figure 10A.6.4 shows the location of these boreholes across the Inch Cape Development Area.

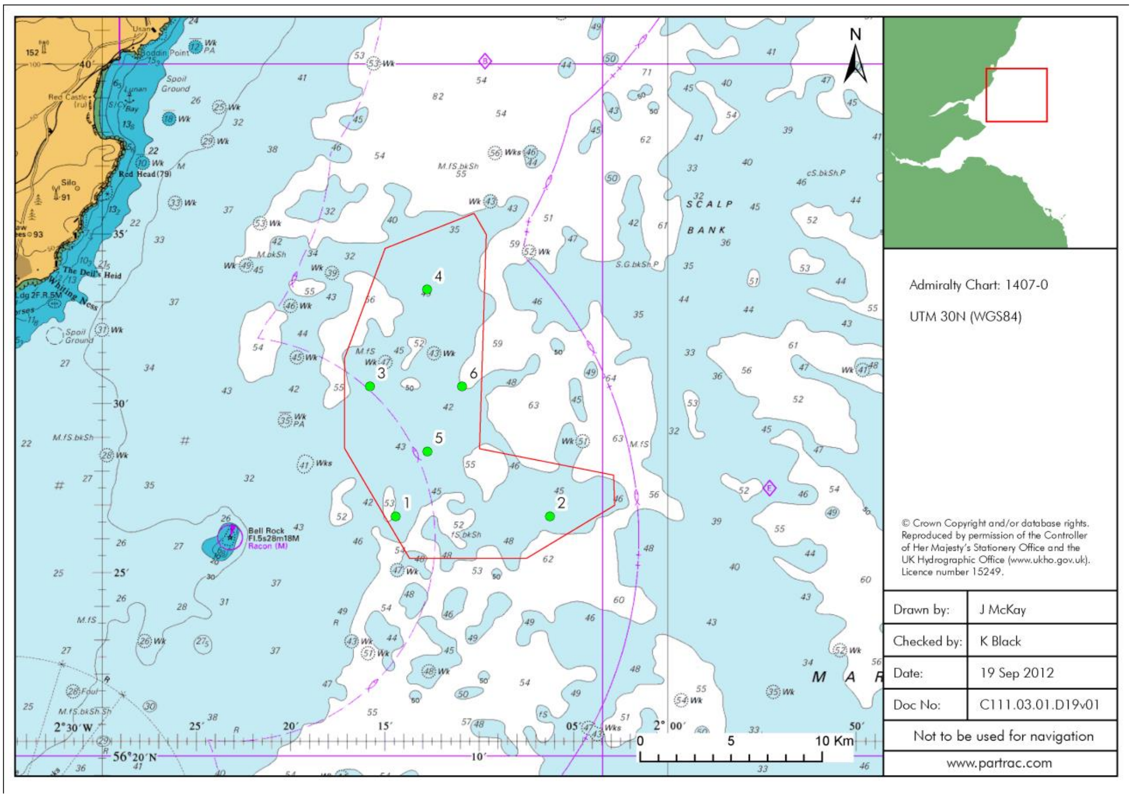

Figure 10A.6.4 Location of six boreholes drilled at the Inch Cape Development Area. Source: Preliminary Geotechnical Site Investigation.

For each borehole the sediment column is subjected to a detailed description and quantitative testing. Copies of the first page (to 30 m sub-bottom depth) of the preliminary borehole logs are reproduced in section 10A.6.6. Although these logs for all boreholes show clearly the surficial (contemporary) medium sand with variable gravel component (up to 1 m thick), they indicate a variable geology both horizontally across the site and over the upper 20 m (a nominal depth of relevance to scour by extreme currents; Table 10A.6.3). None of the boreholes depict a uniform column of sand to 20 m beneath the seafloor (bsf). Borehole 5 is possibly the closest approximation, but contains a layer from 0.1 to 2.4 mbsf of gravelly, stiff brown clay. This clay layer is found relatively close to the seabed surface in all boreholes: Borehole 2 (3.2 – 6.3 mbsf), Borehole 4 (0.5 – 14.3 mbsf), Borehole 3 (0.2 – 19.4 mbsf), and Borehole 1 (2.3 – 4.4 mbsf). These clay horizons are, most probably, the Wee Bankie Formation, which is a basal till found extensively across the Forth Tay region (Stoker *et al*., 1985). Annex 10A.1 contains a map of the depth to the upper surface of the Wee Bankie for the entire Inch Cape Development Area (reproduced in Figure 10A.6.5), which gives a very detailed indication of the site-wide variability. Areas of grey represent out-cropping (exposed) formation, orange-red areas represent depths between ~2 – 10 mbsf, and darker red areas show where the Wee Bankie formation is found at greater depths.

The Wee Bankie Formation is described as a stiff, variably matrix-dominated polymictic (multiple grain sizes) diamicton[5] with some interbeds of sand, pebbly sand and silty clay with boulders (Gatliff *et al*., 1994). It was formed during the Quaternary period as a result of glacial processes. Whilst the veneer sediments are dominantly unconsolidated sands (Table 10A.6.2) and thus potentially mobile under currents, the presence of the Wee Bankie Formation both at the surface or sub-cropping will offer significantly greater resistance to hydrodynamic (erosional) forces[6] at the seabed thereby limiting scour to values less than predicted i.e. lower than S_e. Therefore, by default, in such areas the scour metrics presented in Table 10A.6.3are conservative.

A full analysis of the scour potential for the Development Area would integrate build layout information with more detailed geological data from the Development Area investigation geotechnical core log data. This approach would indicate at which turbine locations fully developed scour would be expected, and those for which scour might be depth-limited. Note, however, that whilst we would envisage stiff sub-surface till sediments provide a high erosional resistance (see Whitehouse *et al*., 2011, for case studies), we would guard against the assumption (commonly made) that stiff till sediments do in fact do so over the medium term. In reality this assumption has never been tested. A judicious approach, appropriate to engineering and layout design, would involve direct testing (e.g. of drill cores, where undisturbed) or direct, *in situ* measurement of scour at a test location.

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[5] A diamicton is a very poorly sorted sediment comprising large sedimentary grains set in a stiff matrix of finer grains.

[6] The fundamental knowledge of the behaviour of diamicton sediments to flow shear lags far behind that for non-cohesive (sandy) sediments. Ideally, scour propensity would be evaluated by collection of some laboratory measurements on retrieved cores.

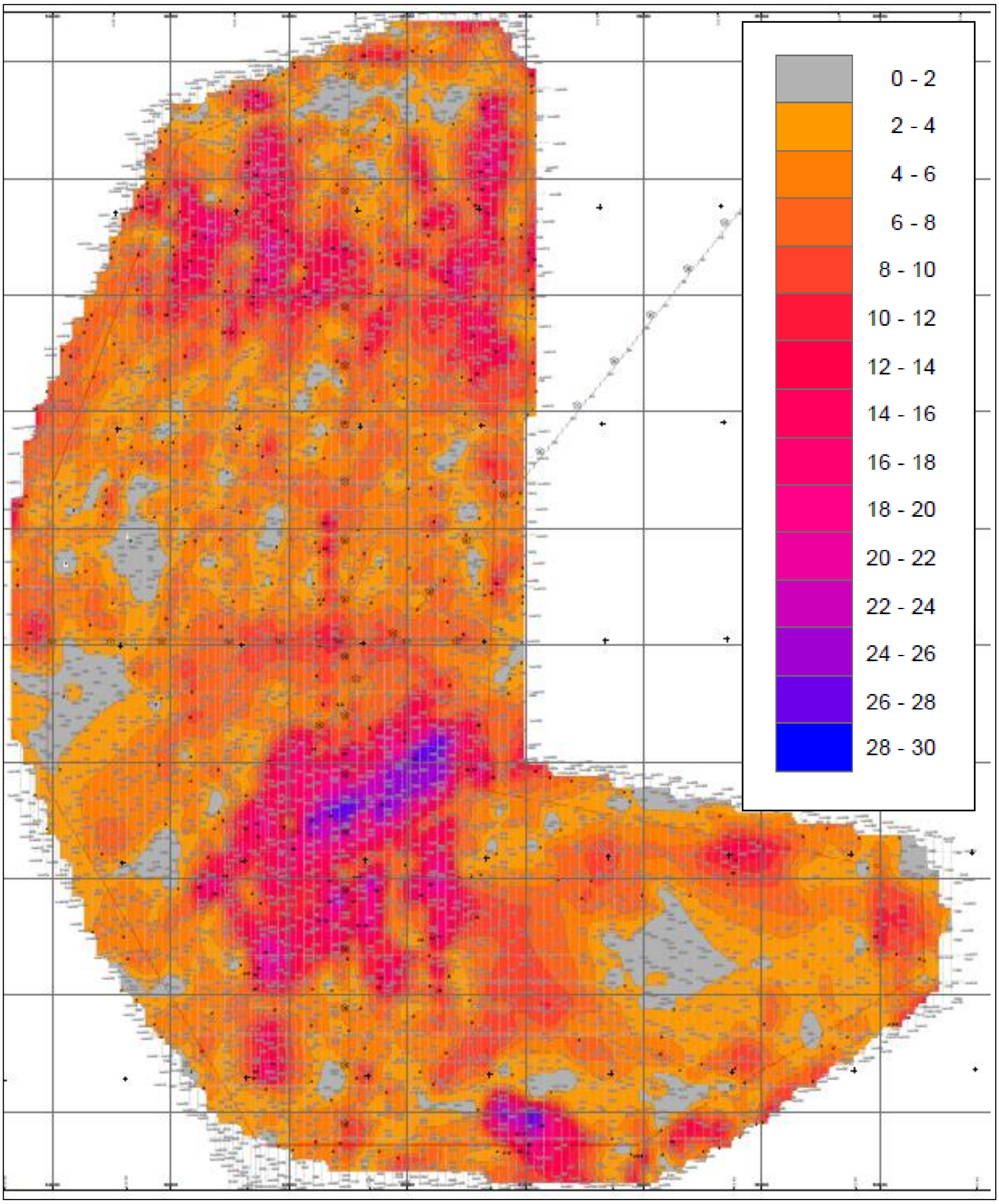


Figure 10A.6.5 Colour contour plot of the depth to the Wee Bankie formation. This is equivalent to representing the thickness of [Holocene + Forth] sediment formations. Legend units are metres. Source: Geophysical Survey.

10A.6.5.4 Backfilling

Backfilling is where the scour pit accumulates sediments during periods in the tidal cycle when scouring is not well developed. Backfilling results in differences between the actual scour depth and the predicted scour depth. The Inch Cape Development Area is a transitional 'clear water – live bed', and the surrounding seabed area is only mobile during upper phase Spring tides (no motion is predicted during Neap tides). Backfilling will not therefore occur during Neap tides, and only to a limited extent during periods of Spring tides. On this basis backfilling rates will be low. This means that the maximum scour extent (S_e), once generated, is likely to remain largely unchanging, except potentially following major storm events when higher levels of suspended sediment are able to settle back to the bed and infill the pit. These events, however, are rare and of comparatively short duration.

10A.6.5.5 Bedforms

Migration of bedforms e.g. megaripples, dunes etc. through a scour pit can modify the scour depth through time. This issue is not generally important here as bedforms are not present at the Development Area (except in the vicinity of gravel lags; Annex 10A.1). If turbines are built in areas where bedforms are observed then this issue may rise in importance.

10A.6.5.6 Comparison with Other Similar UK and International Sites and Studies

Marine scour is a complex phenomenon, and not entirely understood by engineers and scientists (Sumer and Fredsoe, 2002; Sumer *et al*., 2001). Even for the simple case of a monopile foundation, normalised scour depths may vary by more than a factor of four according to the computational assessment method used (e.g. Riechwien and Lesney, 2004), and inter-comparisons between field data and predictive methods indicate both over and under-prediction (e.g. Noormets *et al.*, 2006). For this reason a precautionary approach is required where predictions are made regarding the scour depth, the timescales for scour etc., particularly where the data may be used to inform scour protection placement. The value of observations and data from similar projects in similar environments cannot be over-estimated.

Although jacket structures have been widely used in the oil and gas industry for many decades, these have not been the foundation of choice for offshore WTGs to date. However, as the industry moves into deeper water and more powerful turbines become available additional structural strength is required, and jackets are increasingly being selected as a suitable foundation. Jacket type foundations are more complex structures with different flow blockage areas close to the bed. The interaction with near-bed flows, and the potential for generation of sediment scour, is correspondingly more complicated. Since there are no accepted, universal methods available to predict scour around jackets (Wallingford, 2005), examination of experience elsewhere where jackets have been used may be useful.

Within the UK jacket structures have been used only at the Beatrice Offshore Wind Demonstrator Project in the Moray Firth and at the Ormonde Irish Sea development. Elsewhere jackets have been used at the Alpha Ventus development.

10A.6.5.6.1 European Offshore Wind Development

Vattenfall, Technip and Aberdeen Renewable Energy Group (AREG) are the joint venture (JV) partners behind a Wind Deployment Centre in Scottish waters – the 11-WTG European Offshore Wind Deployment Centre (EOWDC) off Aberdeen Bay. The project has been developed following extensive consultation with stakeholders and studies which have seen the project significantly evolve over the last six years from an offshore wind farm into a deployment centre to test and demonstrate up to eleven next generation offshore WTGs, support infrastructure and other related technology.

The East Anglia ONE Offshore Windfarm Environmental Statement provides predictions for the principal scour metrics for a range of foundation types, including jackets, for a situation where only currents have been used in the analyses. Although there are no details on the jacket type/structure it may reasonably be assumed not to differ substantially from other UK sites. The sediments of the EOWDC site are very similar to those at the Inch Cape Development Area. The data are as follows: S_e is 3.25 m; X_s is 5 m; and V_s is 749 m^3. Since D is not known, no value for S_e / D is available.

Values for S_e and X_s fall mid-way between the Spring and Neap tide predictions for Inch Cape Development Area (Table 10A.6.3); note, however, the leg diameters are not known. The quantitative similarity between the scour metrics data for EOWDC and this study provide a level of reassurance that the predictions presented herein are meaningful, and that jackets on sandy seabed sediments possess a generally similar impact envelope.

10A.6.5.6.2 Beatrice Demonstrator Project

The Beatrice Demonstrator Project was a joint venture between Scottish and Southern Energy and Talisman Energy (UK) to build and operate an evaluation wind farm in the deep water close to the Beatrice Oil field in the North Sea. Built in 2007, with two turbines and a total capacity of 10 MW, it was designed to examine the feasibility of creating a commercial wind farm in deep water and a reasonable distance from the shore. The project was the first OWF development to use a jacket type structure. This was designed and developed by the Norwegian company OWEC Tower, and fabricated in Scotland by Burntisland Fabrications. The site is 22 km from the Scottish coast and in 45 m of water. The water depths, bottom sediments and hydrodynamic conditions are highly similar to the Inch Cape Development Area.

In spite of its position in the market as the first jacket structure to be used in UK waters, an environmental-engineering decision was made not to implement any scour protection i.e. to provide for a design scour allowance. This would appear to be on the basis that scour at similar, earlier structures and pipelines/cables in the Moray Firth has not presented any serious concern. The *Environmental Statement* mentions use of ROVs to provide scour surveys but to our knowledge this has not been performed. Moreover, no obligations to collect data on the scour magnitudes were emplaced by the Scottish regulator. Although there would appear to be no major concerns there is, therefore, virtually no information on the presence and magnitude of scour at the Beatrice site that can be utilised for comparative purposes.

Figure 10A.6.6 The jacket structure used at the Beatrice OWF demonstrator site, Moray Firth.

10A.6.5.6.3 Ormonde OWF

The Ormonde Offshore Wind Farm is located 10 km off Barrow-In-Furness, in the Irish Sea. It is located in 17 to 21 m water depth, mean Spring currents are ~0.5 m s^{-1} and the seabed is predominantly muddy sand. The highest anticipated waves are 4.7 m. These conditions are similar to the Inch Cape Development Area but the water is shallower and the sediments rather finer. 31 jacket foundation structures have been built and Ormonde is the first large-scale commercial wind farm in European waters to use jackets for both the turbine foundations as well as the substation foundations.

The Ormonde Project (2005) Environmental Statement Scoping Report provides predictions for the principal scour metrics for jacket foundations, for a situation where only currents have been used in the analyses. The scour hole due to tidal currents alone was predicted to extend about 3 x D horizontally from the pile and up to about 1.5 x D vertically, where D is the monopile diameter (5 m at the Ormonde site). These estimates, which are at present unsubstantiated at the site by survey data, compare well (fall mid-way) with estimates for the Inch Cape

Development Area (s_e / D = 1.3 – 1.31 and x_s = 2.3 – 3.2D; assuming an unconstrained sediment thickness).

10A.6.5.6.4 Alpha Ventus OWF

The Alpha Ventus OWF is Germany's first offshore wind farm, and was built by a consortium consisting of the utilities EWE, E.ON and Vattenfall. The project is located some 45 km from the coast of Borkum and comprises twelve 5 MW class wind power turbines: six AREVA Wind M5000 turbines and six REpower 5M turbines, resting on two different foundation types. Whereas the AREVA WTGs stand on tripods, the REpower turbines are mounted on jacket foundations in a water depth of 30 metres.

To date we have not been able to obtain relevant information on the jacket foundations at Alpha Ventus.

10A.6.5.6.5 Scale Model Studies

Engineering scale models studies are commonly undertaken to examine the interaction of maritime structures with hydrodynamic forcing over mobile beds. Yang *et al*., (2010) provides a useful example (the only one in the literature) for a jacket foundation in a wave-current climate. 1:36 scale model studies were undertaken in a wave basin to examine local and global scour around the foundations of a typical jacket structure, with Froude scaling being applied to both the hydrodynamics and to sediment density. Each jacket leg was 2.08 m in diameter. Two different water depths were investigated (12 m and 16 m) and the wave field and current fields were applied orthogonally to one another. Figure 10A.6.7 shows a 3D plot of bed bathymetry around the foundation. The principal findings of this work are;

- 0.46 < s_e / D < 1.07;
- generally 0.5< x_s 2.5D;
- s_e is, in the presence of waves, a weak function of water depth;
- scour occurs quickly, with >70% of the depth to s_e occurring within 20 minutes;
- more serious scour is induced at the up-current side of the foundation; and
- scour beneath the leg – leg cross braces occurs but is less excessive than around the legs.

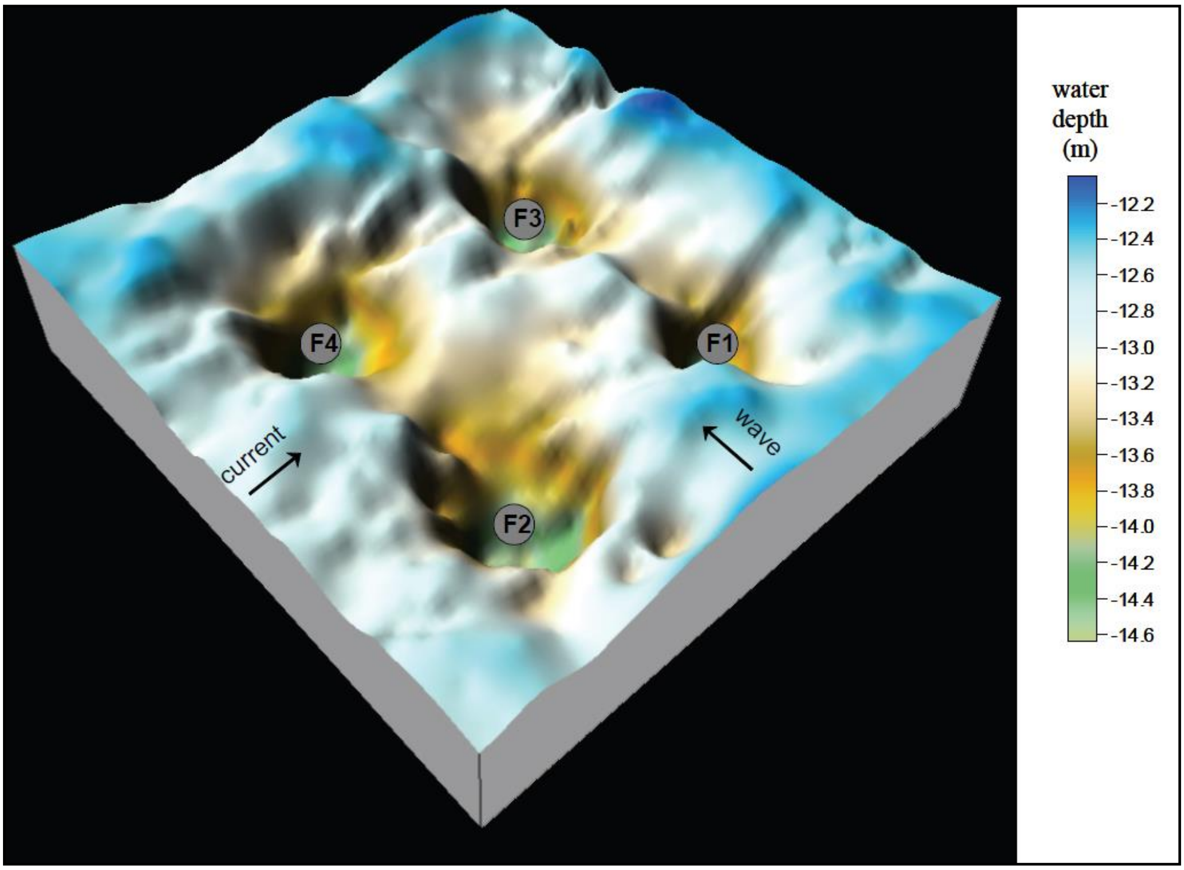


Figure 10A.6.7 Three dimensional bathymetry around the foundation following scouring during 'worst case' (i.e. most severe) hydrodynamic conditions. Note the currents and waves approach at 90°. Scour beneath the leg to leg cross members is evident. From Yang *et al.*, (2010).

The jacket structure is similar to that under consideration in this study, but inclusive of four nearbed structural cross braces. However, these studies represent a hydrodynamic situation which is, in comparison to marine conditions at the Inch Cape Development Area, far more energetic (although the sediment types are comparable). The water depth is about one third that at the Inch Cape Development Area, applied currents ~40 per cent greater in magnitude and wave heights approximately half the water depth. A comparison with anticipated scour at the Inch Cape Development Area is thus only partially valid. Nonetheless, the study provides some useful insight into the scouring and patterns of scour around jacket structures.

10A.6.5.7 Summary

The following are the chief conclusions from the scour analysis. It should be noted that this analysis forms part of the EIA for the Inch Cape Offshore Wind Farm. The analysis is for a representative location within the proposed Development Area, and is conservative in nature due to the limitations in the information about the turbine design and location currently available. The results are considered representative of the potential worst case scour for the purpose of undertaking the EIA, but should not be used for detailed engineering design.

1. The Inch Cape Development Area can be considered a deep water tidally dominated site, with wave action highly limited in its impact upon the seabed.
2. The Development Area is designated as transitional ‘clear water – live bed’ wherein tidal currents are capable of mobilising sand only under upper phase Spring tides.
3. Scour is expected during both Spring and Neap tides but scour rates are anticipated to be far lower during neap tides.
4. Scour depth (s_e) scales geometrically with leg diameter (*D*), s_e / D = 0.66 – 2.20.
5. The lateral extent of scour (x_s) varies within the range x_s = 1.20 – 4.00 *D*.
6. During normal tidal conditions of a (peak) Spring tide global scour is anticipated for only the smallest leg – leg spacing (*G* = 20 m); for larger foundations scour (up to *G* = 60 m) scour is expected to be confined to the immediate environ of each leg.
7. Global scour is expected around structures with *G* = 20 m and *G* = 30 m, and for *G*= 40 m for 1:50 and 1:100 return period currents. Global scour is not expected around the biggest proposed structures (*G* = 60 m).
8. The timescales for scour to develop to 68 per cent of s_e is at least 12 days. However, it is important the caveats on this estimate (see Section 5.1.2)) are acknowledged.
9. Significant backfilling is not expected to occur as a result of the transitional characteristic of the Development Area.
10. Bedform migration within and around scour pits is not an important factor, except where jackets may be sited in bedform fields associated with shallower areas, or close to morphological (raised) mound features.
11. For many locations across the Development Area the presence of only a thin surface sediment veneer over resistant horizons (rock; Quaternary formations e.g. Wee Bankie) will limit likely the vertical extent of scour.

12. There is generally reasonable quantitative agreement with the limited available scour information and data from other sites where jacket foundations have been used.

10A.6.5.8 Overview Scour Assessment for Proposed Offshore Export Cable Corridor and Inter-array Cables

The Offshore Export Cable Corridor for the Inch Cape Offshore Wind Farm is shown in Figure 10A.6.8. The route exits from the southern and south western border of the Development Area, following a south-westerly route to landfall along the northern East Lothian coastline. The route is up to approximately 83 km in length. Cables will be suitably buried or will be protected by other means when burial is not practicable, to provide a level of protection from vessel anchoring, trawling and sediment transport. The principal marine sedimentary impacts for this situation arise via the generation of sediment plumes during burial, during any necessary removal for repair, and during eventual decommissioning, and via (secondary) scouring which may occur around any emplaced scour protection.

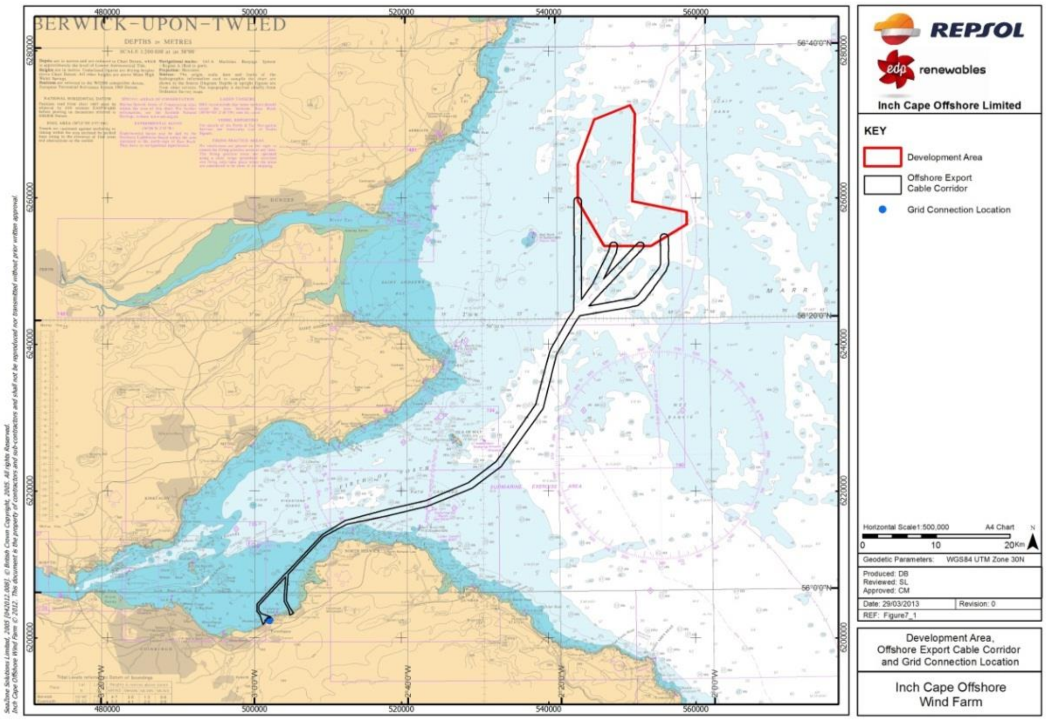


Figure 10A.6.8 Offshore Export Cable corridor and Development Area. Source: ICOL.

10A.6.5.8.1 Scour Around Cable Protection or Unburied Cables

Although it is assumed that the Export Cable and inter-array cables will be buried for protection, there is the potential requirement to protect cables where burial is not possible. Protection methods will include either rock placement, mattresses, sand/grout bags or uraduct/metal shells. An assessment is generally undertaken to determine stable protection dimensions for the oceanographic conditions expected along the cables (these may vary as wave exposure increases into shallower waters). Since the protection would be substantially larger than the surrounding sediment along the cables , scour may occur around the periphery of the protection, a phenomenon termed 'secondary scour'. Although data is required on the bottom sediment sizes to judge scour potential accurately, scour potential due to tidal currents is judged to reduce in a shoreward direction (as current magnitudes decrease; Figure 10A.6.9), whereas scour due to wave action is probably more varied and at a maximum in the shallowest inshore areas (Figure 10A.6.9). The depth of the wave base (i.e. where wave motion is no longer detectable) along the cable route for mean annual wave conditions (Table 10A.6.1) is ~ 6 to 8 m. The depth of the wave base (h) was determined using the criteria $h > 0.01\ T^2$ and $h < 10\ Hm0$, where T = wave period and Hm0 = significant wave height, as given in Soulsby (2007).

Rates of secondary scour are typically very low, highly localised, and in the form of a strip running adjacent to the protection. As noted, greater secondary scour rates might be expected in the shallowest part of the Offshore Export Cable Corridor, where sediment resuspension by waves ordinarily occurs most frequently. This can be prevented by either placement of a fine gravel filter layer next to the protection, or through use of an anti-scour apron. The former is more widely used. Where the cable cannot be buried, and protection is required, scour may therefore occur. A study will be carried out to predict the effects of secondary scour from cable protection and to inform design with the intention of reducing secondary scour

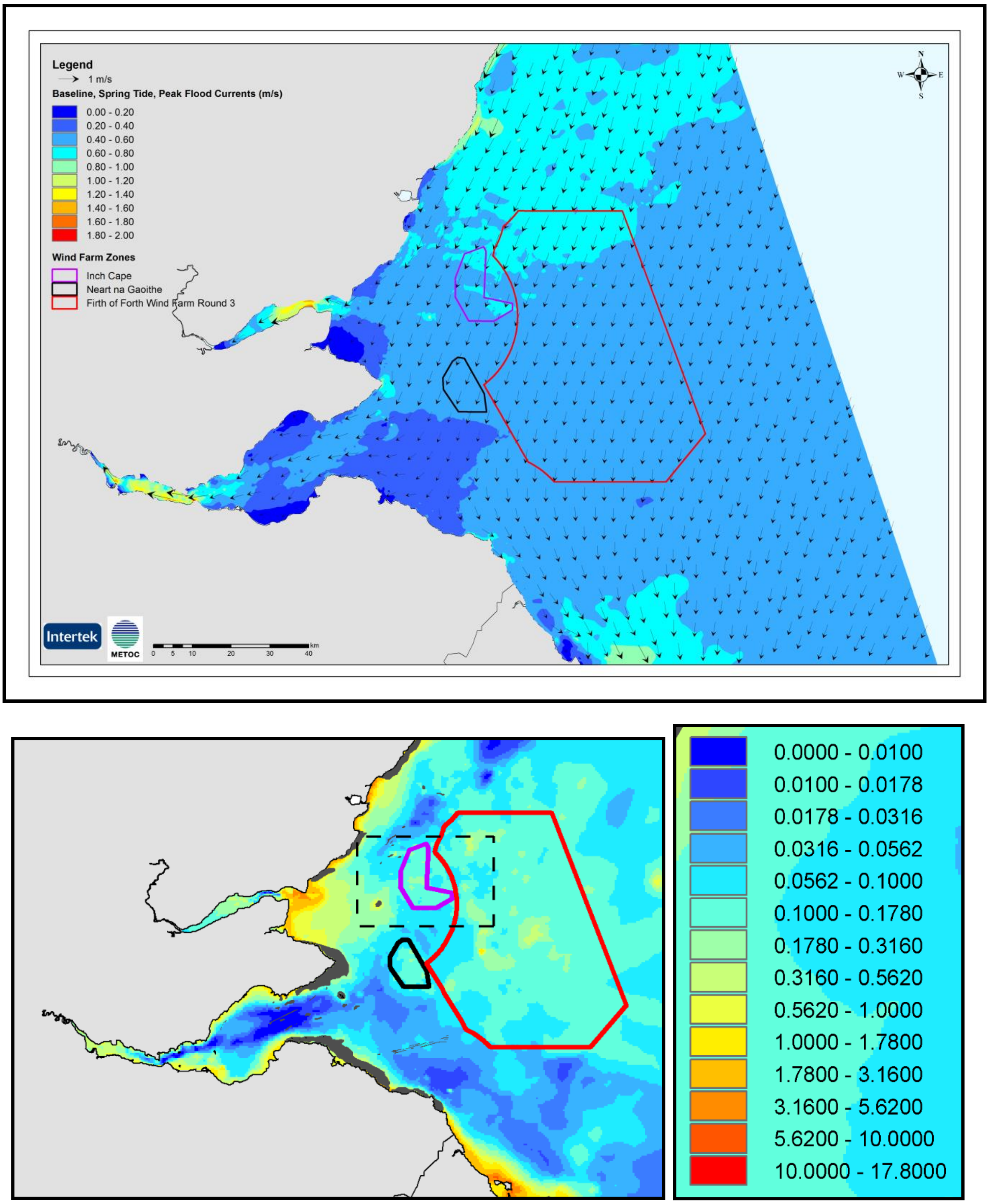
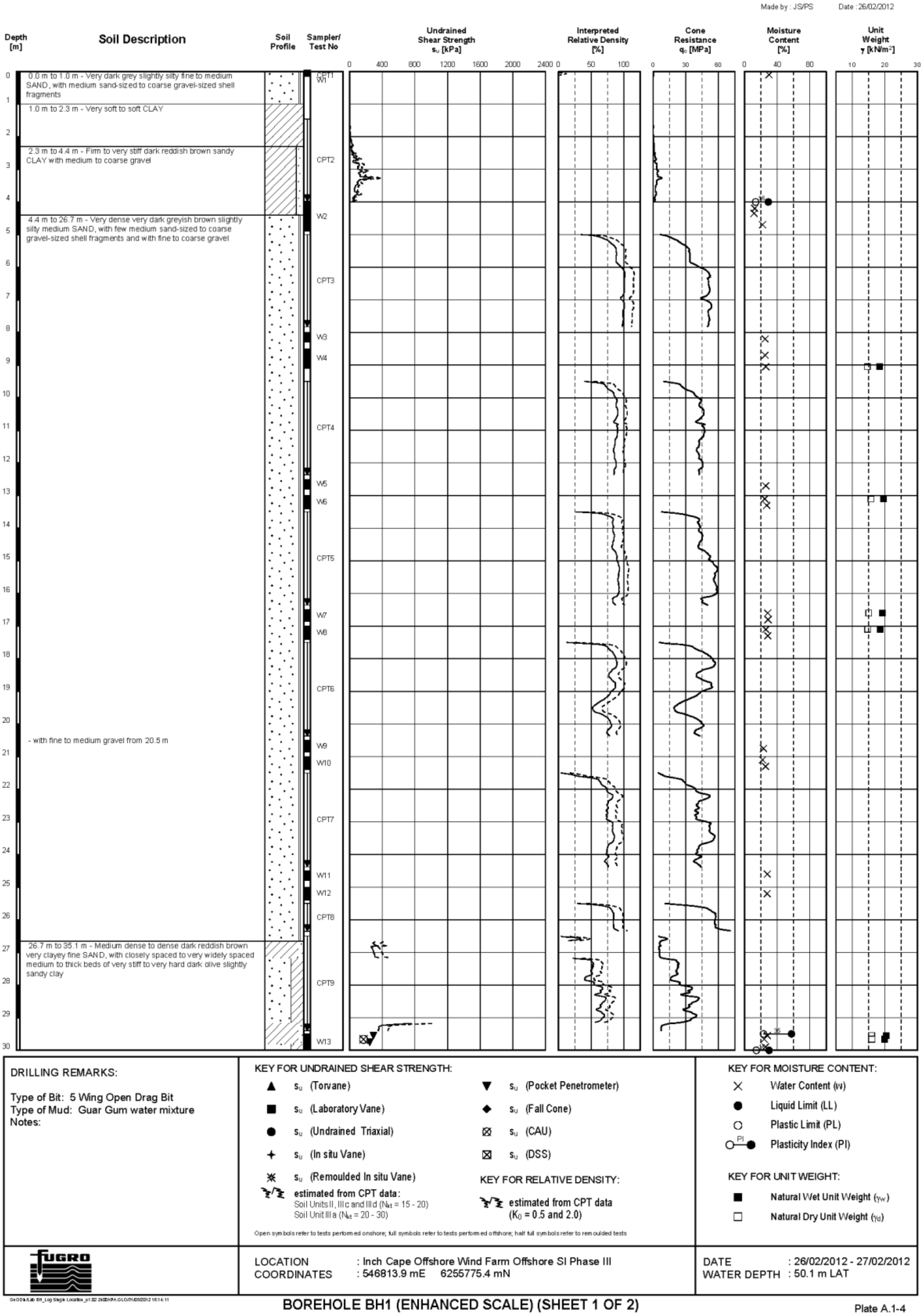


Figure 10A.6.9 Example of hydrodynamic model output: peak Spring tidal flood current vectors (speed, direction) (top panel) and wave bed stress (90th percentile; legend units $N\ m^{-2}$) (bottom panel). Source FTMS.

10A.6.6 PRELIMINARY BOREHOLE LOGS (SOURCE FUGRO)



0.0 m to 1.0 m - Very dark grey slightly silty fine to medium SAND, with medium sand-sized to coarse gravel-sized shell fragments

1.0 m to 2.3 m - Very soft to soft CLAY

2.3 m to 4.4 m - Firm to very stiff dark reddish brown sandy CLAY with medium to coarse gravel

4.4 m to 26.7 m - Very dense very dark greyish brown slightly silty medium SAND, with few medium sand-sized to coarse gravel-sized shell fragments and with fine to coarse gravel

- with fine to medium gravel from 20.5 m

26.7 m to 35.1 m - Medium dense to dense dark reddish brown very clayey fine SAND, with closely spaced to very widely spaced medium to thick beds of very stiff to very hard dark olive slightly sandy clay

DRILLING REMARKS:

Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture
Notes:

KEY FOR UNDRAINED SHEAR STRENGTH:

▲ s_u (Torvane)
■ s_u (Laboratory Vane)
● s_u (Undrained Triaxial)
✦ s_u (In situ Vane)
⋇ s_u (Remoulded In situ Vane)
estimated from CPT data:
Soil Units II, III c and III d (N_{kt} = 15 - 20)
Soil Unit III a (N_{kt} = 20 - 30)
▼ s_u (Pocket Penetrometer)
◆ s_u (Fall Cone)
⊗ s_u (CAU)
⊠ s_u (DSS)

KEY FOR RELATIVE DENSITY:

estimated from CPT data (K_0 = 0.5 and 2.0)

Open symbols refer to tests performed onshore; full symbols refer to tests performed offshore; half full symbols refer to remoulded tests

KEY FOR MOISTURE CONTENT:

× Water Content (w)
● Liquid Limit (LL)
○ Plastic Limit (PL)
○—● Plasticity Index (PI)

KEY FOR UNIT WEIGHT:

■ Natural Wet Unit Weight (γ_w)
□ Natural Dry Unit Weight (γ_d)

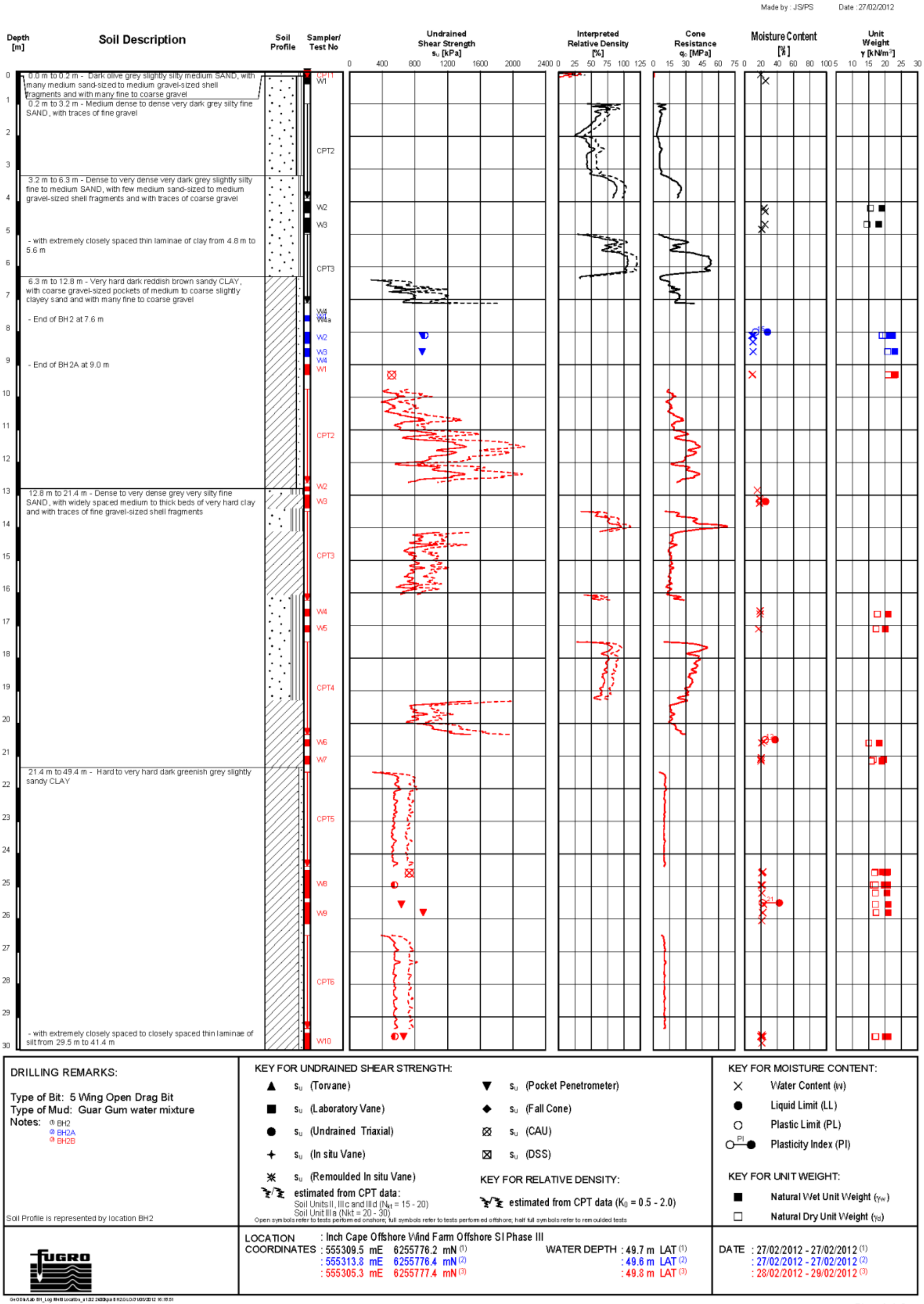
FUGRO

LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase III
COORDINATES : 546813.9 mE 6255775.4 mN

DATE : 26/02/2012 - 27/02/2012
WATER DEPTH : 50.1 m LAT

BOREHOLE BH1 (ENHANCED SCALE) (SHEET 1 OF 2)

Plate A.1-4



0.0 m to 0.2 m - Dark olive grey slightly silty medium SAND, with many medium sand-sized to medium gravel-sized shell fragments and with many fine to coarse gravel

0.2 m to 3.2 m - Medium dense to dense very dark grey silty fine SAND, with traces of fine gravel

3.2 m to 6.3 m - Dense to very dense very dark grey slightly silty fine to medium SAND, with few medium sand-sized to medium gravel-sized shell fragments and with traces of coarse gravel

- with extremely closely spaced thin laminae of clay from 4.8 m to 5.6 m

6.3 m to 12.8 m - Very hard dark reddish brown sandy CLAY, with coarse gravel-sized pockets of medium to coarse slightly clayey sand and with many fine to coarse gravel

- End of BH 2 at 7.6 m

- End of BH 2A at 9.0 m

12.8 m to 21.4 m - Dense to very dense grey very silty fine SAND, with widely spaced medium to thick beds of very hard clay and with traces of fine gravel-sized shell fragments

21.4 m to 49.4 m - Hard to very hard dark greenish grey slightly sandy CLAY

- with extremely closely spaced to closely spaced thin laminae of silt from 29.5 m to 41.4 m

DRILLING REMARKS:

Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture
Notes: (1) BH2
(2) BH2A
(3) BH2B

Soil Profile is represented by location BH2

KEY FOR UNDRAINED SHEAR STRENGTH:

▲	s_u (Torvane)	▼	s_u (Pocket Penetrometer)
■	s_u (Laboratory Vane)	◆	s_u (Fall Cone)
●	s_u (Undrained Triaxial)	⊠	s_u (CAU)
✚	s_u (In situ Vane)	⊠	s_u (DSS)
✱	s_u (Remoulded In situ Vane)		

estimated from CPT data:
Soil Units II, IIIc and IIId (N_{kt} = 15 - 20)
Soil Unit IIIa (Nkt = 20 - 30)

KEY FOR RELATIVE DENSITY:

estimated from CPT data (K_0 = 0.5 - 2.0)

Open symbols refer to tests performed onshore; full symbols refer to tests performed offshore; half full symbols refer to remoulded tests

KEY FOR MOISTURE CONTENT:

✕	Water Content (w)
●	Liquid Limit (LL)
○	Plastic Limit (PL)
○—●	Plasticity Index (PI)

KEY FOR UNIT WEIGHT:

■	Natural Wet Unit Weight (γ_w)
☐	Natural Dry Unit Weight (γ_d)

FUGRO

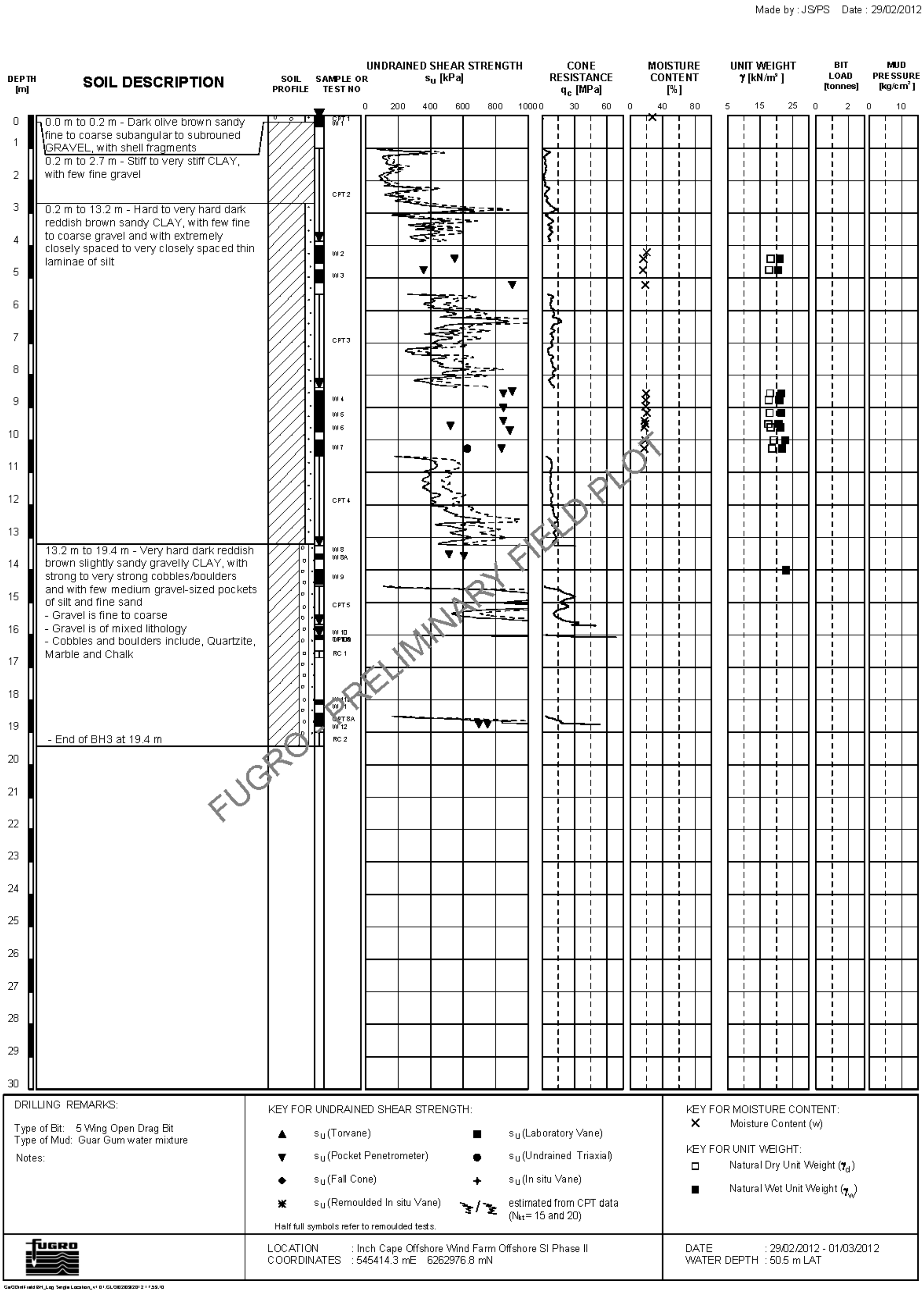
LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase III
COORDINATES : 555309.5 mE 6255776.2 mN (1)
: 555313.8 mE 6255776.4 mN (2)
: 555305.3 mE 6255777.4 mN (3)

WATER DEPTH : 49.7 m LAT (1)
: 49.6 m LAT (2)
: 49.8 m LAT (3)

DATE : 27/02/2012 - 27/02/2012 (1)
: 27/02/2012 - 27/02/2012 (2)
: 28/02/2012 - 29/02/2012 (3)

BOREHOLE BH2, 2A and 2B (ENHANCED SCALE) (SHEET 1 OF 2)

Plate A.1-8



Made by : JS/PS Date : 29/02/2012

SOIL DESCRIPTION

0.0 m to 0.2 m - Dark olive brown sandy fine to coarse subangular to subrouned GRAVEL, with shell fragments

0.2 m to 2.7 m - Stiff to very stiff CLAY, with few fine gravel

0.2 m to 13.2 m - Hard to very hard dark reddish brown sandy CLAY, with few fine to coarse gravel and with extremely closely spaced to very closely spaced thin laminae of silt

13.2 m to 19.4 m - Very hard dark reddish brown slightly sandy gravelly CLAY, with strong to very strong cobbles/boulders and with few medium gravel-sized pockets of silt and fine sand
- Gravel is fine to coarse
- Gravel is of mixed lithology
- Cobbles and boulders include, Quartzite, Marble and Chalk

- End of BH3 at 19.4 m

DRILLING REMARKS:

Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture
Notes:

KEY FOR UNDRAINED SHEAR STRENGTH:

▲ s_u (Torvane)
▼ s_u (Pocket Penetrometer)
◆ s_u (Fall Cone)
✱ s_u (Remoulded In situ Vane)
■ s_u (Laboratory Vane)
● s_u (Undrained Triaxial)
+ s_u (In situ Vane)
estimated from CPT data (N_{kt} = 15 and 20)

Half full symbols refer to remoulded tests.

KEY FOR MOISTURE CONTENT:
× Moisture Content (w)

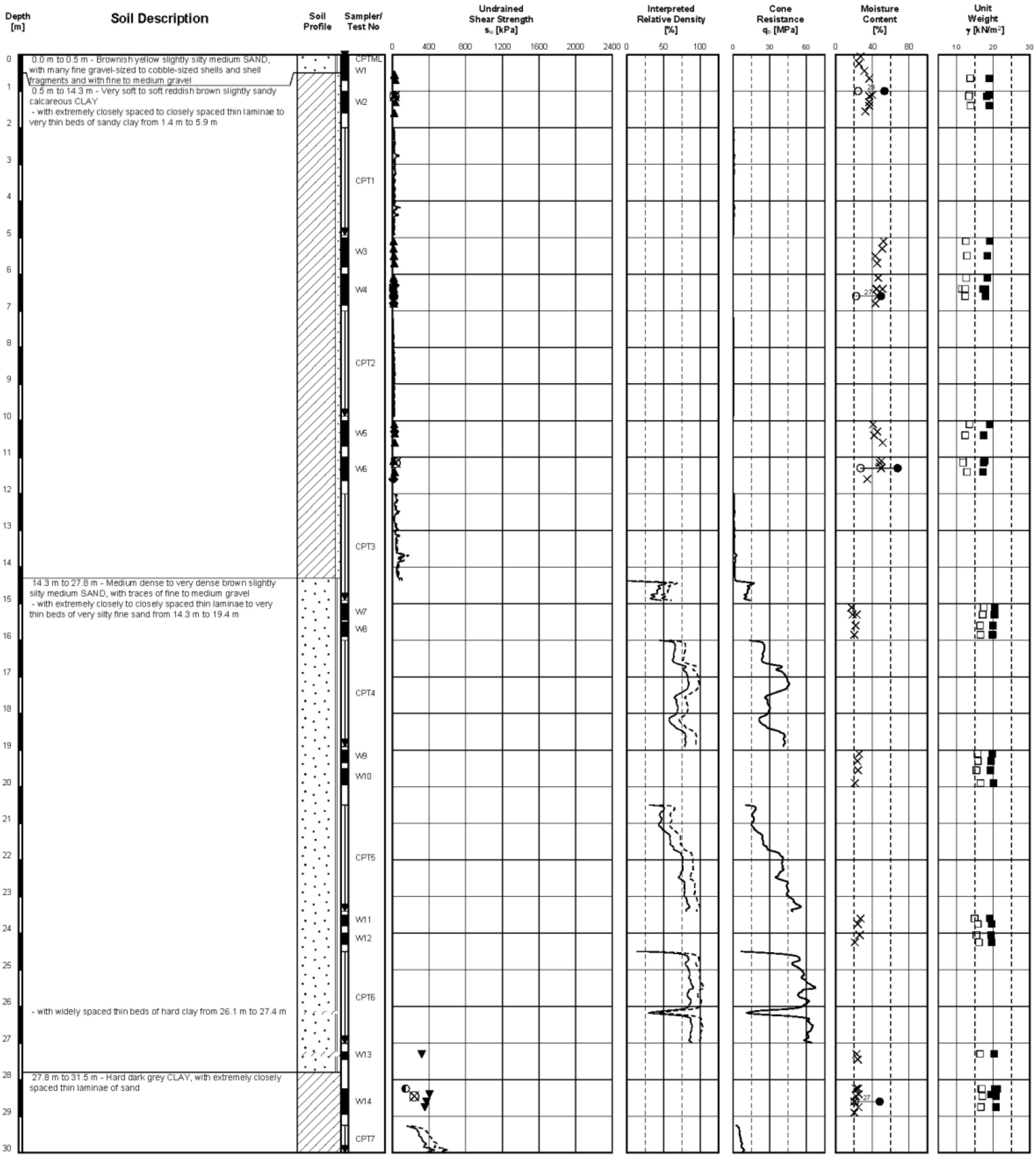
KEY FOR UNIT WEIGHT:
□ Natural Dry Unit Weight (γ_d)
■ Natural Wet Unit Weight (γ_w)

LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase II
COORDINATES : 545414.3 mE 6262976.8 mN

DATE : 29/02/2012 - 01/03/2012
WATER DEPTH : 50.5 m LAT

BOREHOLE BH3 (PRELIMINARY) SHEET 1 OF 1

Made by : JS/PS Date :02/03/2012



0.0 m to 0.5 m - Brownish yellow slightly silty medium SAND, with many fine gravel-sized to cobble-sized shells and shell fragments and with fine to medium gravel

0.5 m to 14.3 m - Very soft to soft reddish brown slightly sandy calcareous CLAY
- with extremely closely spaced to closely spaced thin laminae to very thin beds of sandy clay from 1.4 m to 5.9 m

14.3 m to 27.8 m - Medium dense to very dense brown slightly silty medium SAND, with traces of fine to medium gravel
- with extremely closely to closely spaced thin laminae to very thin beds of very silty fine sand from 14.3 m to 19.4 m
- with widely spaced thin beds of hard clay from 26.1 m to 27.4 m

27.8 m to 31.5 m - Hard dark grey CLAY, with extremely closely spaced thin laminae of sand

DRILLING REMARKS:

Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture
Notes:

KEY FOR UNDRAINED SHEAR STRENGTH:

▲	s_u (Torvane)	▼	s_u (Pocket Penetrometer)
■	s_u (Laboratory Vane)	◆	s_u (Fall Cone)
●	s_u (Undrained Triaxial)	⊠	s_u (CAU)
✦	s_u (In situ Vane)	⊠	s_u (DSS)
⁕	s_u (Remoulded In situ Vane)		

estimated from CPT data:
Soil Units II, III c and III d (N_{kt} = 15 - 20)
Soil Unit III a (N_{kt} = 20 - 30)

KEY FOR RELATIVE DENSITY:

estimated from CPT data
(K_0 = 0.5 and 2.0)

Open symbols refer to tests performed onshore; full symbols refer to tests performed offshore; half full symbols refer to remoulded tests

KEY FOR MOISTURE CONTENT:

×	Water Content (w)
●	Liquid Limit (LL)
○	Plastic Limit (PL)
○—●	Plasticity Index (PI)

KEY FOR UNIT WEIGHT:

■	Natural Wet Unit Weight (γ_w)
☐	Natural Dry Unit Weight (γ_d)

FUGRO

LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase III
COORDINATES : 548552.9 mE 6268361.2 mN

DATE : 02/03/2012 - 02/03/2012
WATER DEPTH : 49.7 m LAT

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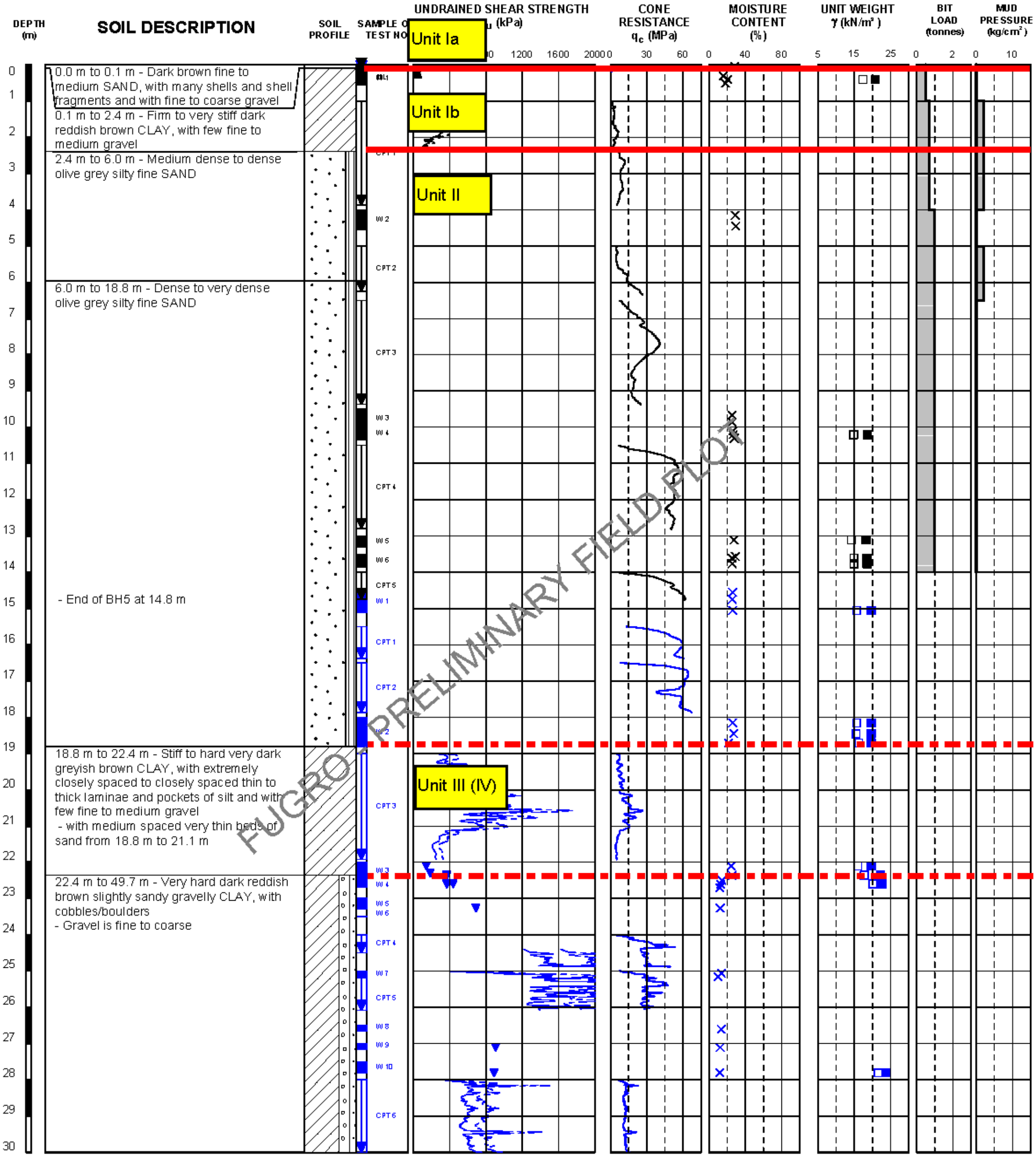
BOREHOLE BH4 (ENHANCED SCALE) (SHEET 1 OF 2)

Plate A.1-14



0.0 m to 0.1 m - Dark brown fine to medium SAND, with many shells and shell fragments and with fine to coarse gravel

0.1 m to 2.4 m - Firm to very stiff dark reddish brown CLAY, with few fine to medium gravel

2.4 m to 6.0 m - Medium dense to dense olive grey silty fine SAND

6.0 m to 18.8 m - Dense to very dense olive grey silty fine SAND

- End of BH5 at 14.8 m

18.8 m to 22.4 m - Stiff to hard very dark greyish brown CLAY, with extremely closely spaced to closely spaced thin to thick laminae and pockets of silt and with few fine to medium gravel
- with medium spaced very thin beds of sand from 18.8 m to 21.1 m

22.4 m to 49.7 m - Very hard dark reddish brown slightly sandy gravelly CLAY, with cobbles/boulders
- Gravel is fine to coarse

DRILLING REMARKS:
Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture
Notes: ① BH5
② BH5A

Soil Profile is represented by location BH5

KEY FOR UNDRAINED SHEAR STRENGTH:

▲	S_u (Torvane)	■	S_u (Laboratory Vane)
▼	S_u (Pocket Penetrometer)	●	S_u (Undrained Triaxial)
◆	S_u (Fall Cone)	✚	S_u (In situ Vane)
✱	S_u (Remoulded In situ Vane)		Estimated from CPT data (N_{kt} = 15 - 20)

Half full symbols refer to remoulded tests.

KEY FOR MOISTURE CONTENT:
✕ Moisture Content (w)

KEY FOR UNIT WEIGHT:
☐ Natural Dry Unit Weight (γ_d)
■ Natural Wet Unit Weight (γ_w)

FUGRO

LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase II
COORDINATES : 548559.2 mE 6259387.1 mN ① WATER DEPTH : 49.1 m LAT ①
: 548563.7 mE 6259387.8 mN ② : 49.7 m LAT ②

DATE : 02/03/2012 - 02/03/2012 ①
: 04/03/2012 - 05/03/2012 ②

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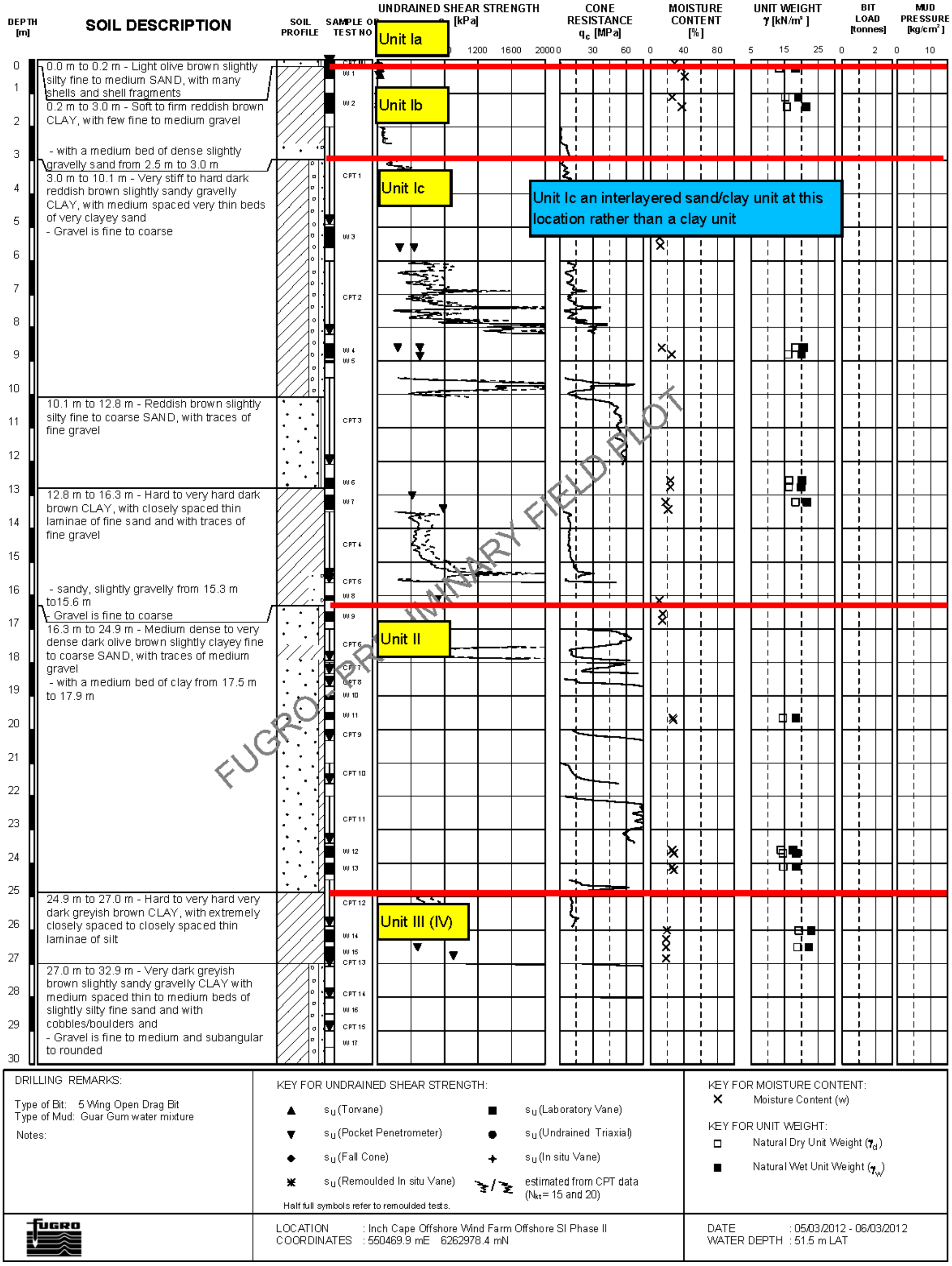
BOREHOLE BH5 (PRELIMINARY) SHEET 1 OF 2

Made by : JS/PS Date :



Unit Ic an interlayered sand/clay unit at this location rather than a clay unit

0.0 m to 0.2 m - Light olive brown slightly silty fine to medium SAND, with many shells and shell fragments

0.2 m to 3.0 m - Soft to firm reddish brown CLAY, with few fine to medium gravel
- with a medium bed of dense slightly gravelly sand from 2.5 m to 3.0 m

3.0 m to 10.1 m - Very stiff to hard dark reddish brown slightly sandy gravelly CLAY, with medium spaced very thin beds of very clayey sand
- Gravel is fine to coarse

10.1 m to 12.8 m - Reddish brown slightly silty fine to coarse SAND, with traces of fine gravel

12.8 m to 16.3 m - Hard to very hard dark brown CLAY, with closely spaced thin laminae of fine sand and with traces of fine gravel
- sandy, slightly gravelly from 15.3 m to15.6 m
- Gravel is fine to coarse

16.3 m to 24.9 m - Medium dense to very dense dark olive brown slightly clayey fine to coarse SAND, with traces of medium gravel
- with a medium bed of clay from 17.5 m to 17.9 m

24.9 m to 27.0 m - Hard to very hard very dark greyish brown CLAY, with extremely closely spaced to closely spaced thin laminae of silt

27.0 m to 32.9 m - Very dark greyish brown slightly sandy gravelly CLAY with medium spaced thin to medium beds of slightly silty fine sand and with cobbles/boulders and
- Gravel is fine to medium and subangular to rounded

DRILLING REMARKS:

Type of Bit: 5 Wing Open Drag Bit
Type of Mud: Guar Gum water mixture

Notes:

KEY FOR UNDRAINED SHEAR STRENGTH:

▲	s_u (Torvane)	■	s_u (Laboratory Vane)
▼	s_u (Pocket Penetrometer)	●	s_u (Undrained Triaxial)
◆	s_u (Fall Cone)	+	s_u (In situ Vane)
✱	s_u (Remoulded In situ Vane)		estimated from CPT data (N_{kt} = 15 and 20)

Half full symbols refer to remoulded tests.

KEY FOR MOISTURE CONTENT:

✕ Moisture Content (w)

KEY FOR UNIT WEIGHT:

□ Natural Dry Unit Weight (γ_d)

■ Natural Wet Unit Weight (γ_w)

FUGRO

LOCATION : Inch Cape Offshore Wind Farm Offshore SI Phase II
COORDINATES : 550469.9 mE 6262978.4 mN

DATE : 05/03/2012 - 06/03/2012
WATER DEPTH : 51.5 m LAT

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BOREHOLE BH6 (PRELIMINARY) SHEET 1 OF 2

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