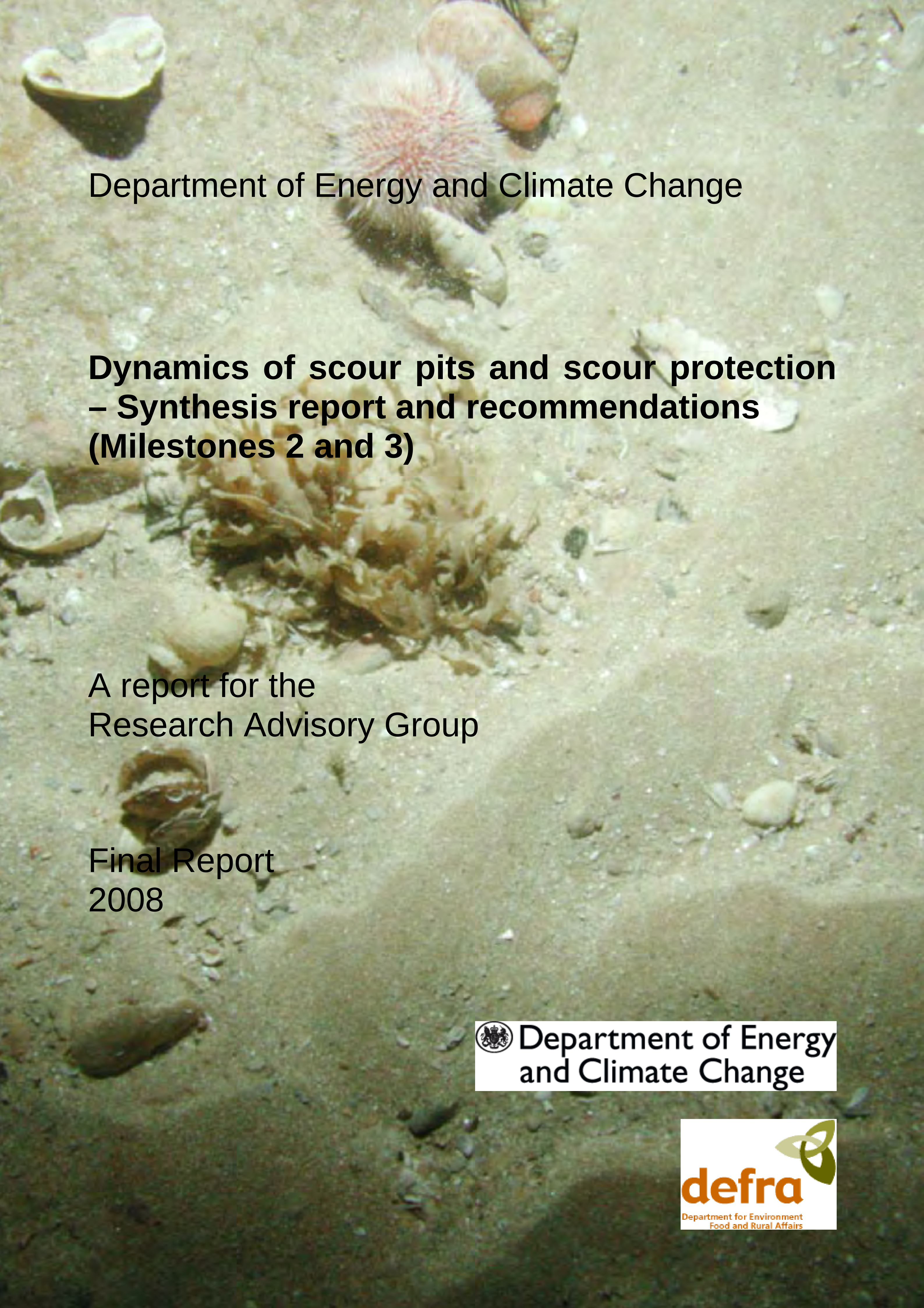

Department of Energy and Climate Change

Dynamics of scour pits and scour protection – Synthesis report and recommendations (Milestones 2 and 3)

A report for the
Research Advisory Group

Final Report
2008

Department of Energy and Climate Change

defra
Department for Environment Food and Rural Affairs

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Appendix

1. Introduction

This document provides a synthesis of the work undertaken by HR Wallingford in conjunction with ABPmer and CEFAS for the RAG research project SED02: *Dynamics of scour pits and scour protection*. The principal items covered by this study are listed below:

- Identification, collation and review of all available field evidence for scour from built Round 1 wind farm projects and, in addition, any further data available from other relevant European marine projects. The Round 1 wind farm data was brought together by the project SED01 – ABPmer *et al.* (2007).
- Review of past UK and European research relating to scour and scour protection for the wind farm industry.
- Review of publications and guidance relating to scour and scour protection within other marine industries (oil and gas, cables, jetties, met masts and other one-off structures), including types of scour protection and their potential impact on coastal processes and navigation.
- Review the design and installation of scour protection for Scroby Sands, and relate to performance as recorded by earlier DTI funded investigations.
- Review the design and installation of scour protection for other UK and European sites, potentially including scour in relation to cabling as well as foundations.
- Identification of gaps in the scour and scour protection knowledge base, especially on mobile sandbanks. Make recommendations for the research required to fill these gaps.

The first five of these items have been covered in the detailed research presented within the report in Appendix 1 and summarised in the present report. The last item is covered in the present report.

1.1 REPORT STRUCTURE

This report contains a summary of the sites reviewed (Section 2), a summary of the literature reviewed (Section 3), a collation and synthesis of the Round 1 scour data and data from other sites as well as comments on monopile and other foundation types (Section 4), a summary of information on scour protection (Section 5). There is an overall assessment of the scour data (Section 6) and recommendations for further research arising from the present study (Section 7). A reference list is included in Section 8 and Appendix 1 contains the earlier more detailed report on the analysis of data used in the present report.

2. Wind farm sites for which data is used in the present study

Four Round 1 UK offshore wind farm projects and one Irish project form the principal datasets used in this study (see Figure 1 for locations):

- Barrow
- Kentish Flats
- Scroby Sands
- North Hoyle
- Arklow Bank.

These datasets are supplemented by a conference paper describing some of the scour measurements undertaken around the met mast at Scarweather Sands (Harris *et al.*, 2004).

The sites studied, whilst sharing some characteristics are all unique. This is both a benefit, as it allows the study of different physical conditions in relation to scour, and also a problem as it makes it more difficult to draw common conclusions based on the datasets. In terms of the wind turbine foundations, all sites use monopile structures, although North Hoyle is unique in using a tripod structure for one of its meteorological masts. The sites have the following characteristics:

- Barrow:
  moderately exposed to waves, moderate currents, sand/gravel and clay, stable seabed environment, deep water
- Kentish Flats:
  moderately exposed to waves, moderate currents, superficial fine sand overlying stable seabed environment, shallow water
- Scroby Sands:
  exposed to waves, strong currents, sand, dynamic sandbank environment, shallow water, presence of mobile bedforms
- North Hoyle:
  moderately sheltered from waves, moderate currents, stable seabed environment, deep water
- Arklow Bank:
  exposed to waves, strong currents, sand/gravel, dynamic seabed environment, shallow water
- Scarweather Sands:
  very exposed to waves, strong currents, medium sand, dynamic seabed environment, shallow water.

Figure 1: Locations of wind farm sites for which data was analysed in the present study.

3. *Literature Review*

The processes of scour have been discussed in numerous papers and publications and the main points are summarised below:

3.1 PROCESSES OF SCOUR

Placing a structure in the marine environment will lead to a change in the flow pattern in its immediate locality due to its presence (Hoffmans and Verheij, 1997; Whitehouse, 1998; Sumer and Fredsøe, 2002). These changes will result in one or more of the following occurring:

- Flow contraction
- Horseshoe vortex formation in front of the structure
- Lee-wake vortices behind the structure (with or without vortex shedding)
- Reflection and diffraction of waves
- Wave breaking
- Turbulence generation
- Pressure differentials in the soil leading to liquefaction.

With the occurrence of these phenomena there is usually an observed increase in the local sediment transport capacity and, therefore, an increased tendency to scour, i.e. a localised lowering of the seabed around the foundation (Figure 2). Therefore, an understanding of the scour potential is important in the context of offshore wind farms since it may lead to some or all of the following:

- Compromised structural stability of the foundations
- Increased sediment transport (both suspended and bedload), including transfer of sediment between coastal areas and potential changes to benthic habitats or changes to navigation routes
- Damage to intrafield or export cables due to exposure and freespans.

3.2 GUIDANCE DOCUMENTS

Three main guidance documents have been reviewed together with output from the Opti-Pile EC project:

- DNV guidance DNV-OS-J101 (Det Norske Veritas, 2004)
- ETSU report (Cooper and Beiboer, 2002)
- Offshore wind farms - guidance note for EIA in respect of FEPA and CPA requirements.

The DNV design standard provides a methodology for assessing scour around a vertical pile. However, no specific methodology is given for scour around gravity base, or non-standard type structures. For vertical piles the DNV guidance uses the empirical expression of Sumer *et al*. (1992). This provides prediction equations for the scour depth and extent in sandy sediments as well as time-evolution. The mean predicted scour depth is $S/D = 1.3$ for the situation where sediment is mobile everywhere on the seabed due to currents and waves, and not just around the base of the foundation. Sumer and Fredsøe (2002) note that this prediction is associated with a standard deviation, based on the scatter in the available data, of 0.7 which means that for design purposes the maximum scour depth could be $S/D = 2.0$ with one standard deviation.

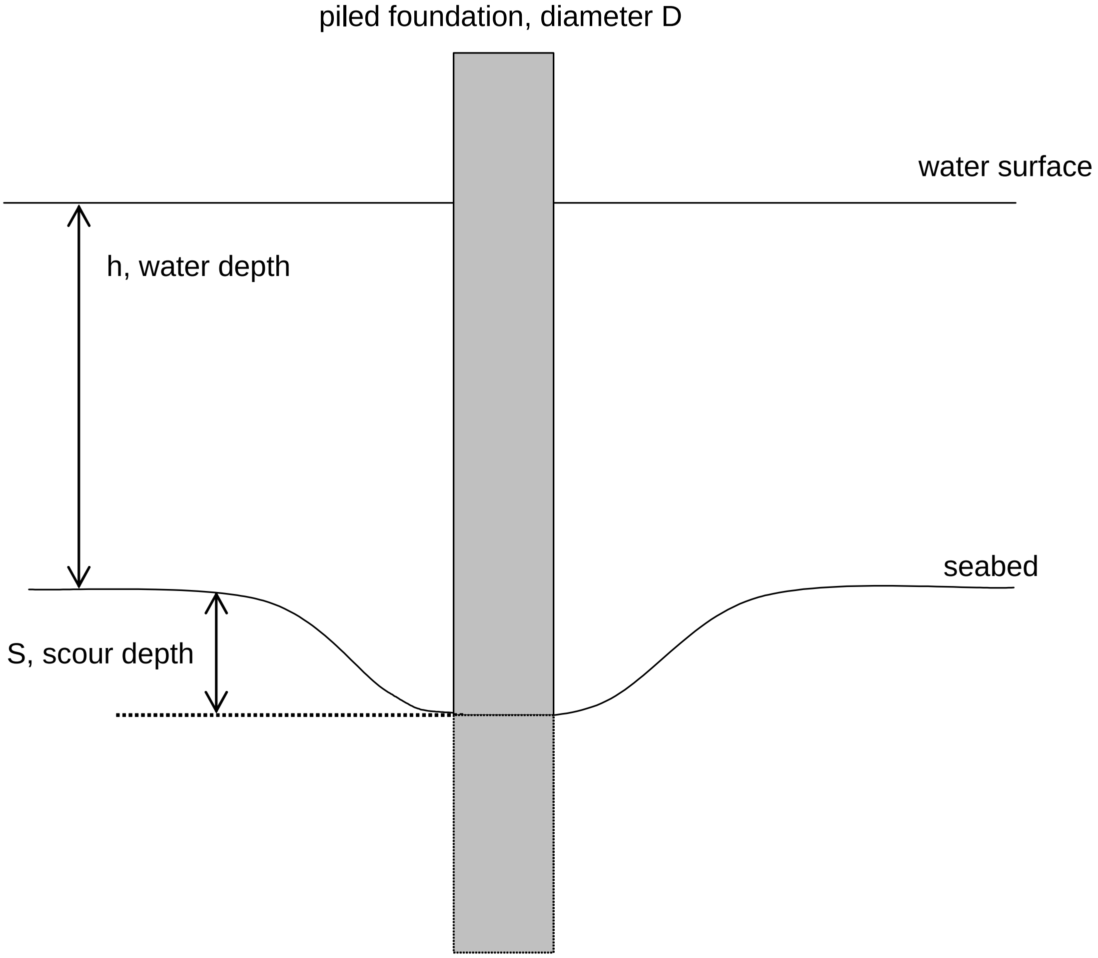

Figure 2: **Definition sketch for scour parameters used in the present report.**

The aim of the ETSU report was to identify, review and assess the potential effects on coastal processes related to the development of offshore wind farms around the UK coast. It also contained a brief review of scour processes with respect to offshore wind turbines. Various relationships were given in the text for determining the equilibrium scour depth, but the approaches outlined in more detail were those of Eadie and Herbich (1986) and Johnston and Erasito (1994). As the Eadie and Herbich approach may have limits on applicability due to the low Reynolds numbers used in their experiments, the ETSU report put forward the approach of Johnston and Erasito. However, one of the examples presented relates to Scroby Sands and this methodology yields results in respect to the velocities that have no real physical meaning and, therefore, in this regard this approach is unsatisfactory and cannot be recommended as a method to be adopted. However, it should be noted that in the Scroby Sands example it does yield similar results to those obtained using the method of Sumer *et al*. (1992) adopted in the DNV guidance.

The Opti-Pile project (den Boon *et al.*, 2004) produced a spreadsheet tool for predicting scour depth and extent in waves and currents. It draws on and combines already available semi-empirical methods from the sediment transport and scour literature (i.e. Soulsby, 1997 and Sumer and Fredsøe, 2002). The maximum predictable value of scour depth was S/D = 1.75 as this gave the best fit to the previously available laboratory data. It also included methods for predicting the stability of scour protection material (rock dump) placed around the pile, both for the case of static protection where the rock is placed following installation of the foundation and prior to scour forming, and dynamic protection where the scour hole that is formed following installation is filled (fully or partially) by rock. Allowance was also made for regional changes in bed level around the bed protection. The spreadsheet was calibrated with physical model tests for the Q7 wind farm in the Dutch sector and the method gave a reasonable comparison with the N7 monopile data (Rudolph *et al.*, 2005) discussed in Section 4.8.1.

Analysis of the spreadsheet has been made by Høgedal and Hald (2005). They compared the calculation of scour formation (depth and extent) around a monopile foundation with a large number of measurements from the Scroby Sands site. It was shown that the Opti-Pile design tool predicted the scour depth very well. Comparison was also made with the data from N7 in the southern North Sea, discussed below, and making predictions using the reported wave and currents for the site gave predictions which encompassed the measured values. Subsequent analysis of the scour protection elements of the spreadsheet were performed by Whitehouse *et al.* (2006). The tool gave the correct form of behaviour for rock stability when compared with physical model tests of scour protection design for the Arklow Bank site but it was concluded that the protection elements of the tool should be recalibrated for use in such shallow water with such fast currents.

Finally, it was noted that the guidance note for EIA in respect of FEPA and CPA requirements, provides a framework for undertaking coastal process assessments, but does not provide any information on specific methodology.

4. Site Specific Data Sets - Conclusions

Data for five wind farm sites were analysed (Appendix 1) and the following conclusions were made:

4.1 BARROW

Scour depths were measured at thirteen of the 30 4.75m diameter (D) monopile foundation positions at Barrow in July 2005, within nine weeks of completing the installation of the first monopile. Scour depths up to S/D = 0.44 were observed in the sandy deposits in the west of the site. Much lower scour depths (up to S/D = 0.04) were measured in the glacial till to the eastern side of the wind farm. There was an indication that scour depths in glacial till increased with time following installation and, to a lesser extent, in sand.

In September 2006 all thirty of the foundations were surveyed. The observed scour depths in areas with a good thickness of sandy sediment had increased and the maximum value of S/D = 1.21. In the areas with a superficial cover of sand the scour depths were limited by the thickness of that layer to scour depths of up to and around 0.5D.

The measured scour depths were over predicted by DNV guidelines and the Opti-Pile Design Tool. The most likely reasons for this are the hydrodynamic conditions prior to the measurements in September 2006 may not have been those that would produce the largest scour and the possibility of silt within the sand, which may make it cohesive and less susceptible to scour than sand without fines.

4.2 KENTISH FLATS

Scour depths were measured at four of the 5m diameter turbine foundations in January 2005, some three months after completion of the 30 turbine foundations. The sites monitored were on the east side of the turbine array and the seabed had surficial covers of fine sand and shell overlying clay, other than where there were greater thicknesses of sands and clays present in the channel of the palaeo-Swale river.

The maximum scour depth was less than 0.28D in January 2005, increasing to 0.46D in November 2005 and decreasing again to 0.34D in April 2006. It is not clear how much of the initial “scour” depression around the turbines is due to hydraulic scour processes, or whether it was caused by “drawdown” of the soil during foundation installation. Depressions were evident in the seabed surveys at the locations where the jack-up barge legs had been present during installation. These depressions may have arisen from penetration of the legs into the soil rather than through scour processes. At the turbine foundations the scour depth at one location (E2) increased with time during the three surveys whereas the scour depth at the other three locations increased in the first two surveys and then decreased in the last survey. Assuming the survey data are consistent, and the time variation is not an artefact arising from survey error, this suggests that seabed sediment transport processes are able to produce fluctuations in the depth of the scour pit around the foundations at this site.

4.3 SCROBY SANDS

The scour depths at this site were measured in March 2004 following installation of the 30 foundation piles with diameter of 4.2m; the foundations were installed over the period November 2003 to February 2004. Therefore, the March 2004 survey would contain results from turbines that had been installed for up to four or five months as well as those that had been installed for around a month. The scour depths recorded in the unlimited thickness of sandy sediment forming the bank ranged between 0.95D and 1.38D. The range of scour depths is expected to have resulted from spatial variations in water depth and wave-current exposure as well as time elapsed since installation. Inevitably there will always also be some natural variability in the scour produced under similar prevailing conditions.

Rock dump scour protection was installed in the existing scour pits around each foundation between the March 2004 survey and a survey in July 2004. With the information presently to hand it is not known the minimum period of time that scour took to form before installing the scour protection. However, according to den Boon *et al.* (2004) scour was allowed to form for a few tidal cycles before installing the scour protection. Subsequently, secondary scour pits have been formed associated with the placed scour protection. In July 2004 the scour (i.e. maximum bed depth recorded adjacent to the rock protection) was smaller in absolute terms than the scour depths recorded in March 2004. Since then the range of scour depths has increased with time and scour depths with the protection in place can be deeper than the absolute scour depth with the pile foundation only, but also shallower, depending on how the flow has interacted with the scour protection and local morphology of the bank surface. In November 2006 the range of **secondary** scour depths compared to the original pile diameter were 0.21D to 1.66D but the scour depressions were **not** adjacent to the foundation pile owing to the presence of the scour protection rock.

The level of the sandbank surface is dynamic and will undergo change over a period of time. However, from the data it was noted that the range of ambient bed depths were in the range 3m to 11.5m below CD in March 2004 and 3m to 11m below CD in November 2006. This indicates a tendency for the bank to be stable overall at the locations surveyed, but does not indicate that the bed levels at an individual turbine have remained stable over this same period of time.

4.4 NORTH HOYLE

The scour depths at this site were measured from a survey conducted in the period August to October 2004. The foundation units each comprise of 4.0m diameter monopiles which were installed over the period April to July 2003. The bed sediments are predominantly gravels and sandy gravels and below the top metre of soil there is more compact gravelly clay. The scour depths recorded in 2004 were no greater than 0.125D – although scour was recorded at only 10 of the 30 foundations - and in the April-May 2005 survey no scour was recorded at any of the foundations. No scour protection material was placed although there was some redistribution of drill cuttings which arose during the installation process on the seabed at that time, and some rock dumping was carried out to protect the cables.

The information on the met masts is included under Section 4.6.

4.5 ARKLOW BANK

The scour depths at this site were measured following installation of the seven wind turbines over a period of nine weeks during late summer and early autumn in 2003. There was a short delay between installation of the 5m diameter monopile foundations and the scour protection rock, which was sufficient for scour holes to develop around the monopiles, due to the tidal current alone (Whitehouse *et al*., 2006). Side scan sonar was used to measure the size of the scour holes prior to installation of the scour protection. That survey data was not available in the present study but one example indicates scour had formed to a depth of 0.8D at this time.

Following installation of the scour protection post-installation surveys were undertaken in June 2004, almost nine months after installation, September 2004, three months later, and, finally, 19 months after installation in April 2005. The secondary scour depths, i.e. not adjacent to the foundation itself, were maximum at foundation pile 5 at 4m in June (this equates to 0.8D) increasing to 4.3m in September (0.86D) and decreasing to 1.9m (0.38D) in April 2005. The secondary scour depths recorded in the surveys at the other turbines were all less than the values at foundation pile 5 which was located in the shallowest water depth of 3.4m below Mean Sea Level.

There was no information available on the as-built rock armour configuration. Diver observations of the rock armour indicated that the placed armour distribution was uneven around each pile. However, no rock armour was observed at foundation pile 5 and (at time of writing) it is not clear whether it was installed there or not; if it was not installed this could have been the reason for the largest scour depths being observed there at this site. It was noted that the ambient bed level fell at six out of the seven turbines which would have led to exposure of the placed rock armour and generation of a falling apron at the edge of the armour.

Data was also obtained from met masts at two sites:

4.6 NORTH HOYLE MET MASTS

Survey data was available from three met masts with slender foundation piles. The scour depth in 2004 at the 3.2m monopile met mast 1 was (with some uncertainty) 0.094D and at the tripod foundation met mast 2 the scour depth was 0.39D around each of the three 0.76m diameter raker piles. The scour depth recorded in 2004 at the 1.89m diameter met mast 3 on Constable Bank to the west of the wind farm was 0.79D. The pattern of scour in 2005 was different in detail but the scour depth was the same.

4.7 SCARWEATHER SANDS MET MAST

The data available for this site on the Scarweather Sands sandbank with medium grade sand relates to the installed 2.2m monopile foundation with no scour protection. The time variation in scour depth was measured using a multi-beam echo sounder. The foundation was installed in May 2003 and the measurements were made in the latter part of June of the same year. The average scour depths were measured at low water and high water and were found to vary between 0.59D and 0.27D, respectively. This indicates that even under the conditions experienced during the variation of the tide there is a temporal variation in scour depth. Additional data for the variation in scour depth with time was collected but was not available at the time of performing the present review.

4.8 OTHER STRUCTURES WITH MONOPILE FOUNDATIONS

4.8.1 N7 monopile Dutch Sector

The scour data has been published (Rudolph *et al.*, 2005) for scour with currents and waves having occurred over a period of nearly five years around a 6m diameter monopile foundation. This foundation was installed at a coastal site in a water depth of 7m below Mean Sea Level with a bed of fine to medium dense sand. The maximum scour depth after 9 months was 0.55D and after nearly five years 1.05D. The rate of development of scour had slowed at this time but had not necessarily ceased. The average scour depths at the same times, 9 months and five years, were lower – namely 0.5D and 0.8D. The data appear to indicate a progressive increase in scour although it provides snapshots on a time-varying process and hence it is not known whether the scour depths are deeper or shallower periodically, for example following storms.

4.8.2 Otzumer Balje

The scour data for this site was published in a poster by Noormets *et al.* (2003). A monopile foundation with diameter of 1.5m was installed in a channel of the Wadden Sea. The mean water depth was 13.3m, the maximum tidal flow 1.4m/s and the bed material was 0.3mm sand. The survey data five to six months after installation indicated a scour hole of 1.47D. There was some evidence of variations in scour hole depth between spring and neap tides, with the scour hole being shallower by 0.27D on neap tides.

4.9 OTHER FOUNDATION TYPES

There were no data available from field monitoring of scour or scour protection around other types of foundations such as gravity base structures, suction caissons or tripod/quadruped. Gravity base foundations have been used at Horns Rev in Denmark and there was no scour data available from that site. There was some laboratory data available from the studies by Whitehouse *et al.* (2004, 2005) on suction caisson foundations.

The results obtained in the physical model tests provide a clear insight into the potential scour development around suction caisson foundations in (long-crested, random) waves and/or a steady current. The waves and currents were run at a 90° to each other to represent a coastal condition. The scour development around a 19m diameter flat topped skirted caisson foundation supporting a 4.6m diameter monopile showed an approximately linear increase in scour depth with time. This was because the flow contraction against the 2m upstand on the skirt initiated the scour process in sandy sediment, which was then reinforced as more of the skirt became exposed, providing a greater blockage to the flow. The deepest potential scour depth with the caisson was 9.3m in a test with waves and currents and corresponded closely to the 9.5m skirt depth initially embedded in the bed. A test with current only produced a much lower scour depth than with the waves and currents, and with waves only the scour was smaller again. Different connection details were tested and the use of a conical top connection produced a faster scour development than the flat topped caisson. A quadruped structure with 6m diameter caisson foundations was also tested. Scour development at the individual caissons varied in depth depending on whether there was any sheltering effect from waves or currents from adjacent footings.

5. *Scour protection*

There are a variety of approaches that can be taken to prevent or mitigate against scour around foundations:

- Rock armour placed on the seabed around the foundation
- Rock armour placed in the scour hole around the structure
- Rock armour placed on the seabed prior to foundation installation
- Sandbags/geotextile bags placed on the seabed around the foundation
- Concrete mattresses placed on the seabed around the foundation
- Frond mats placed on top of concrete mattresses or anchored directly to the seabed around the foundation
- Attachments to the foundation pile to inhibit the scouring due to vortex action at the bed.

Scour protection was placed definitely at two sites, Scroby Sands and Arklow Bank. The scour protection placed at Scroby and Arklow utilised the scour hole filling method. The stability of the rock protection has not been examined explicitly as part of the present study. The cross-sections of bed levels through the Scroby site indicated the top level of the scour protection had not changed significantly since installation, although it was expected that some of the rock had moved out from the placed area into the secondary scour hole around the protection, i.e. in the form of a falling apron. However, the difficulty of identifying levels in the rock layer from the multibeam echo sounder surveys meant that the rock level was higher (e.g. by 0.25m on some surveys) between adjacent surveys. It was not clear whether this was a real change or an artefact of the survey data. The scour protection material at Arklow was investigated by diver survey, which found that the pattern of rock placement was irregular and that in some places there were noticeable voids between placed rocks through which sand or gravel was visible. At both sites the **secondary scour** has been observed around the scour protection as is discussed below.

The case of rock armour being placed before driving or drilling the foundation can be considered, although there will be a limitation on the size of rock that can be placed. Observations of the performance of small rock (median size 0.05m) with a layer thickness over sand of 0.4 to 0.7m placed on sand have been made by Louwersheimer *et al.* (2007). The rock was placed prior to driving a 4.6m pile into the seabed, the pile driving led to a lowering of the rock layer, which may have also experienced lowering due to movement of the rock by waves and currents. The pile installation was considered to have drawn down the rock by 0.4m in a radius of about 1.7m and hydraulic forces may have removed an additional 0.1m of rock. The scour depth at the adjacent 2.9m met mast after 3 years was 0.8D, which illustrated the presence of a scouring environment. This method of pre-placement of rock (slate) has been used successfully at Burbo but at the time of writing there is no data available on the interaction of the foundation with the rock.

The use of sandbags offshore has met with varying success over the years Whitehouse (1998). Recently, research into the stability of sandbags (sand filled geotextile containers) has been investigated for the Butendiek wind farm (Grune *et al.*, 2006). The testing was carried out in the Large Wave Channel (GWK) of the Coastal Research Centre (FZK) in Germany. The wave tests investigated the stability of bags of different sizes and percentage filling of the bag with sand, as well as different layout geometries. Tests performed with single containers and container groups placed around a 0.55m diameter monopile in up to 5m of water in irregular waves led to identification of stable and unstable configurations. It was concluded that the stability of containers was not only a function of their total weight but the percentage filling of the bag and interaction effects between groups. Further tests were planned to evaluate the performance of two layers of containers placed around a 0.55m diameter monopile in the flume.

The use of concrete mattresses was proposed for the Cape Cod wind farm off the east coast of the USA and they have been used to protect subsea structures, gravity base structures and large monopile foundations elsewhere in the North Sea.

The scour tests (Whitehouse *et al.*, 2004, 2005) showed the potential need for provision of scour protection measures as scour in the sandy seabed was likely to occur under relatively common conditions of tides and waves (1:1 year return period); as it would for a monopile. A rock dump solution was implemented and tested. The rock dump used 200kg mass rock placed in a concentric ring of 5m diameter and nominally 1m (2 rock layers) thick directly onto the sandbed. This was effective for the 19m and 6m diameter foundations.

The rock tested was apparently stable under the conditions tested, including a simulated reversal of the tidal flow direction, and appeared to provide adequate protection against scour development around the caisson skirt. The erosion of the seabed around the outer edge of the protection led to a local drop in bed level which reinforced the tendency for the edge of the rock dump to spread to form a ‘falling apron’. This produced a thinning of the rock dump and settlement of individual rocks into the bed. In principal the concept works but the following factors need to be borne in mind:

- The stability of the rock in higher return period events needs to be tested
- The influence of bed lowering on the falling apron needs to be taken into account – this influences the overall width of protection to be placed
- The need for a filter layer between the rock protection and the seabed should be considered.

An alternative approach is to dredge a shallow hole in the seabed in which to place the foundation, but this may not remove the need to place scour protection material.

6. Overall assessment of scour data

The scour data available from the built sites (up to November 2006) has been brought together and plotted to show how the scour depths from the different sites compare in terms of scour depth and ambient water depth, i.e.

water depth away from the influence of scour (Figure 3). This figure shows that the data from the different sites occupy a number of clusters.

The influence of ambient water depth has been investigated in Figure 3, which shows the Barrow site is in deepest water and has a range of scour depths from zero to nearly 6m. Scroby Sands is in shallower water but has scour depths in the range 4 to 5.5m in the deepest water depth cluster and 4 to 6m in the shallower cluster. The one data point available for Arklow Bank has a similar value to the lower limit of the Scroby site in the shallower depth cluster. The Kentish Flats site has similar water depths to the lower depths at Scroby but lower scour depths. The North Hoyle site has similar water depths to the deeper Scroby depth cluster but scour depths of less than 0.5m.

The influence of sediment type is evident in the Barrow data, where the near zero scour depths occur on the glacial till bed material. Similarly low values occur at North Hoyle where there is a less mobile gravely bed overlying more resistant gravely clay, and at Kentish Flats where there is a layer of fine sand overlying clay. Scroby Sands and Arklow Bank have sandy deposits, with the sediment being coarser at Arklow than at Scroby.

The Scroby Sands and Arklow Bank sites have the fastest currents and the other sites investigated have smaller currents, still capable of mobilising sand but not gravels or clay sediments. The North Hoyle and Kentish Flats sites are expected to have slightly less wave exposure than the other sites investigated, and hence less potential sediment transport due to waves.

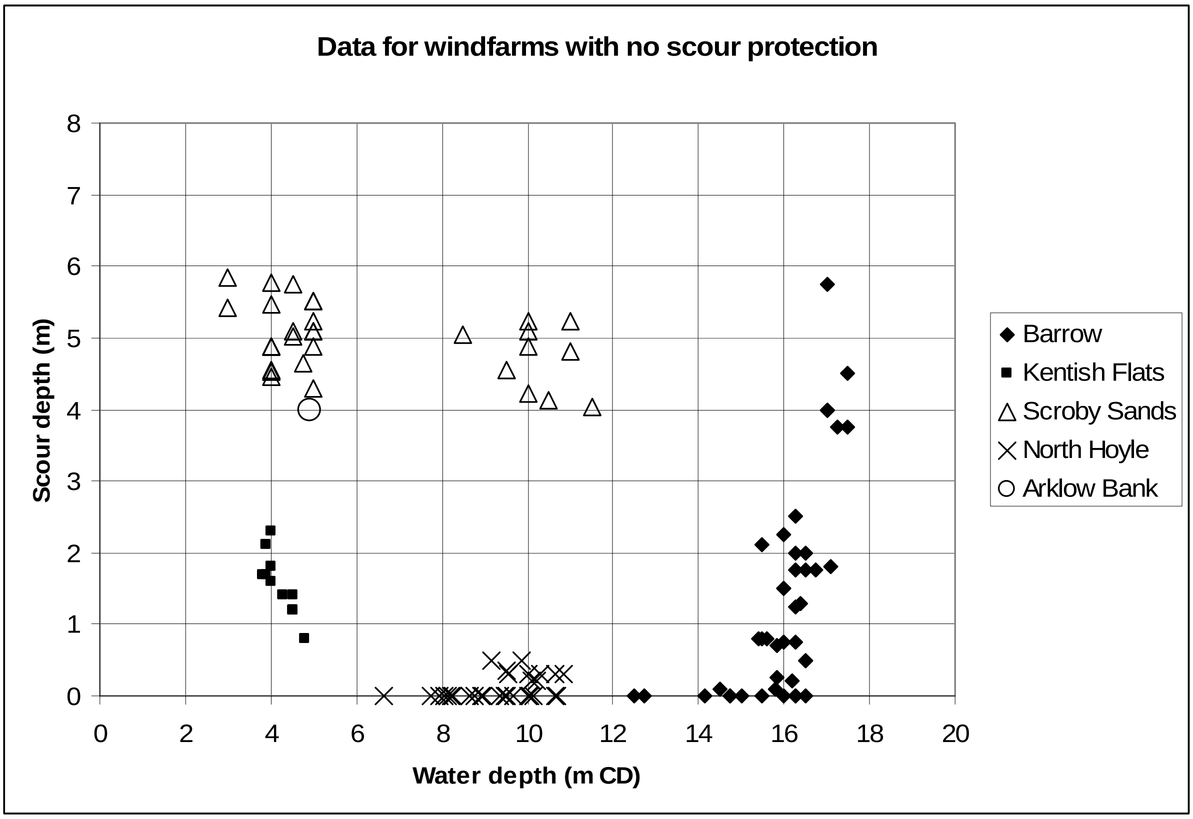

Figure 3: Scour data for wind farms with no scour protection.

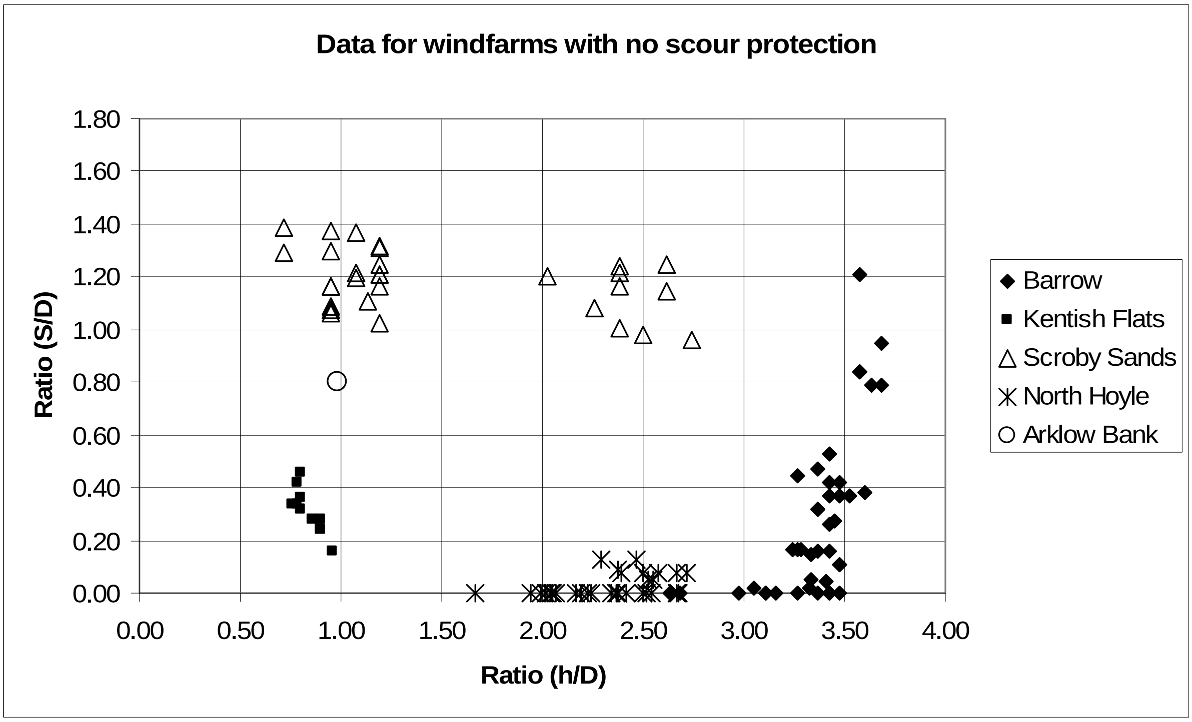

Figure 4: Non-dimensional plot of scour data for wind farms with no scour protection.

The data has been re-plotted in terms of the ratio of scour depth to pile diameter and water depth to pile diameter ratio (Figure 4). This is an accepted form of scaling for scour data (Whitehouse, 1998, Sumer and Fredsøe, 2002). The deepest scour equates to a ratio of S/D = 1.4 and the DNV guidance (Section 3.2) uses S/D = 1.3. The largest scour depth at Barrow (S/D = 1.21) was obtained after more than one year following installation and the Scroby data (S/D = 1.38) four to five months after installation. It is expected that the Scroby data would have represented a case for which scour could have developed quite fully at that time, although the influence of the flow and wave conditions just prior to the survey may have had an influence on the scour depth at that time. It is possible that the scour at Barrow on the sandy sediments may get deeper with time, so it will be valuable to examine the monitoring data collected in future.

A similar plotting exercise was carried out for the two sites where scour protection material had been placed, namely Scroby Sands and Arklow Bank. The result is shown in Figure 5 which is plotted in a comparable fashion to Figure 3 for the case with no scour protection. The scour plotted in this figure is the **secondary scour**, i.e. the deepest level of the bed adjacent to the placed scour protection.

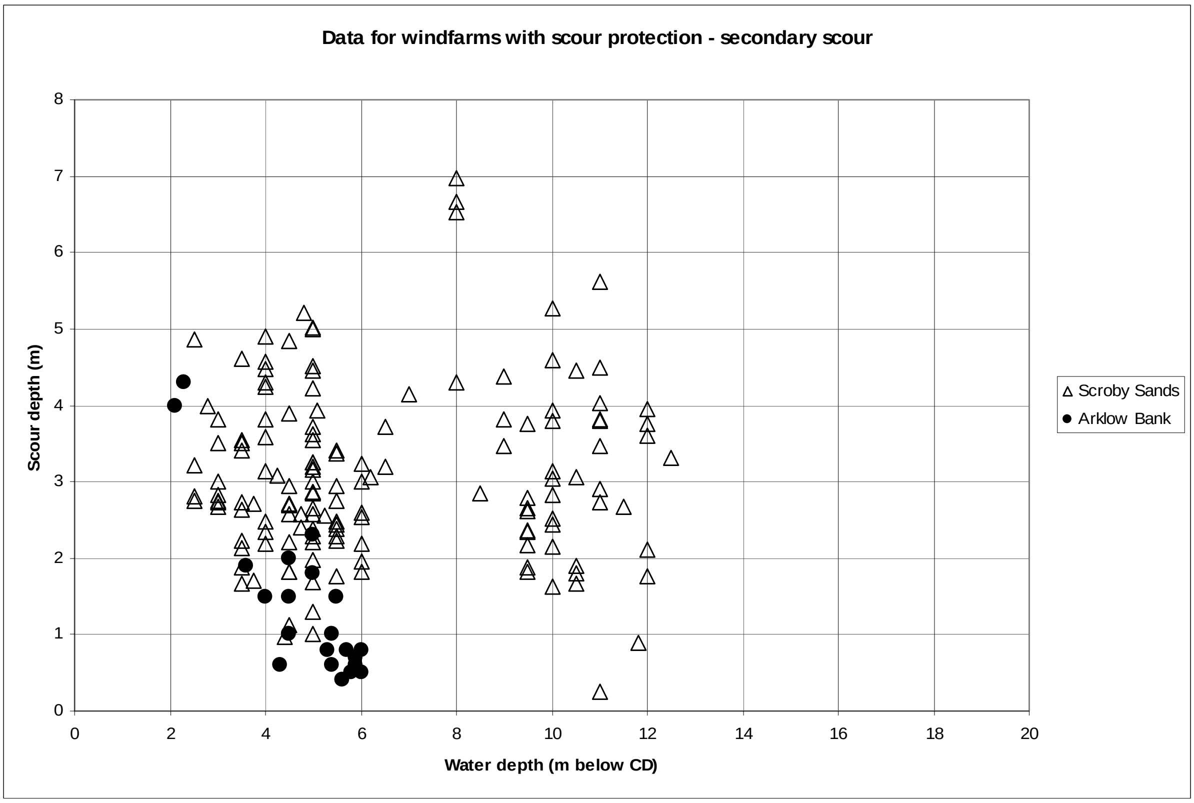

Figure 5: Scour data for secondary scour for wind farms with scour protection.

The data for Scroby Sands occupies two similar, but less distinct, clusters in terms of water depth to the scour data. The range of scour depths is much greater, in some cases scour is less than half a metre and in other cases up to 7m – the latter value being larger than the maximum value plotted in Figure 3. This may be because the scour had not fully developed at the time of the data plotted in Figure 3. The data points for Arklow Bank lie in the lower part of the shallower depth cluster from Scroby Sands. The two scour depths of over 4m are for the first survey after placement of the protection material and subsequent scour depths are less than 2.5m. A similar plot to Figure 4 has not been included in the present report because the diameter of the foundation is not the only factor influencing the local flow and sediment processes; the rock dump also has an influence on the local flow field (e.g. at Scroby Sands).

7. Conclusions and recommendations for further research

The data that is available for scour around offshore windfarm foundations, and the scour interaction with scour protection, has been collated and supports the view that scour is a progressive process where the seabed sediment is naturally mobile and there is an adequate thickness of that sediment for the scour to form. Where the seabed is comprised of stiff clay, there is a superficial layer of sediment overlying clay or the wave and current conditions are not generally strong enough to cause the seabed sediment to be naturally mobile, the scour will be slower or limited in depth.

In comparison with the existing predictive formulae in guidance (DNV, 2004) and the Opti-Pile method (den Boon *et al.*, 2004) the following conclusions can be made; both approaches are based on laboratory measurements of scour around cylindrical foundations. DNV guidance suggests that with current-induced scour the scour depth S in relation to the foundation diameter D can be taken as S/D = 1.3 and the Opti-Pile method assumes the greatest scour depth that can be achieved is S/D = 1.75. The data available to the present study indicates the maximum depth of scour observed is S/D = 1.38. This is slightly larger than the value provided in DNV guidance but it is not clear whether that value (observed at Scroby Sands prior to placement of scour protection) was fully developed and what range of wave and current forcing had been experienced prior to the measurement being made.

Scour will arise from a continuously operating combination of tidal currents, either with negligible or a moderate amount of wave stirring, on a day by day basis. Based on laboratory experience the stronger currents occurring under spring tides can be expected to produce deeper scour than under neap tides. Under more extreme conditions, e.g. storm surges, larger currents may be generated and wave action can become significantly more energetic. Under these conditions the seabed sediment will be naturally more mobile. However, it is not clear whether the scour in an unlimited thickness of sandy sediment will be deeper or shallower during a storm with strong wave action. The range of tidal, seasonal (including storm events) and longer term variations in currents, wave action and water levels can be expected to influence the way in which scour develops at a foundation, and this has an influence on monopile stability. Time series data of bed levels is available for analysis from the Scarweather Sands meteorological mast. This can be used to examine changes at tidal and event scale, but for a smaller diameter pile than is used for the wind farm foundations. Therefore the data required to assess the range of scour responses is not available presently from any offshore windfarm site.

It is considered good practice for scour evaluation that during the design process of the foundation an appropriate analysis is made for local scour arising from the influence of waves and currents taking account of spring and neap conditions and the influence of storm events, as well as the relative magnitude of waves and currents which will vary from location to location. In those locations where a strong reversing tidal flow exists it would be advisable to evaluate the influence of that current pattern on scour development. The potential for scour interaction between adjacent foundations needs to be assessed. Finally, the influence of variation in bed level over the design life of the windfarm needs to be considered; this may arise from regional changes or local changes due to migration of seabed features such as banks, sandwaves or channels.

The scour protection that has been placed appears to be effective in preventing bed lowering adjacent to the foundations. The interaction of the placed scour protection with the surrounding seabed levels has been examined from the available data. Where material has been placed in the scour hole formed around the foundation and the top level of the protection is above the level of the surrounding seabed level it is evident that the mound of protection material has produced a secondary scour response. The data that is available does not presently have the resolution to evaluate whether there has been any displacement of the protection material itself by wave and current action.

The scour protection design needs to take appropriate account of the factors considered relevant to good practice for scour evaluation outlined above.

The conclusions of the research presented in this report, and in the report in Appendix 1, have led to the identification of a number of gaps in the present state of knowledge that could be filled by additional research, either in terms of analysis of pre-existing data or through the collection of new data. Therefore the following recommendations arising from the research are listed:

1. Overall, it would be valuable to extend the present analysis with data from more recent monitoring at the sites included in this study as well as new data from other sites. New data needs to be catalogued centrally in a consistent fashion so that future operational research can be facilitated. A comprehensive database will assist with future design and operation of offshore windfarm foundations.

2. Carry out analysis of the time variation of scour over the period of tides, spring-neap cycles and the influence of storm events. There is evidence that the scour depth can vary at short time-scales and also at long time-scales, even with an increase in scour depth over a period of five years.

3. Based on the work in Opti-Pile it is understood that the maximum scour depth is formed during strong periods of current action (e.g. spring tides) and that the scour depth can decrease during storms. It is

during storms that the greatest wave loading on the foundation and wind loading on the tower will be experienced. Work by Høgedal and Hald (2005) has examined the analytical basis for a scour depth that can be used for working out fatigue loads on the tower. Further analysis of the in-combination effect of scour evolution and wave and wind loading needs to be undertaken.

4. To fill a specific gap in knowledge it would be useful to carry on with at least annual collection of data on scour depth and extent at representative foundations in one of the built wind farms to examine the long-term development.

5. To examine the range of scales of contribution to scour development it would be beneficial to start monitoring from the time of installation of any future sites (for example London Array, Thanet, Gabbard, Gunfleet, Lynn/Inner Downsing). This will capture the initial development and then if the monitoring is carried out for a number years it will provide the information required to extract the relative importance of waves and currents on scour development. Ideally the monitoring would be carried out in parallel with measurement of environmental data - directional wave information, current speed and direction, water depth and ambient bed level. A tide gauge installed on one of the foundations would provide a control dataset for water levels. Multibeam echo sounder data would provide the overall scour pattern around the foundation and a permanently installed downwards looking echo sounder would provide information on the variation of scouring in time, for correlation with the environmental data.

6. As more data becomes available it would be useful to undertake further evaluation of the performance of the predictions of scour in the guidance (DNV, 2004), both for scour depth and for extent at mobile sandy seabed sites. The scour extents at some of the sites, e.g. Scroby Sands, are larger than would be expected due to a simple relationship between scour depth and scour extent linked by the angle of repose of the bed sediment.

7. Bed sediments of silty sand or sandy clay do not respond in the same way as sands without fines. Their resistance to erosion and rate of erosion need to be examined so that a clearer understanding of scour for multi-modal sediment distributions can be achieved. Therefore it will be informative to study further the role of unconsolidated fine sediments in scour evolution. This can be achieved by monitoring the rate of erosion using appropriate equipment for *in situ* measurements of sediment erosion or by monitoring the scour development at a site with these types of soil following foundation installation (e.g. using a downwards looking echo sounder installed on the foundation).

8. The role of consolidated clays in limiting scour development in the overlying sand has been demonstrated through the presently available data. However, there is uncertainty in the scour response of these clays. The erosion rate of exposed clays due to hydraulic forces, abrasion through transport of granular sediments and weathering of the exposed surface on the seabed need to be examined further to determine the controlling mechanisms and the long-term progressive scour response.

9. Owing to the presence of scour like depressions at some of the clay sites that may have been produced during foundation installation it would be useful for geotechnical engineers to advise as to the behaviour of clay sediments during installation and the bed deformation that can be expected to produce a scour like depression.

10. Carry out an ongoing analysis of the performance of the scour protection placed at the sites described in this study, and on new projects. As well as measurements of scour protection level and profile it would be useful to have sample visual information to show how the surface of the scour protection material varies with time. This could be obtained from a video camera lowered to the seafloor, or controlled by a diver or from a Remotely Operated Vehicle (ROV).

11. It would be useful to distil further guidance on the role of placement methodology in the evolution of the scour protection and the interaction of the protection with the surrounding seabed. In the longer term it will be useful to have data with which to evaluate the scour protection performance under the influence of

regional changes in bed level, which can be especially important on sandbanks, or due to the movement of bedforms such as sandwaves and channels – the latter is being addressed in another RAG project (SED06).

12. It was found that in some cases, such as Scroby Sands, the cabling between turbines became exposed in the secondary scour pits formed around the scour protection. At the Arklow Bank site the cabling was exposed or abraded by armour rock (and possibly sediment movement) where it exited the J-tubes above the seabed. Further assessment is required of the occurrences of exposure of cables and what mitigation measures have or can be taken, e.g. re-trenching through jetting, rock dump or placement of concrete mattresses. If material has been placed over the cable it will be informative to see what data is available on the possible secondary scouring effects that may have been caused.

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Appendix 1 Technical Note DDS0442/01 Review of datasets on scour and scour protection (Milestone 1 report)

SED02 Seabed and Coastal Processes Research Dynamics of scour pits and scour protection

Review of datasets on scour and scour protection (Milestone 1 report)

Technical Note DDS0442/01

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Contents

Annexes

1. Introduction

This report has been prepared by HR Wallingford, in conjunction with ABPmer and CEFAS, and was submitted as Milestone 1 of the DTI research project SED02*: Dynamics of scour pits and scour protection*. It brings together data and information to inform the completion of the synthesis and recommendations report to be issued subsequently as Milestones 2 and 3.

The work forms part of the research theme of Seabed and Coastal Processes, and is part of a wider programme of research advanced by the pan-Government Research Advisory Group (RAG).

The emphasis on the present research was on the understanding of scour and scour protection around built windfarm foundations, leading to improved regulatory assessment of future wind farm proposals, industry guidance on scour protection design and placement, and reducing the risk of wind farms affecting coastal process to the extent that they interfere with navigation.

The report is intended to:

- Provide reviews of the scour data available to the end of 2006 within the database collated by the parallel project SED01 (HR Wallingford, 2006)
- Provide the basis of understanding for drafting of the synthesis report to be delivered as Milestone 2 in SED02
- Provide the basis for drawing conclusions and making recommendations to be delivered as Milestone 3 in SED02.

1.1 REPORT BASIS

This report is prepared with individually compiled review material from the project team. It has not been subjected to synthesis and hence there may be some inconsistencies and errors, which will only come to light when the Milestone 2 report has been prepared.

1.2 INPUT DATA

We have brought forward information from the following areas:

- The literature on scour and scour protection
- Direct linkage to offshore wind developers through ABPmer, CEFAS and HR Wallingford’s past and present involvement in UK and European projects
- The review and feed of data on scour from the parallel DTI research SED01: *Review of Round 1 sediment process monitoring data – lessons learnt*
- Direct linkage to European research on scour and related subjects through the EC OPTI-PILE programme
- Significant experience of scour and scour protection within other marine industries
- Direct linkage to MCEU through CEFAS.

2. Project aims and objectives

2.1 PROJECT BACKGROUND

Scour around marine structures is well recognised as an engineering issue. Where scour is anticipated to be sufficiently severe to cause problems of structural stability or other related damage, scour protection is required (Hoffmans and Verheij, 1997; Whitehouse, 1998; Sumer and Fredsøe, 2002). Despite research over many years, particularly in the offshore oil and gas industry, there is still a high level of uncertainty as to the potential extent of scour in relation to offshore wind turbine foundations and, therefore, uncertainty as to the need for scour protection. Unnecessary use of scour protection may result in impacts on seabed morphology, sediments, benthic ecology, fisheries and navigation. Lack of understanding of scour processes within the wind farm industry led to placement of the scour protection at Scroby Sands, for example, which has led to secondary scour around the scour protection, which has been noted as an unintended problem (CEFAS, 2006).

The core aim of this present research is to provide a higher level of understanding of scour and scour protection to inform the design and evaluation of wind farms. This work may also be informative for other renewable technologies that have foundations subject to scour.

3. Scope of work

The project scope of work was divided into two elements, which are described in Sections 3.1 and 3.2 below.

3.1 ELEMENT 1 – COLLATE AND REVIEW AVAILABLE RESEARCH, FIELD EVIDENCE AND GUIDANCE

In Element 1 of the study, a review of the following items has been included leading to the present Milestone 1 report:

- Identification, collation and review of all available field evidence for scour from built Round 1 projects (output from SED01) and, in addition, any further data available from other built European projects

- Review of past UK and European research relating to scour and scour protection for the wind farm industry

- Review of publications and guidance relating to scour and scour protection within other marine industries (oil and gas, cables, jetties, met masts and other one-off structures), including types of scour protection and their potential impact on coastal processes and navigation

- Review the design and installation of scour protection for Scroby Sands, and relate to performance as recorded by earlier DTI funded investigations

- Review the design and installation of scour protection for other UK and European sites, potentially including scour in relation to cabling as well as foundations

- Identify gaps in the scour and scour protection knowledge base, especially on mobile sand banks.

3.2 ELEMENT 2 – RECOMMENDATION FOR STAGE 2

This builds on Element 1 by synthesising information from the data analysis and reviews. The project team will develop the Milestone 2 report with key conclusions and recommendations based on the findings of the research, which identify the ways in which improved understanding and analysis can be achieved. The development of justifications, methods, time-scales and costs will need to be done at a later stage.

4. *Review of information and data on scour and scour protection*

The following sections describe the work that has been completed in the present stage of the study. The sections of this report will form the basis of the subsequent report on synthesis and recommendations arising from the research.

4.1 INTRODUCTION

The processes of scour have been discussed in a number of papers and the main points are summarised in 4.2. In addition, a review and commentary has been provided on existing guidance in the following Annexes:

- DNV guidance DNV-OS-J101 (Annex 2)
- ETSU report by Cooper and Beiboer (Annex 3)
- Opti-Pile EC project (referred to in Annex 5 – more information will be presented in the Milestone 2 report)
- Offshore wind farms – guidance note for EIA in respect of FEPA and CPA requirements with specific mention of scour (Annex 4)

A summary of information from these annexes will be brought together in the Milestone 2 report. We will conclude with some remarks about the present situation with respect to predictive capability based on laboratory and analytical approaches and other published literature.

4.2 SCOUR PROCESSES

Placing a structure in the marine environment will lead to a change in the flow pattern in its immediate locality due to its presence. These changes will result in one or more of the following occurring:

- Flow contraction
- Horseshoe vortex formation in front of the structure
- Lee-wake vortices behind the structure (with or without vortex shedding)
- Reflection and diffraction of waves
- Wave breaking
- Turbulence generation
- Pressure differentials in the soil leading to liquefaction

With the occurrence of these phenomena there is usually an observed increase in the local sediment transport capacity and, therefore, an increased tendency to scour. Therefore, an understanding of the scour potential is important in the context of offshore wind farms since it may lead to some or all of the following:

- Compromised structural stability of the turbines
- Increased sediment transport (both suspended and bedload), including transfer of sediment between coastal areas.
- Development of freespans for infield or export cable route

Scour processes in the marine environment are more complex than that due to steady flow alone (e.g. rivers) due to the effect of waves and the combined effect of currents and waves. Herbich (1981) and Herbich *et al.* (1984) presented results from some of the first detailed investigations on the impact of scour on marine structures. Much of their work was based on empirical type design rules since knowledge of many of the hydrodynamic processes was still poorly understood. More recently, Whitehouse (1998) presented a review of the developments in scour into the 1990's, whilst Sumer and Fredsøe (2002) have provided a comprehensive account of scour at marine structures, incorporating state-of-the-art knowledge. Det Norske Veritas (DNV) published a design code for the design of offshore wind turbine structures (DNV, 2004) and recent research (Offshore Centre Denmark, 2006) presented state-of-the-art knowledge and methods to estimate local scour depths at monopiles located offshore.

The development of offshore wind farms, potentially, requires the investigation of two principal scour issues. Firstly, the scour related to the presence of a pipeline/cable and secondly, the scour due to the presence of the turbine structures, whether that is a single pile structure, gravity base or hybrid design (e.g. tripod structure). In addition, there is the potential issue of short-term scour around the vessels or structures used during the construction phase of the work.

The local scour processes need to be considered in the light of changes in bed level occurring at a regional scale – i.e. erosion, leading to bed lowering, or deposition, leading to accretion – or lateral movement of sandbanks, sandwaves or channels leading to changes in bed level at the foundation or along a cable route.

4.3 THE AVAILABLE DATASET

We have constructed a dataset of key parameters from the SED01 database for each foundation that was surveyed. The scour dataset was specified as needing to comprise:

- Structure information – dimensions and installation date
- Environmental data – water depth/variation, current (tide/surge), waves (height/period), sediment type (particle size, depth of sediment thickness), bedforms
- Depth of scour at structure – defined as depth of hole below surrounding local seabed level at the time of survey
- Maximum extent and minimum extent of scour hole – total diameter including the structure, asymmetry of scour pattern and heading of asymmetry

A summary of the environmental data is available in the SED01 report (HR Wallingford, 2006) and only a broad categorisation of environmental conditions was required for the present analysis. In some specific cases where the data has been compared with available predictive methods, environmental data has been used. The dataset has the following general format with information listed in columns beneath relevant headings:

DTI SED02
Site SITE **Date compiled:** DATE
Monopile diameter (m) **By:** NAME

Survey date	Pile Nr/ID	Ambient bed level	Scour protection	Deepest bed level	Scour depth	Maximum radius	Minimum radius	Orientation of maximum radius	Bedforms	Comment
(dd-mm-yy) or as given by data provider		(m wrt datum)	(y or n)	(m wrt datum)	(m)	(m)	(m)	(deg clockwise from north)	(short description - height, wavelength)	(e.g. very asymmetric, one deep spot, is bedform encroaching on scour hole)

The dataset includes information on the structure dimensions (and type if not a monopile foundation), the ambient and local scoured seabed level around the foundation – hence the scour depth is calculated directly – and the extent of scouring. A record is available for each foundation that has been monitored. Information on bedforms are included, if present, and other comments made as relevant. The dataset also records in which surveys bed protection was present and scour parameters adjacent to the scour protection have been extracted. Care must be taken not to draw conclusions on foundation scour from the scour depths obtained with scour protection in place. For sites with multiple surveys the dataset has been used to investigate spatial and temporal variations in scour development; although the time period of observations is usually at around six-monthly intervals so short-term changes are not captured in the dataset.

The wind farm projects included in the dataset are:

- Barrow
- Kentish Flats
- Scroby Sands
- North Hoyle
- Arklow Bank.

This list of sites for which it was possible to analyse and incorporate data was finalised by the project team on 11 October 2006. This precluded the use of the Scarweather project data, which was not released for use until the beginning of 2007. However, a conference paper describing some of the scour measurements around the met mast at Scarweather was used to provide a review of scouring at this site.

4.4 ANALYSIS AND INTERPRETATION OF DATA ON SCOUR AT BUILT ROUND 1 PROJECTS AND OTHER BUILT EUROPEAN PROJECTS

In general, the sites (Figure 1) are characterised as follows with a review having been completed of the various aspects of the scour and scour protection. In reviewing the dataset a short description and analysis of each project was carried out to discuss whether scour was observed, the characteristic dimensions and variations observed. Owing to the amount of contrasting information available it was not possible to make a consistent format for presentation and evaluation in each case. However, the most relevant information relating to scour has been brought together for each site. These are all sites with monopile foundations:

- Barrow
    - exposed to waves, moderate currents, sand/gravel and clay, stable seabed environment, deep water
    - a review of the scour at this site is included in Annex 5
- Kentish Flats
    - exposed to waves, moderate currents, fine sand, stable seabed environment, shallow water
    - a review of the scour at this site is included in Annex 6
- Scroby Sands
    - exposed to waves, strong currents, sand, dynamic seabed environment, shallow water environment, presence of bedforms
    - a review of the scour at this site is included in Annex 7
- North Hoyle including met mast
    - sheltered to waves, moderate currents, stable seabed environment, deep water
    - a review of the scour at this site is included in Annex 8

- Arklow Bank
  - exposed to waves, strong currents, sand/gravel, dynamic seabed environment, shallow water
  - a review of the scour at this site is included in Annex 9.

Figure 1: Location of built windfarms included in the present review of scour.

Data from met masts has also been included for Scarweather (Annex 10) and North Hoyle (Annex 8). The Scarweather site is exposed to waves, strong currents, medium sand, dynamic seabed environment, shallow water.

The Annexes to the present report are intended to be read in a standalone fashion. The overview and synthesis of the data listed above has been carried forward to the Milestone 2 project report. This draws out the key points from examination of the combined dataset and investigates similarities and differences between the sites associated with the depth and extent of scour, and the rate of scouring where that data is available.

4.5 ANALYSIS AND INTERPRETATION OF DATA ON SCOUR PROTECTION AT BUILT ROUND 1 PROJECTS AND OTHER BUILT EUROPEAN PROJECTS

The influence of scour protection on scour development has been examined for each of the sites based on the reviews listed in Section 4.3. The role of appropriate scour protection in helping foundation stability is understood, but as to the secondary effect on the surrounding seabed and the long-term stability of the scour protection, those are aspects that need further investigation.

The type of information that has been examined for the datasets available to SED02 is whether scour protection was installed, if so was it installed at all foundations, what type of protection was installed (static/dynamic/other), and the stone size, volumes, methods of placement. Also it is important to determine whether the scour protection was installed prior to foundation installation, immediately after foundation installation, or after some time had elapsed time since pile installation.

To summarise the situation with respect to installed scour protection the following list indicates whether scour protection is present or not (Yes/No) at the times for which the last datasets at each site were available to the present study:

• Barrow	No
• Kentish Flats	No
• Scroby Sands	Yes
• North Hoyle including met mast	No
• Arklow Bank	Yes
• Scarweather Sands	No

The results of the analysis have been used to investigate the role of scour protection in causing scour in the surrounding seabed. The information contained in the Annexes to the present report is intended to be read in a standalone fashion. The overview and synthesis of the data on scour protection has been carried forward to the Milestone 2 project report.

4.6 ANALYSIS AND INTERPRETATION OF DATA ON SCOUR AND SCOUR PROTECTION AT OTHER STRUCTURES

We have reviewed and included short descriptions of the analysis relating to scour observed at:

- The N7 monopile structure in the Dutch Sector of the North Sea (Annex 11)
- The scientific monitoring mast in the Otzumer Balje tidal inlet, Netherlands (Annex 12)

4.7 ALTERNATIVE FOUNDATION OPTIONS AND ALTERNATIVE PROTECTION MEASURES

We have examined the limitations of the conclusions that have been drawn. For example, limitations arise because not all the proposed foundation types for wind farms have been examined within the available dataset. The sites analysed are all for the case of monopile foundations (of varying diameters). Scour data is not available from built wind farm installations for hybrid (e.g. tripod), gravity base, or suction caisson foundations. There is one set of scour data around the North Hoyle met mast which is a tripod structure. The observed local scour depth in 2004 (Annex 8) in absolute terms was comparable to the scour at the wind farm monopiles.

The scour protection at Scroby Sands and Arklow Bank has been formed from rock dump laid post foundation installation. Apparently, the scour protection for Burbo Bank (data not available to this review) was pre-installed and the foundation was installed through the scour protection.

There are other options for scour protection such as the frond mattresses proposed for the Cape Cod wind farm off the USA east coast. Apparently this type of installation has been tested on the environmental monitoring tower at that site but at present information on the performance of that system is not available to the project.

Also, sandbags have been used in offshore situations with mixed success (Whitehouse, 1998). Recently, work has been conducted on the use of geotextile sand filled bags for offshore wind farm foundation scour protection. Results were obtained from work undertaken in the large wave flume in Germany (the GWK) on the use of geotextile sand containers (sand bags) as scour protection for the Butendiek wind farm (Grune et al, 2006). The stability of these containers under varying wave conditions and with varying levels of sand content and placement strategies was tested.

5. Taking the results forward

Based on the datasets in this report we have been able to draw conclusions on the analysis of scour related to the influence of:

- Sediment type including fine grained sediments
- Water depth
- Current regime
- Wave regime
- Scour protection.

These are presented in the report for Milestones 2 and 3.

6. References

CEFAS (2006). Scroby Sands Offshore Wind Farm – Coastal Processes Monitoring. Final Report AEO262 prepared for Marine Environment Division, Defra and Department of Trade and Industry. April 2006.

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Herbich, J.B., Schiller, R.E., Watanabe, R.K. and Dunlap, W.A. (1984). Seafloor Scour: Design Guidelines for Ocean-founded Structures. Marcel Dekker Inc., New York. xiv + 320pp.

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HR Wallingford (2006). SED01 - Review of Round 1 scour monitoring data- lessons learnt. Report produced by HR Wallingford and ABPmer. Technical Note DKR3990-01.

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Whitehouse, R.J.S. (1998). Scour at Marine Structures. Thomas Telford, London.

Annexes

Annex 1 Scour processes

Processes of scour

Placing a structure in the marine environment will lead to a change in the flow pattern in its immediate locality due to its presence. These changes will result in one or more of the following occurring:

- Flow contraction
- Horseshoe vortex formation in front of the structure
- Lee-wake vortices behind the structure (with or without vortex shedding)
- Reflection and diffraction of waves
- Wave breaking
- Turbulence generation
- Pressure differentials in the soil leading to liquefaction

With the occurrence of these phenomena there is usually an observed increase in the local sediment transport capacity and, therefore, an increased tendency to scour, i.e. a localised lowering of the seabed around the foundation. Therefore, an understanding of the scour potential is important in the context of offshore wind farms since it may lead to some or all of the following:

- Compromised structural stability of the turbines
- Increased sediment transport (both suspended and bedload), including transfer of sediment between coastal areas
- Development of freespans for infield or export cable route

Scour processes in the marine environment are more complex than that due to steady flow alone (e.g. rivers) due to the effect of waves and the combined effect of currents and waves. Herbich (1981) and Herbich *et al.* (1984) presented results from some of the first detailed investigations on the impact of scour on marine structures. Much of their work was based on empirical type design rules since knowledge of many of the hydrodynamic processes was still poorly understood. More recently, Whitehouse (1998) presented a review of the developments in scour into the 1990’s, whilst Sumer and Fredsøe (2002) have provided a comprehensive account of scour at marine structures, incorporating state-of-the-art knowledge. Det Norske Veritas (DNV) published a design code for the design of offshore wind turbine structures (DNV, 2004) and recent research (Offshore Centre Denmark, 2006) presented state-of-the-art knowledge and methods to estimate local scour depths at monopiles located offshore.

The development of offshore wind farms potentially requires the investigation of two principal scour issues. Firstly, the scour related to the presence of cable(s) and secondly, the scour due to the presence of the turbine structures, whether that is a single pile structure, gravity base or hybrid design (e.g. tripod structure). In addition, there is the potential issue of short-term scour around the vessels or structures used during the construction phase of the work.

The local scour processes need to be considered in the light of changes in bed level occurring at a regional scale – i.e. erosion, leading to bed lowering, or deposition, leading to accretion – or the lateral movement of sandbanks, sandwaves or channels leading to changes in bed level at the foundation or along a cable route.

References:

Det Norske Veritas (2004). *Design of Offshore Wind Turbine Structures*. Offshore Standard DNV-OS-J101, 138pp.

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Annex 2 Review of DNV guidance

DNV - Offshore Standard DNV-OS-J101 Design of Offshore Wind Turbine Structures:

Section 10 of the guidance deals with foundation design and looks at pile and gravity type foundations as well as the stability of the seabed. With specific reference to scour the guidance notes the following:

> "*The risk for scour around the foundation of a structure shall be taken into account unless it can be demonstrated that the foundation soils will not be subject to scour for the expected range of water particle velocities.*
>
> *The effect of scour, where relevant, shall be accounted for according to at least one of the following methods:*
> 1. *adequate means for scour protection is placed around the structure as early as possible after installation.*
> 2. *the foundation is designed for a condition where all materials, which are not scour-resistant, are assumed removed*
> 3. *the seabed around the structure is kept under close surveillance and remedial works to prevent further scour are carried out shortly after detection of significant scour."*

Appendix J of the DNV design standard provides a methodology for assessing scour around a vertical pile. However, no specific methodology is given for scour around gravity base, or non-standard type structures.

For vertical piles, the expression given for determining the equilibrium scour depth, *S*, under waves alone is valid for live-bed conditions:

$$\frac{S}{D} = 1.3\{1 - \exp[-0.03(KC - 6)]\} \qquad KC \geq 6$$

Where *D* is the diameter of the cylinder (in metres), and *KC* is the Keulegan-Carpenter number (a dimensionless parameter), which is defined by the equation:

$$KC = \frac{u_{0m}T}{D}$$

where u_{0m} is the maximum near-bed undisturbed wave velocity (m/s) and *T* is the peak wave period (s).

The above empirical expression for the equilibrium scour depth was proposed by Sumer et al. (1992).

Breusers *et al.* (1977) presented a simple expression for scour depth under live-bed scour for currents alone and this has been extended by Sumer *et al.* (1992) who assessed the statistics of the original data such that:

$$\frac{S_C}{D} = 1.3 + \sigma_{S/D}$$

where $\sigma_{S/D}$ is the standard deviation of S_C/D, with S_C being the equilibrium scour depth under steady flow and D the pile diameter. Based on experimental data $\sigma_{S/D}$ is taken to be 0.7. However, assuming $\sigma_{S/D}$ is zero gives:

$$\frac{S_C}{D} = 1.3$$

Therefore for a steady current KC approaches infinity and the equilibrium scour depth, S, approaches $1.3D$. Whilst under wave dominant conditions no scour exists when KC is less than 6. In addition, it is prudent to exercise caution for KC values above the upper boundary of those tested (i.e. $KC \geq 30$).

The width of the scour hole is estimated based on the angle of friction for the sediment and assumes that the slope of the scour hole equals this friction angle.

Most semi-empirical equations for scour, such as those listed above, are based on a theoretical understanding of the key processes calibrated with limited (often laboratory) data. The theoretical basis for scaling scour depth on pile diameter has been proven based on sediment transport theory. For large structures the scaling of the scour needs to take account of other factors such as the limiting effect of water depth, and, in the case of wave diffraction effects, need to be evaluated to ensure that the structure falls within the slender-pile regime. For more information the reader should consult the available literature referenced below.

The formulae given are based primarily on the work of Sumer *et al.* (1992). However, under steady flow or tidal conditions it is arguable that the work of Breusers *et al.* (1977) and more recently den Boon *et al*. (2004) is equally as valid and in many situations may provide a better fit to the observed data as this method allows for an adjustment with respect to water depth. The formula of Sumer *et al*. for scouring under waves is the principal approach used currently. However, as these empirical approaches are based on laboratory scale experiments there are still questions as to how well they perform under prototype conditions, which can only be resolved by evaluating them with field data of appropriate quality.

The DNV guidance document for wind farms provides no specific methodology for non-standard type structures or gravity base type structures. Existing guidance for offshore (oil and gas) structures may present relevant information in those cases.

References:

Breusers, H.N.C, Nicollet, G. and Shen, H.W. (1977). Local scour around cylindrical piers. *J. of Hydraulic Res.,* IAHR, Vol 15, No. 3, pp. 211-252.

Den Boon, H., Sutherland, J., Whitehouse, R., Soulsby, R., Stam, C-J., Verhoeven, K., Høgedal, M. and Hald, T. (2004). Scour Behaviour and scour protection for monopile foundations of offshore wind turbines. *Proceedings of the European Wind Energy Conference [CD-ROM].*

Det Norske Veritas (2004). *Design of Offshore Wind Turbine Structures*. Offshore Standard DNV-OS-J101, 138pp.

Sumer, B.M., Fredsøe, J. and Christiansen, N. (1992). Scour around a vertical pile in waves. *J. Waterway, Port, Coastal, and Ocean Engng.* ASCE, Vol. 118, No. 1, pp. 15 – 31.

Annex 3 Review of ETSU guidance

ETSU W/35/00596/00/REP - Potential effects of Offshore Wind Developments on Coastal Processes (Cooper and Beiboer, 2002):

The overall aim of the ETSU document was to identify, review and assess the potential effects on coastal processes related to the development of offshore wind farms around the UK coast. As part of this, Appendix G.4 contains a brief overview of the scour process with respect to offshore wind turbines. A variety of relationships are given in the text, but two empirical approaches are outlined in more detail: the work of Eadie and Herbich (1986) and that of Johnston and Erasito (1994). As pointed out in the report, the Eadie and Herbich method may have limited applicability to prototype scale due to the low Reynolds numbers used in their experiments. Therefore, the method put forward to assess the maximum scour depth under combined wave and current flows is that of Johnston and Erasito (1994).

$$S = \left(2.2x10^{-4}\right)\left(\frac{U_t D}{\nu}\right)^{0.619}$$

Where S is the equilibrium scour depth, D is the diameter of the cylindrical pile, ν is the kinematic viscosity and U_t is the combined wave-current velocity. For this assessment the pile diameter was taken as 3m. The equilibrium scour depth represents the maximum possible scour depth that may occur, having achieved this depth the hole may fill in again as the forcing conditions vary with time.

Within the Appendix are various examples of scour estimates made at comparable marine installations. The examples are taken from existing studies and come from a range of sources. Some of the values quoted are observed values, whilst others are estimates based on a variety of methods. The final example relates to Scroby Sands and makes use of the Johnston and Erasito approach. The method relies on the Herbich *et al.* (1984) expression for combined wave-current flow as well as the assumption that the maximum tidal stream velocity and predicted wave-induced current can be combined in a linear manner. The results yielded in respect to the velocities have no real physical meaning and, therefore, in this regard this approach is unsatisfactory (see below).

Herbich *et al.* (1984) gives the combined wave-current velocity, U_t as:

$$U_t = U + \pi H\left[\frac{1}{T} \pm \frac{U}{L}\right]\frac{\cosh\left[\frac{2\pi}{L}\left(\frac{H}{2}+h\right)\right]}{\sinh\left(\frac{2\pi h}{L}\right)}$$

where U is the freestream velocity, L is the wavelength, T is the wave period, H is the wave height and h is the still water depth.

The assessment makes use of the breaking criterion from basic wave theory and is based on the following expression:

$$H_b = \gamma h$$

Where h is the mean water depth, H_b is the breaking wave height and γ is the breaker height coefficient.

In coastal regions the depth of water governs the breaking wave height. The coefficient γ varies within the range 0.7 to 1.3 depending upon the beach slope and wave steepness. In this instance a value of 0.78 was used. However, this value should not necessarily be considered as a satisfactory value. McCowan (1891) proposed that a solitary wave breaks when the water particle velocity at the wave crest matches the wave celerity. This occurs at:

$$H_b = 0.78h$$

Laboratory experiments suggest that this value agrees better with oscillatory waves than for solitary waves, therefore, the choice of coefficient may also be questionable, but is within the range of normal values. Data from Scroby Sands provided by CEFAS indicates that waves are depth limited in the shallowest areas of the wind farm and that the local significant wave height is limited to around 0.6h.

For present purposes we have assumed the values used in the original ETSU report as follows:
H = 5.5m
T = 8.6s
h = 7.05m (calculated from the wave breaking criteria as 5.5/0.78)
L = 67m (using linear theory)

Maximum tidal stream velocity = 1.65m/s
Predicted wave induced current (linear wave theory) = 1.2m/s

$$U = 1.65 + 1.2 = 2.85\text{m/s}$$

Therefore U_t is determined as:

$$U_t = 2.85 + \pi 5.5\left[\frac{1}{8.6} \pm \frac{2.85}{67}\right]\frac{\cosh\left[\frac{2\pi}{67}\left(\frac{5.5}{2}+7.05\right)\right]}{\sinh\left(\frac{2\pi\times 7.05}{67}\right)}$$

$$U_t = 2.85 + 17.28\left[0.116 \pm 0.043\right]\frac{1.453}{0.710} = 2.85 + \left[4.1 \pm 1.5\right]$$

$$U_t = 8.5 \text{ or } 5.5\text{m/s}$$

Using Johnston and Erasito gives:

$$S = 2.2\times 10^{-4}\left(\frac{8.5\times 3}{10^{-6}}\right)^{0.619} = 8.45\text{m}$$

Which is equivalent to 2.8D. Since the ETSU report, Sumer and Fredsøe (2002) note that the behaviour of scour under combined wave and current flows switches between a wave-dominated regime where the vortex shedding is little influenced by the presence of a current to the current-dominated regime where the horseshoe vortex remains hardly influenced by the presence of the waves. Therefore, in an environment like Scroby Sands, it is considered that the greatest scour depth attained will be equivalent to that obtained under currents. Therefore, a better approach perhaps would be the adoption of the Breusers *et al.* (1977) methodology, whilst, still semi-empirical in its approach, it has a more physical meaning with respect to estimating the likely scour depth under currents. They presented a simple expression for scour depth under live-bed scour and this has been extended by Sumer *et al.* (1992) who assessed the statistics of the original data such that:

$$\frac{S_C}{D} = 1.3 + \sigma_{S/D} \qquad (3)$$

where $\sigma_{S/D}$ is the standard deviation of S_C/D, with S_C being the equilibrium scour depth under steady flow and D the pile diameter. Based on the experimental data available to them $\sigma_{S/D}$ was taken to be 0.7. For design purposes they recommend the maximum scour depth can be taken as 2 times the standard deviation, that is, 1.3 + 2 x 0.7. This gives a maximum equilibrium scour depth for a 3m pile (i.e. comparable to the ETSU report) of 8.1m.

Therefore, whilst it is considered that the Johnston and Erasito approach cannot be recommended as a method to be adopted for the estimation of equilibrium scour depth the two approaches give similar results for this example.

References:

Breusers, H.N.C, Nicollet, G. and Shen, H.W. (1977). Local scour around cylindrical piers. *J. of Hydraulic Res.,* IAHR, Vol 15, No. 3, pp. 211-252.
Cooper, B. and Beiboer, F. (2002). Potential effects of offshore wind developments on coastal processes. Report produced for ETSU by ABPmer and Metoc. Report ETSU W/35/00596/00/REP.

Eadie, R.W. and Herbich, J.B. (1986). Scour about a single, cylindrical pile due to combined random waves and currents. *Proc. 20th international conference on coastal engineering,* ASCE, Nov 9-14; pp. 1858-1870.

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Johnston, A.J. and Erasito, S. (1994). Scour in the vicinity of piles. *Proc. Int. Conf. on Hydraulics in Civil Engng.,* Brisbane, pp. 315-320.

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Annex 4 Summary of relevant FEPA/CPA guidance

OFFSHORE WIND FARMS
Guidance note for Environmental Impact Assessment in respect of FEPA and CPA requirements
Version 2 - June 2004
Prepared by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) on behalf of the Marine Consents and Environment Unit (MCEU)

The full reference can be found at:

http://www.cefas.co.uk/publications/files/windfarm-guidance.pdf

The sections dealing with scour are highlighted below in <<red>>.

3 Coastal & Sedimentary Processes

3.1 Aims & Scope

All developments should be assessed according to the following:

- on a **site-specific** basis,
- to include **direct impacts** on hydrodynamics and sediment dynamics, and
- to include **indirect impacts** of these on other disciplines (e.g. benthos, fisheries, coastal protection, water quality, sediment quality, conservation-designated sites).

For any wind farm proposal it is necessary to assess the magnitude, and significance of change, caused directly to the following:

Sediments
(e.g. composition, geochemical properties, contaminants, particle size) – sample collection may usefully be combined with the benthic sampling programme.
Hydrodynamics
(e.g. waves, tidal flows) – using surface and/or seabed-mounted buoys, ADCP. [*Note: It is important that all field data provide information on seasonal variations such as calm and storm events; therefore, deployment may be for weeks or months at a time*.]
Sedimentary environment
(e.g. sediment re-suspension, sediment transport pathways, patterns and rates, and sediment deposition) – using charts, bathymetry, side-scan sonar. [*Note: The large-scale sediment transport patterns in many of the Round 2 offshore wind farm sites have not been traditionally monitored, and may, therefore, be relatively unknown, which means that new field studies are essential to provide both baseline understanding and validation of any numerical modelling studies*.]
Sedimentary structures
(e.g. channels, banks, large-scale bedforms, bioturbation, depth of mixed layers).
Suspended sediment concentrations
(SSCs) – using adequately calibrated instrumentation.

Consideration of the above issues should be made with respect to the following:

Spatial scales:

- Near-field (i.e. the area within the immediate vicinity of the turbine grid)
- Far-field (e.g. the coastline, sites of scientific and conservation interest)

Consideration of the above issues should be made with respect to the following:

Periods and timescales:

- Baseline conditions.
- Development "construction" phase.
- Development "post-construction" phase.
- Sedimentary "recovery" phase, or period during which a new equilibrium position is attained with the wind array in place.
- Long-term "lifetime" of the wind array.
- Development "post-decommissioning" phase, with wind array no longer in place.

3.2 Baseline Assessment

In order to assess potential impacts the developer must first fully understand the natural physical environment of their site and the surrounding area, including:

- Identification of processes maintaining the system, reasons for any past changes, and sensitivity of the system to changes in the controlling processes.
- Identification and quantification of the relative importance of high-energy, low frequency ("episodic" events), versus low-energy, high frequency processes.
- Identification of the processes controlling temporal and spatial morphological change (e.g. longevity and stability of bedforms), which may require review of hydrographic records and admiralty charts.
- Identification of sediment sources, pathways and sinks, and quantification of transport fluxes. [*Note: Any numerical models should be validated and calibrated, and should present field-data in support of site conditions, boundary conditions, complex bathymetry, flows and sediments, to include measurements of hydrodynamics, and suspended sediment, in order to demonstrate accuracy of model performance, and should include sensitivity analysis or estimate of errors in order to enable confidence levels to be applied to model results*.]
- Identification of the inherited geological, geophysical, geotechnical and geochemical properties of the sediments at the site, and the depth of any sediment strata. [*Note: A sediment sampling campaign (including surface samples and cores) should have far-field spatial coverage and include the range of sedimentary environments, with consideration of the controlling hydrodynamic flows, sediment pathways and sites of particular interest.*]

3.3 Impact Assessment

With knowledge of the site and its surroundings, informed by the above baseline assessment, the magnitude and significance of the impact of the development may be quantitatively and qualitatively assessed using hypothesis-driven investigation. This assessment should specifically include an assessment of the following:

- Scour around turbine structures and the justification and requirements, if any, for scour protection material.

- Scour around any supply cables overlying the sediment surface and the resulting potential for higher SSCs, and the development of "free-spans" in the cable.

- Spatial design of the turbine grid array and the subsequent effect on the spatial distribution of wave patterns, tidal flows, and sedimentation (within the nearfield), and additionally on wave direction and wave energy (at far-field and coastal sites).

- Non-linear interaction of waves and currents and the subsequent quantification of the extent to which bed sediment is mobilised.
- Sediment mobility and the natural variability of sediment depth within the nearfield and the effect on turbine strength/ stability, choice of foundation material and turbine structure, and burial depth for any cables.
- Effect of cable laying procedure on local levels of SSCs.
- Assessment of the scales and magnitudes of processes controlling sediment transport rates and pathways. This may also include mixed seabeds (silts, sands and gravels), and therefore any interpretations from numerical model output should acknowledge and assess the effect of any differences in sediments (between model and actual), particularly when assessing the significance of transport fluxes.
- Assessment of the impacts of climate change on the sedimentary processes, e.g. changes in wave height, direction, and frequency of occurrence.

CEFAS and the Environment Agency can advise on site specific issues and help to identify data sources. A useful starting point for CEFAS data is:
http://www.cefas.co.uk/data.htm

3.4 Survey Design

Survey specifications should be submitted to the MCEU who will seek scientific and nature conservation advice (from CEFAS, Environment Agency and the Conservation Agencies) to ensure that data and analyses are adequate to meet the regulatory requirements. However, the onus is on the developer and their environmental consultants to design the plan of works. The developers and their consultants should, therefore, only contact MCEU once they have devised a plan of works (including the collection of new data and computer modelling) to address the issues identified in this section. At the scoping discussions, MCEU (in consultation with CEFAS) will comment on whether or not the proposed tools are fit for purpose to ensure that the data are of sufficient quality to be used to assess the potential environmental impacts. Any computer modelling must be calibrated (and subsequently validated) with site specific data to assess the potential impacts of:

- Presence / absence of the wind farm
- Effects of different numbers of turbines and layouts
- Seasonal differences including storm events
- Wave diffraction (including effects of wind forcing)

These survey specifications must clearly state the issues to be investigated, set hypotheses concerning the potential environmental impacts of the development to inform a detailed rationale to explain the choice of techniques to be utilised. They should describe in detail:

- Data collection techniques
- Data standards
- Analytical techniques
- Statistical techniques
- Quality control

Although not produced for the offshore wind industry the document ‘Guidelines for the conduct of benthic studies at aggregate dredging sites, DTLR May 2002’ provides a useful insight into the techniques, equipment and design of marine seabed and oceanographic surveys. This document can be downloaded at:

http://www.cefas.co.uk/publications/files/02dpl001.pdf

3.5 Mitigating Actions

Where there may be sedimentary concerns regarding issues documented within the ES, particularly with results of any predictive modelling studies, a requirement for monitoring, both during, and following construction may be incorporated into the conditions of the FEPA licence.

3.6 Monitoring

The Environmental Statement must include recommendations for future monitoring of the identified potential impacts of the wind farm, these proposals must be hypothesis driven with measurable outputs.

Annex 5 Barrow dataset

Barrow Offshore Wind Farm Scour

Barrow Wind Farm

Barrow Offshore Wind Farm is situated about 8km SW of Walney Island in the Irish Sea (Figure 1). Thirty monopile foundations have been placed within the site, each of 4.75m diameter, D. The geophysical and sediment sample surveys undertaken by Titan Environmental Surveys Ltd, in 2002 showed that the seabed at the wind farm site consists mainly of sand with concretions overlying tillite and clays, except in the shallower south east corner of the site, where exposures of tillite and clays dominate and the surface sand becomes patchy. The depth of surface sediment reached 10m in the north-west but this depth includes bedded muddy sands as well as the surface layer of sand. A further pre-construction geophysical survey was carried out in 2005 by Osiris Projects (Report C5002, May 2005) which confirmed the earlier distribution of sediment.

Calibrated numerical modelling (HR Wallingford, 2002) showed that the tidal currents ran approximately E – W over the wind farm. Peak spring and neap current speeds at the site were reported to be 0.67m/s and 0.34m/s (HR Wallingford, 2004). The 1-year return period significant wave height, H_s, is 4.8m at the western edge of the wind park, with a corresponding peak wave period of T_p = 9.8s. A significant wave height of 0.5m is only exceeded 25% of the time.

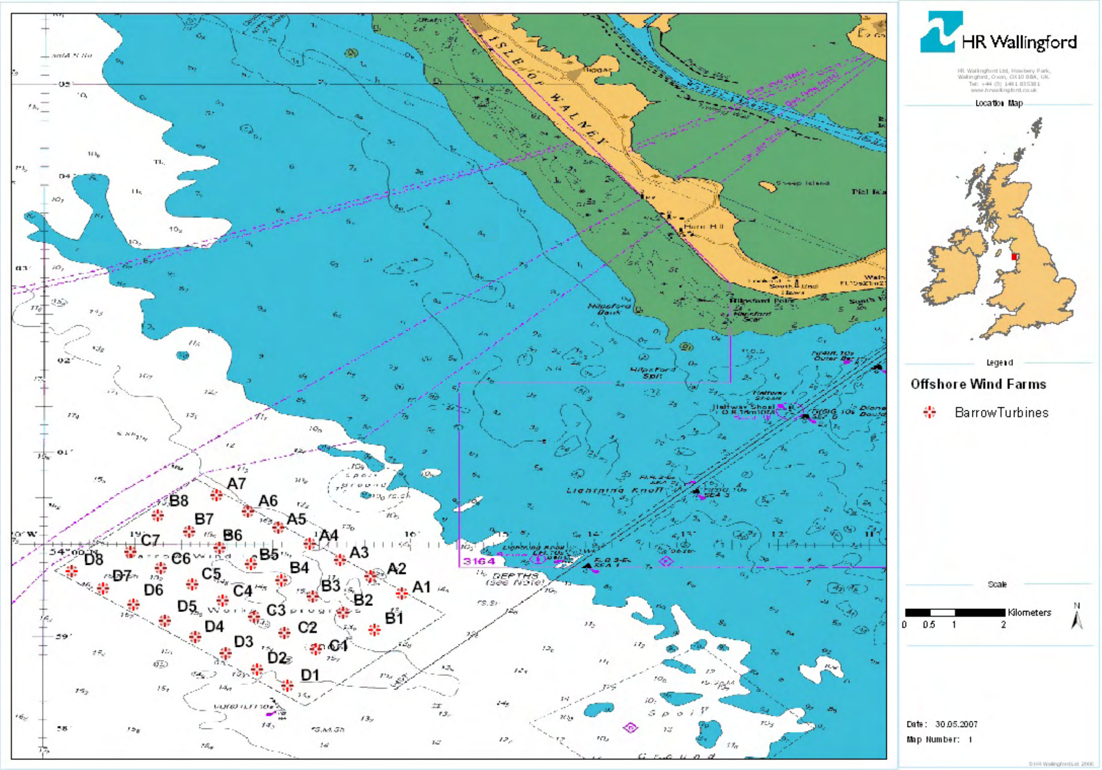

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Figure 1: Location map for Barrow windfarm turbines.

Measured Scour 2005

The installation of the monopiles began in May 2005 and continued for over three months. No scour protection was installed. Titan Environmental Surveys Ltd (2005) conducted a multibeam echosounder Scour Pit Survey around 13 of the monopiles of the wind farm site on 23 July 2005, commissioned by Vestas / KBR. This provided detailed information on the bathymetry and seabed morphology around the installed turbines, during the installation period.

Table 1 gives the ambient bed level, scour depth, maximum and minimum radius of the scour hole and the number of days between the date the foundation was established and the scour survey. The maximum and minimum radii were determined by measuring the maximum and minimum distance from the outer wall of the monopile to the point where the scour hole reached the ambient bed level, determined from the scour survey. Table 1 also includes the type of surficial sediment (Osiris Projects, 2005) and the approximate depth of the surficial sediments (Titan Environmental Surveys Ltd, 2002 drawing CS0036/D6/V1). Note that the negative number of days to survey in Table 1 is correct as the date the foundation was established is the last day that work was done, so clearly Turbine 08 was worked on for over 17 days.

Table 1: Scour depths, July 2005.

Pile Nr/ID	Ambient bed level	Scour depth, S	Maximum radius	Minimum radius	Days to survey	Surficial sediment	Depth of surficial sediment
	(m CD)	(m)	(m)	(m)			(m)
T-01	-17.1	1.8	9.1	5.9	53	Sand	10.0
T-04	-16.4	1.3	6.9	4.7	24	Sand	9.0
T-08	-15.6	0.8	9.8	5.0	-17	Sand	2.0
T-18	-15.5	2.1	9.8	6.6	46	Sand	2.5
T-20	-15.4	0.8	10.0	4.9	44	Sand	1.0
T-21	-15.85	0.25	8.6	6.1	37	Sand	0.1
T-24	-15.8	0.1	5.9	1.7	59	Glacial till	0.0
T-25	-16.2	0.2	6.1	2.4	54	Glacial till	0.0
T-26	-15.85	0.7	9.1	5.1	62	Sand	0.2
T-27	-15.5	0.8	15.7	5.1	41	Sand	0.5
T-28	-12.5	0.0	0.0	0.0	34	Glacial till	0.0
T-29	-14.5	0.1	1.2	0.0	32	Glacial till	0.0
T-30	-14.15	0.0	0.7	0.0	19	Glacial till	0.0

Scour depth is plotted as a function of ambient bed level in Figure 2. Mean Sea Level is 5.1m above CD.

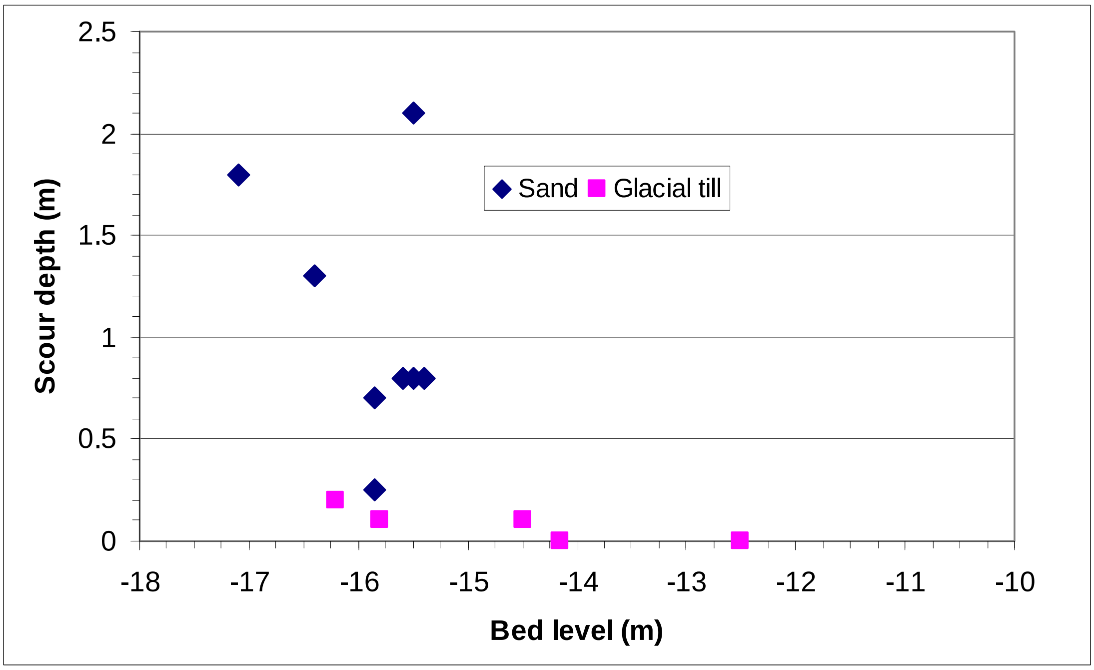

Figure 2: **Scour depth as a function of bed level for sand and glacial till seabeds.**

Figure 2 and Table 1 show that the scour depth is strongly dependent on the seabed type. All the scour depths in glacial till were lower than the scour depths in sand. The lowest scour depth in sand occurred for Turbine 21, where the depth of surficial sediment was estimated to be similar to the depth of scour. Figure 3 shows the scour depth as a function of the number of days between establishing the foundation and the scour survey. A straight line was fitted to the scour depth in the glacial till as a function of time. This indicates that the scour depths increase with time e.g. at about 4mm per day for one of the turbines but with a delay until the scour was picked up by monitoring. So deeper scour depths might be achieved in the future, although the monitoring data from 2006 shown later indicates a reduction in scour depth – possibly due to infilling of the scour footprint with mobile sediments from a veneer of sand. Figure 3 indicates that the maximum scour depths in the sandy seabed are deeper, but does not provide enough detail to evaluate the time for scour to develop to equilibrium. Continued monitoring of the scour depths at the monopiles is, therefore, advised.

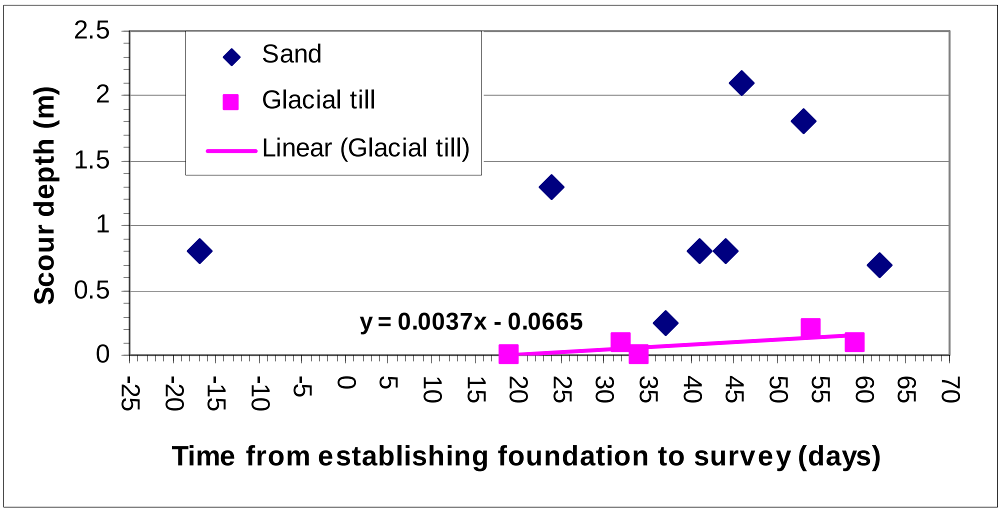

Figure 3: **Scour depth as a function of time from establishing the foundations.**

Measured Scour 2006

Osiris projects were commissioned to carry out a scour monitoring survey by RSKENSR Environment Limited in September 2006. The primary objective of the study was to map the post construction bathymetry within a series of 100m x 100m boxes, centred at each turbine, providing a detailed scour assessment.

Table 2 gives the ambient bed level, scour depth, maximum and minimum radius of the scour. The maximum and minimum radii were determined by measuring the maximum and minimum distance from the outer wall of the monopile to the point where the scour hole reached the ambient bed level, determined from the scour survey. Table 2 also includes the type of surficial sediment (Osiris Projects, 2005) and the approximate depth of the surficial sediments (Titan Environmental Surveys Ltd, 2002 drawing CS0036/D6/V1).

Table 2: Scour depths – September 2006.

Pile Nr/ID		Ambient bed level	Deepest bed level	Scour depth	Max radius	Min radius	Depth of surficial sediment
		(m wrt datum)	(m wrt datum)	(m)	(m)	(m)	(approx, m)
T-01	D8	-17.5	-22	4.5	1.1	2.0	10
T-02	D7	-17.5	-21.25	3.75	1.0	1.7	10
T-03	D6	-17.25	-21	3.75	1.1	2.1	9.4
T-04	D5	-17	-22.75	5.75	2.5	1.5	8.4
T-05	D4	-17	-21	4	1.0	2.6	6.2
T-06	D3	-16.5	-18.5	2	1.2	2.0	2.8
T-07	D2	-16.25	-17	0.75	1.2	2.0	1.8
T-08	D1	-16	-17.5	1.5	3.0	1.1	2
T-09	C7	-17	-21	4	1.1	2.0	9.2
T-10	C6	-17	-21	4	1.0	4.5	8
T-11	C5	-16.75	-18.5	1.75	0.9	1.9	3.9
T-12	C4	-16.5	-18.25	1.75	1.3	2.6	2.5
T-13	C3	-16.25	-18	1.75	1.0	3.8	2.1
T-14	C2	-16.25	-17.5	1.25	1.0	1.8	1.5
T-15	C1	-16.5	-17	0.5	0.8	2.0	1.1
T-16	B8	-16.25	-18.75	2.5	1.1	1.9	2.8
T-17	B7	-16.25	-18.25	2	1.8	2.2	2.7
T-18	B6	-16	-18.25	2.25	2.0	1.8	2.5
T-19	B5	-16	-17.5	1.5	0.8	1.7	1.5
T-20	B4	-16	-16.75	0.75	1.2	1.5	1
T-21	B3	-16.25	-16.25	0	0	0	0.2
T-22	B2	-15.5	-15.5	0	0	0	0
T-23	B1	-14.75	-14.75	0	0	0	0.1
T-24	A7	-16.25	-16.25	0	0	0	0

Pile Nr/ID		Ambient bed level	Deepest bed level	Scour depth	Max radius	Min radius	Depth of surficial sediment
T-25	A6	-16.5	-16.5	0	0	0	0
T-26	A5	-16.5	-17	0.5	4.0	0.5	0.2
T-27	A4	-16	-16	0	0	0	0.5
T-28	A3	-12.75	-12.75	0	0	0	0
T-29	A2	-15	-15	0	0	0	0
T-30	A1	-14.75	-14.75	0	0	0	0

Figure 4 compares the scour depths measured in July 2005 during the construction with the scour measured in September 2006 for 13 of the monopiles. Note that only 13 of the turbines had been installed at the time of the first survey. The turbines to the north and east (A1-A7) lie on glacial till, which does not appear to be easily eroded. Negligible scour has been measured during both of the surveys. This is not the case for turbines D5 and D8, where the scour depths have increased by 4.45m and 2.7m, respectively. These two wind turbines lie to the west, where the seabed is fine to medium sand. The scour around turbine B6 appeared largely unchanged (~2.25m) this is due to the thickness of the surficial sediment which is limited to ~2.5m.

The key parameters that determine the amount of scour are the composition and thickness of the surficial sediment layer. Figure 5 shows the measured scour depths for all 30 of the monopiles with respect to the thickness of the surficial sediment layer. This shows that scour around some of the turbines has been restricted by the thickness of the surficial layer. These generally lie to the east, where the seabed consists of glacial till. The turbines that have experienced the greatest seabed scour are those which lie to the west, where the bed consists of fine to medium sand and the thickness of the surficial layer is greatest.

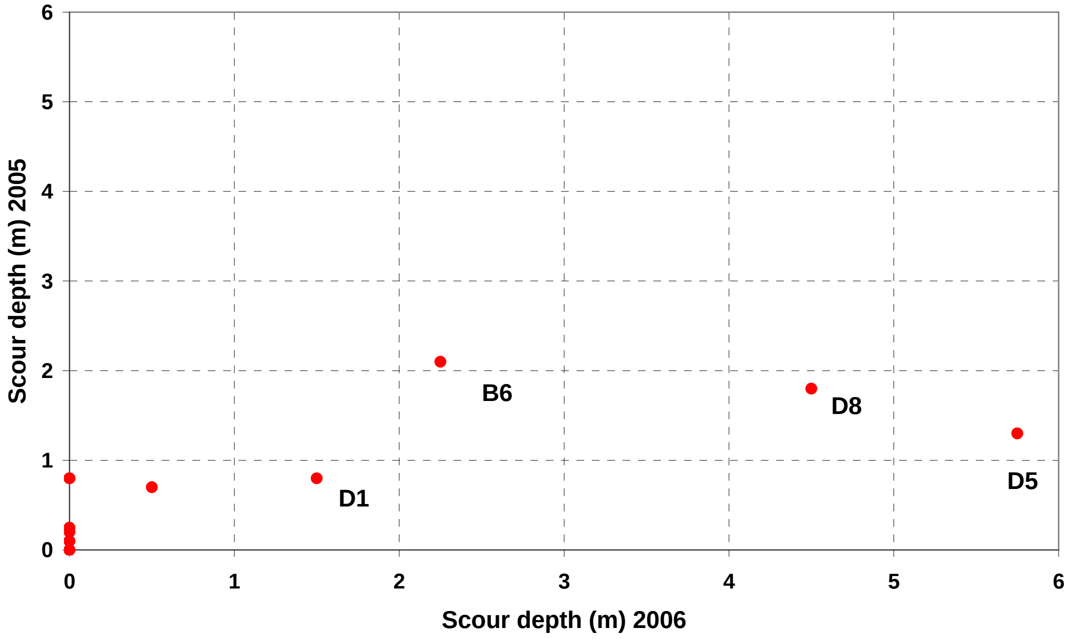

Figure 4: Comparison between scour depths measured during July 2005 and September 2006.

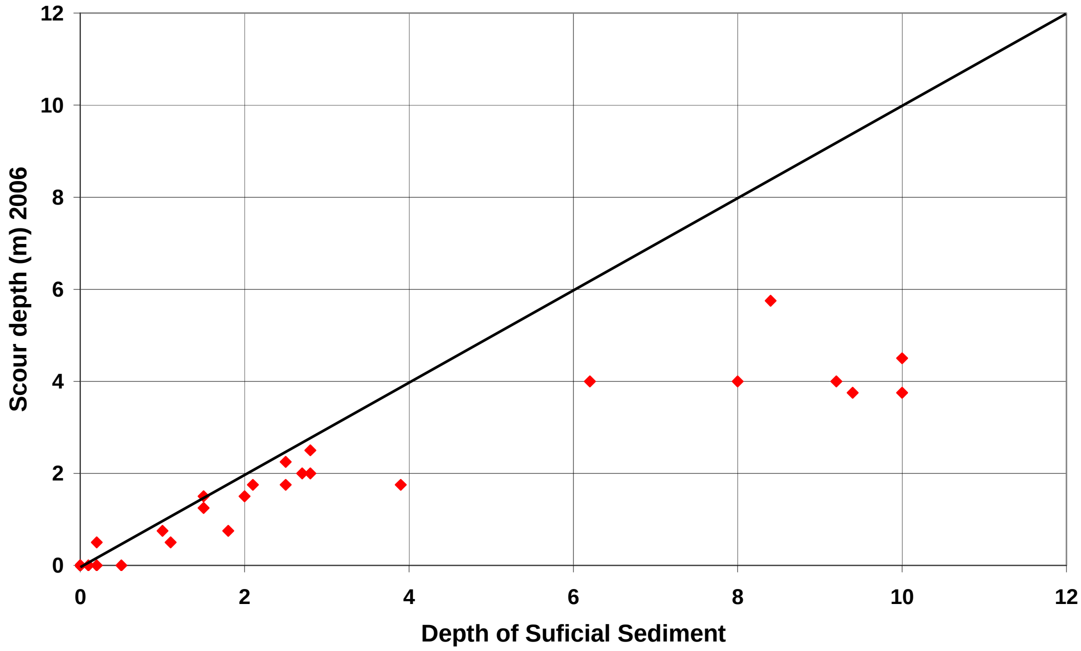

Figure 5: **The scour depths measured in September 2006 with respect to the depth to the surficial sediment layer.**

Predicted Scour

The maximum scour depth in July 2005 was S/D = 0.44, which is considerably lower than the DNV guidelines (S/D = 1.3 ± 0.7). This corresponded well with the predicted scour depth S/D = 0.5 (HR Wallingford, 2002), which was an engineering judgement with evidence available at that time based on observed scour depths for a large pile in a sandy seabed.

A subsequent scour assessment (HR Wallingford, 2004) conducted using the OptiPile design tool for sandy seabeds (Den Boon et al, 2004) predicted much larger potential scour depths, with S/D = 1.54 for peak spring tides and S/D = 1.05 for peak neap tides. These figures reduced with the addition of waves. The maximum scour depth in September 2006 was S/D = 1.21, which lies closer to the DNV guidelines value and between the two OptiPile values.

Wave heights, periods and directions were downloaded from the Liverpool Bay WaveNet[1] buoy (http://www.cefas.co.uk/wavenet/) for the construction period until the scour survey. This showed that the scour survey was conducted on a calm day (H_s increasing from 0.1m to 0.5m through the survey) that followed three days with wave heights almost continuously over 1m, with a highest wave height of 2.2m and an average of around 1.5m for the period.

The highest wave and corresponding measured wave period were used to calculate a root-mean-square (rms) wave orbital velocity at the seabed of 0.09m/s at Turbine T-01. The peak spring tidal current speed of 0.667m/s and rms orbital velocity of 0.1m/s were entered as the maximum ranges in the Opti-Pile Design Tool with sediment d_{50} = 0.09mm and d_{84} = 0.15mm (obtained from a borehole sample taken at the location of turbine T-01, HR Wallingford, 2004, Table 4). The calculated scour depths are shown in Table 3 for a range of conditions between zero current

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and wave orbital velocities and the maximum during the period. The highlighted results are those that gave a lower scour depth than the observed maximum. Table 3 indicates that deeper scour than the maximum observed was predicted for a steady current of 0.335m/s, which is lower than the peak neap tide current speed.

Table 3: OptiPile Design Tool predictions of scour depth in fine sand. Highlighted results are lower than the maximum observed scour depth.

Wave	Current speed					
Urms	0.201	0.268	0.335	0.402	0.536	0.67
m/s	(ms^{-1})	(ms^{-1})	(ms^{-1})	(ms^{-1})	(ms^{-1})	(ms^{-1})
0	0.000	0.854	2.903	4.953	7.344	7.344
0.020	0.000	1.352	3.131	5.038	7.013	7.128
0.040	0.594	1.795	3.354	5.121	6.616	6.861
0.050	0.838	1.970	3.452	5.158	6.417	6.723
0.060	1.018	2.115	3.538	5.192	6.222	6.584
0.080	1.244	2.324	3.676	5.046	5.846	6.309
0.100	1.361	2.448	3.768	4.596	5.496	6.043

Possible reasons for over prediction of scour

The DNV scour estimate and the OptiPile Design Tool were derived from physical model tests of scour around a monopile in a fine non-cohesive sand bed. Therefore, they only apply to non-cohesive fine sand beds. The material will start to exhibit cohesive behaviour when there is 5% to 10% of cohesive material in the mix. Generally this means when there is 5% to 10% (or more) of clay (d < 0.002mm).

HR Wallingford (2004) reported that sample B4 from the borehole at turbine T-01 had 11% of material by weight with a diameter less than 0.002mm. The effect of this will be to increase the resistance to scouring and also the length of time it will take to form an equilibrium scour hole. It will not necessarily reduce the maximum depth of scour hole that may be attained. Continued monitoring of the scour depths at the monopiles is, therefore, advised.

Another possible explanation for the lower scour depths is that for neap tides sediment will be mobilised for only a short period of the tidal cycle, while for spring tides the sediment will be mobile around the monopile for perhaps half the tidal cycle.

Clay within some of the borehole samples had a shear strength of order 100kPa. HR Wallingford (2004) concluded that the erosion of clay may be initiated by the hydraulic forces at a 1-year return period or higher, particularly as the factor for acceleration and turbulence due to the monopiles could easily equal 1.5. The erosion rate of exposed clay during the events that can cause erosion will be slow, of the order of one millimetre per hour. If the clay is fissured or has a rough surface, or if there is a thin veneer of mobile sandy sediment, then erosion may proceed more rapidly and at lower values of applied shear stress. HR Wallingford (2004) expected that the 100kPa clay at the site would limit the depth and rate of scour erosion around the pile foundations. This has been supported by the observed scour depths at the sites with a clay till seabed.

Conclusions and recommendations

Scour depths were measured at 13 of the Barrow Wind Farm monopiles in July 2005, i.e. within 9 weeks of finishing the installation of the first monopile. Scour depths up to S/D = 0.44 were observed in the sandy deposits in the west of the site. Much lower scour depths (up to S/D = 0.04) were measured in the glacial till to the eastern side of the wind farm. There was some indication that scour depths in glacial till and (to a lesser extent) in sand increased with time during the installation period.

The scour depths observed in the areas with a good thickness of sandy sediment in September 2006 had increased; the maximum value was S/D = 1.21.

The measured scour depths were over predicted by DNV guidelines and the OptiPile Design Tool. The most likely explanations for this are that:

- There is silt within the sand, which may make it cohesive;
- There are clay layers (some with shear strength of 100kPa) that will be resistant to erosion under normal circumstances between installation and monitoring;
- At some locations the thickness of sediment above the clay layer limits the scour development;
- Conditions were above threshold for only part of the tidal cycle.

To better understand the scour development with time the scour pits should be monitored again, at time intervals of 6 months to 1 year to ascertain whether the scour pits have increased in depth and extent or whether the values measured are representative of scour depths near equilibrium. Surveys at this interval will miss variations that occur over smaller time-scales associated with spring-neap tidal cycles and due to the influence of storm wave action. Understanding this temporal variation is important in evaluating how much variability might be expected on the periodic monitoring.

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Annex 6 Kentish Flats dataset

Site
On Sunday 22 August 2004 the large installation vessel "MPI Resolution" arrived at the Kentish Flats site with the first six foundations. The vessel was positioned at the most eastern position in the row nearest land and jacked itself out of the water by means of the six huge legs. On Tuesday 19 October 2004 the last of the 30 monopiles was installed. (source: Elsam A/S website, accessed 1 May 2007). The 30 installed turbines at locations shown on Figure 1 have 5 m diameter monopile foundations with a cable connection to shore at Herne Bay. The cable lay was completed in the autumn of 2005.

The water depths and general morphology can be described as 3m below LAT to 5m below LAT. It is an apparently stable and shallow plateau, with only superficial bedforms. The bed comprises of fine sand and shells as superficial cover offshore and nearshore. The sub-stratum is formed from firm London Clay near or at surface, except for in the palaeo-channel of the Swale which cuts across the site and is infilled by recent clays and sands.

The tidal regime has a range of 2.9m on neaps and 4.7m on springs. The current regime is characterised by a peak speed of 0.9m/s offshore and up to 0.5m/s along the cable route. The tidal flow is rectilinear and oriented west south-west to east north-east and has a weak rotational residual current.

Waves are from a north-easterly associated with wind sea dominated conditions with severe storms. Secondary, locally generated wind waves, also come from the north-west. The design conditions are (1:1 year) H_s=3.3m (depth limited at lower water levels) and (1:10 year) H_s=5.8m (depth limited). Breaking waves during severe conditions offshore and are common across the shallows on the cable route.

Scour assessment
HR Wallingford (2002) made a preliminary assessment of scour based on available research and experience. Scour to a depth of 1.5D vertically could be expected in areas of unrestricted fine sand. Scour would be less in areas limited by the substrate, but detailed field information on sub-strata was not available to the preliminary work.

Later work for the Environmental Impact Assessment (EIA; Emu, 2002) indicated competent clay near surface with little mobile material, except in the palaeo-Swale channel. Therefore, scour was expected to be minimal over the site, with some limited scour likely in the palaeo-channel infill material.

Scour protection was left as an option by the EIA and was not installed or planned at the time of writing the present report.

Monitoring
The MCEU /FEPA monitoring conditions in their licence were as follows:
- Post construction bathymetric survey of at least four foundations representative of the soil types; and,
- Six-monthly repeat bathymetric surveys over three years to assess the need for scour protection. Surveys to include the cable route.

The surveys completed to date are as follows:
- EIA (using a single beam echo-sounder in summer 2002);
- Pre-construction (swath bathymetry in August 2004)

- Three post-construction (swath bathymetry in January 2005, November 2005, April 2006)

The scour data was presented on paper charts and the scour depths were extracted for four foundations (Table 1). It is noted that charts plotted with contours at 0.5m intervals, or even 0.25m, would have made for an easier and more accurate assessment.

Summary of survey results
Scour pits around the monopiles were clearly visible in the surveys conducted. The time-series of scour depths at the four foundations that were monitored are shown in Figure 2 and indicate that there is not a large variation in scour depths with time. The scour increased slightly between post-construction Surveys 1 and 2, reaching a maximum depth of 2.3m over a footprint up to 10m total diameter. The scour pit slope angles were very steep at close to 1:1. Between Surveys 2 and 3 the scour depths diminished indicating that some transport and deposition had occurred across the site.

The four foundations monitored are all in one area of the site, selected as an area where scour might be expected according to information available at the time of planning the monitoring programme.

These results contradict the expectations for minimal scour based on the assumed firmness of the London Clay beds and expected resistance of the palaeo-Swale beds. The data in Table 1 has turbines E2 and F2, which are close to the alignment of the palaeo-Swale channel deposits which run in a meandering pattern across the site from the south-east to north-west. The turbines F3 and F4 are outside of these deposits. However, the surveys are only representative of one part of the site, so other areas may show different results.

Scour depths are slightly greater on their west and south-west side, but the footprints show no apparent elongation along any axis, apart from the footprint of the inter-turbine cable routes which run in a north-west to south-east direction in the area of the four monitored foundations.

During construction penetration of the legs of the jack-up barge led to the formation of depressions in the seabed. The pits created by the jack-up legs partially filled over the period of the three surveys, but were still clearly visible, indicating low sediment transport/deposition across the site. Also the inter-turbine cable routes are visible in the surveys as shallow depressions and mounds.

However, some further inspection might be beneficial to establish whether the monopile pits are indeed caused by scour, arising from hydraulic forces, or whether they were largely a result of surface deformation during pile penetration. Emu (2005) state that it is not evident whether the changes seen have been “caused by scouring or by the activities involved during the piling operation in the construction phase.”

Comparison with guidance
It is concluded that the scour formation is less extensive than would be evaluated based on the existing prediction using DNV (2004) of S/D = 1.3. This is probably due to the limited mobility of the sediment at the site.

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Table 1: Kentish Flats scour data extracted from surveys (2005-2006).

Survey date	Pile Nr/ID	Ambient bed level (m wrt CD)	Scour depth (m)
16-Jan-05	E2	-4.8	0.8
16-Jan-05	F2	-4.5	1.2
16-Jan-05	F3	-4.3	1.4
16-Jan-05	F4	-4.5	1.2
20-Nov-05	E2	-4.5	1.2
20-Nov-05	F2	-4.0	2.3
20-Nov-05	F3	-3.9	2.1
20-Nov-05	F4	-4.0	1.8
05-Apr-06	E2	-4.5	1.4
05-Apr-06	F2	-4.0	1.6
05-Apr-06	F3	-3.8	1.7
05-Apr-06	F4	-3.9	1.7

Note: see comments in text about cause of depressions

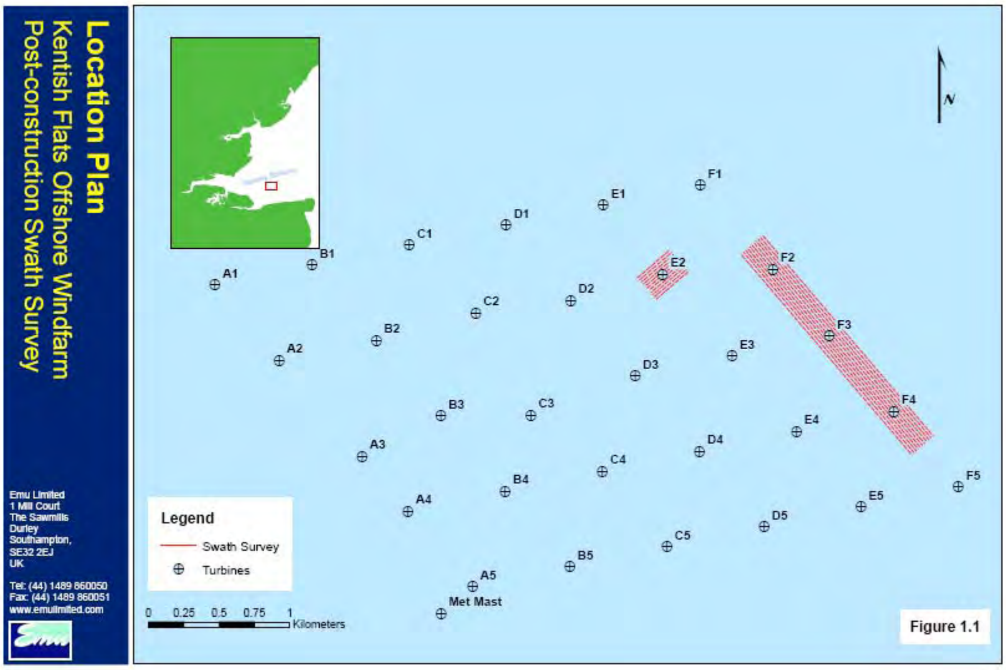

Figure 1: Kentish Flats wind turbine layout with highlighted area showing the turbine locations analysed in this report (Source of figure: Figure 1.1 from Emu, 2005)

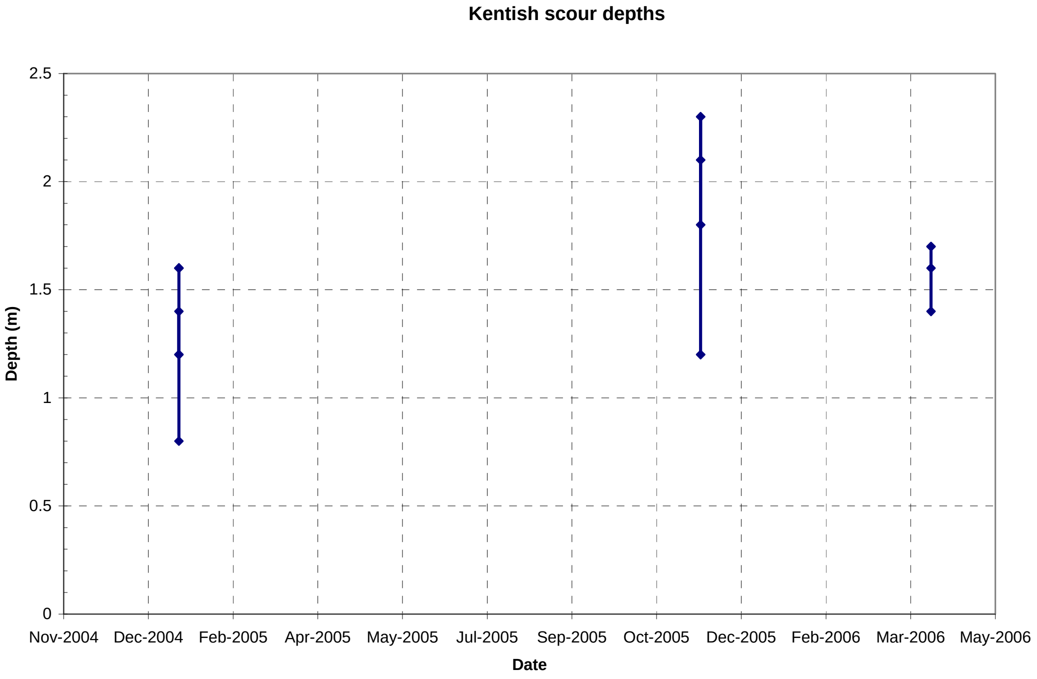

Figure 2: **Variation of scour depth in space and time at Kentish Flats Offshore Wind Farm for the four monitored foundations. At each date the scour depths are plotted as a vertical spread of datapoints (Note: see comments in text about cause of depressions).**

Annex 7 Scroby Sands dataset

Scroby Sand Offshore Windfarm

1. Introduction

The Scroby Sand Offshore Wind Farm (OWF) was developed by E.ON UK (formerly PowerGen Offshore renewables) and consists of 30 steel monopiles of diameter 4.2m driven into the seabed, typically up to 30m in depth below the seabed/water interface. Each monopile supports a tower and nacelle containing a 2MW Vestas V80 turbine and three blades. Scroby was the first OWF to receive planning consent through FEPA and CPA legislation as well as the Electricity Act.

Construction took just under a year with three export cables bringing power ashore (see (This product has been derived in part from material obtained from the UKHO © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office. Not to be used for navigation.)

Figure 1). The minimum distance between monopiles is 320m between turbines 17 and 21.

Table 1: Construction Timetable for Scroby Sands OWF.

Activity	Dates
Piling	Nov 2003 to Feb 2004
Turbines	April 2004 to May 2004
Intra array cables	May 2004 to Aug 2004

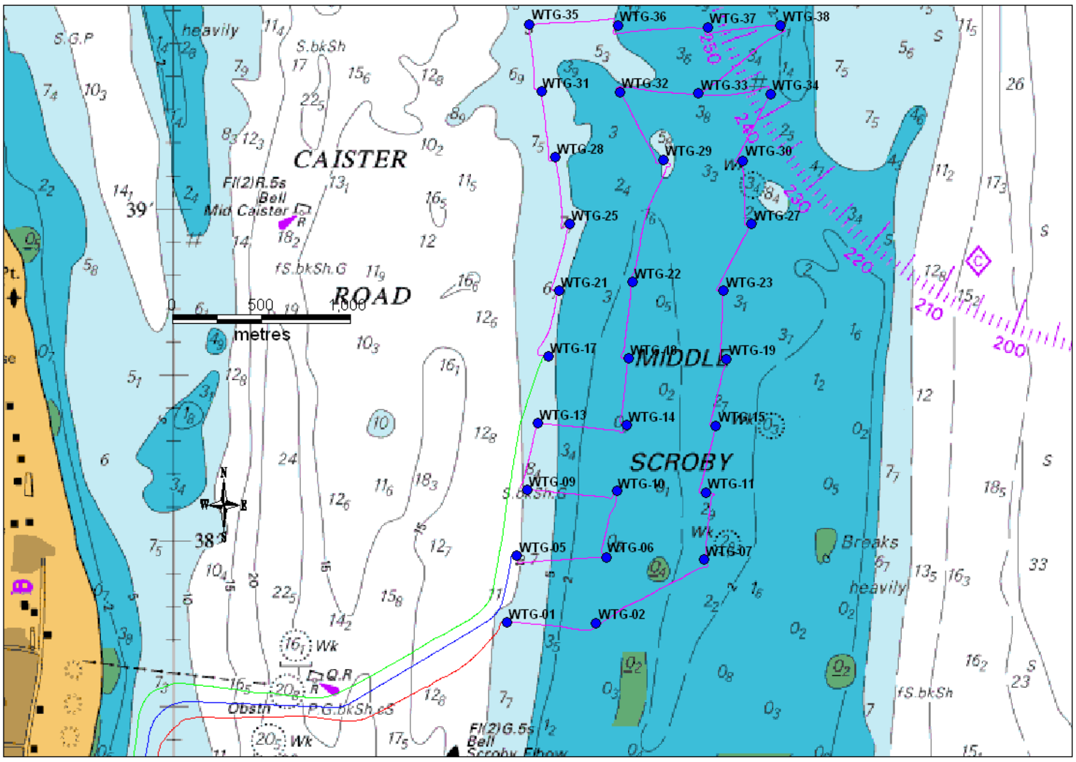

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Figure 1: Chart showing the layout of Scroby OWF with turbine numbers and also the intra-cable routing.

Scroby Sands is a large sandbank system and forms part of the system of banks lying off the East Anglian coast at Great Yarmouth. The bank is shore parallel and has present day dimensions of approximately 11.4km in length (north to south) and 1.8 km in width (east to west). The offshore facing side of the bank is steeper than the inshore side. The bank lies about 3 km offshore and is drying at its southern end on low spring tides. It is partially covered by sand waves on its upper surface and flanks, and the surface of the bank comprises fine to medium sand with a median grain size d_{50} of around 0.2 to 0.4mm.

The mean spring tidal range at the wind farm site is 2.1m and the tidal current velocities range from 1 – 1.25m/s. The tidal currents are essentially rectilinear but there may be some deviation from this as a result of flow separation or diversion around the sandbanks. A 1:50 year storm surge will increase predicted water levels by up to 2.5m.

The wind farm site is exposed to winds and waves from the north east. The significant wave heights that can be expected here are between 0.5 and 1m for 10% of the year and 5m for 1:1 year waves. Waves with a 50 year return period, however, are known to reach 7m. The nearshore sandbanks cause significant variations in wave conditions over relatively small distances, and wave breaking will occur under storm conditions in the shallow subtidal areas. In other areas the bank surface is emergent and this will cause total breaking of waves.

1.1 Sidescan Sonar surveys

A number of sidescan sonar surveys have been undertaken of Scroby Sands Bank using a high resolution sidescan sonar system. Good coverage was achieved in very shallow water, typically 3-5m depth, with horizontal ranges of up to 100m. Sidescan sonar mosaics were produced such as that shown in Figure 2.

The major features identified by the sidescan sonar were a sandwave field in the north-west corner of the site, the scour pits associated with the monopiles and two wrecks.

1.2 Swathe Bathymetry

The earliest high quality bathymetric survey of Scroby Sands Bank was undertaken by Coastline Surveys for Powered in April 2002 as part of a baseline survey. Subsequent swathe bathymetry surveys were undertaken for operation purposes (ship/barge movements) and more latterly as part of the FEPA licence monitoring conditions on approximately six monthly intervals for E.ON (UK). Table 3 gives a timeline and reason for each of the surveys. These datasets have been made available for analysis of scour in the present project.

Table 2: Timetable of the Sidescan sonar surveys of Scroby Bank.

Survey	Date	Comments
1	April 2003	Before Construction
2	Oct 2003	During Construction
3	Oct 2005	After Construction

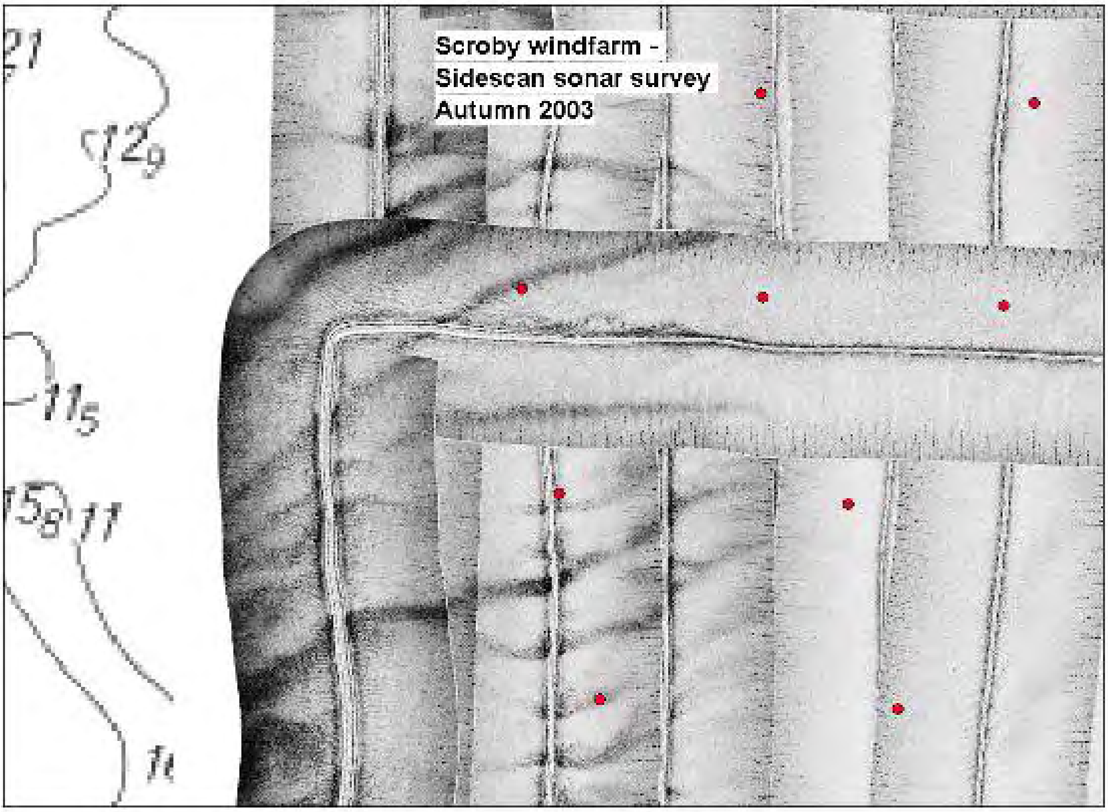

Figure 2: **Image showing the north-east portion of the sidescan sonar survey of Scroby Bank undertaken in August 2003 showing the sand wave field. WTG-38 is in the top right hand corner of the image.**

Table 3: **Timeline of bathymetric surveys.**

Survey	Date	Contractor	Type	Comments
1	April 02	Coastline Surveys	Single beam echo sounder	Baseline
2	March 04	Andrews	Swathe bathymetry	Pre Scour Protection
3	July 04	Andrews	Swathe	Post Scour Protection
4	February 2005	Andrews	Swathe	Winter
5	September 2005	Andrews	Swathe	Summer
6	April 2006	Andrews	Swathe	Spring
7	November 2006	Andrews	Swathe	Winter

1.3 Swathe survey data

The swathe bathymetry surveys provide a time-series of the evolution of Scroby Bank over a period of 2 years, and including the original survey a period of 4 years is available in which to assess the changes scouring and the level of the bank. From the swathe datasets (gridded at 1m centres) analysis was undertaken using the Fledermaus © environment, which allows visualisation and analysis of large datasets (see Figure 3 for an example).

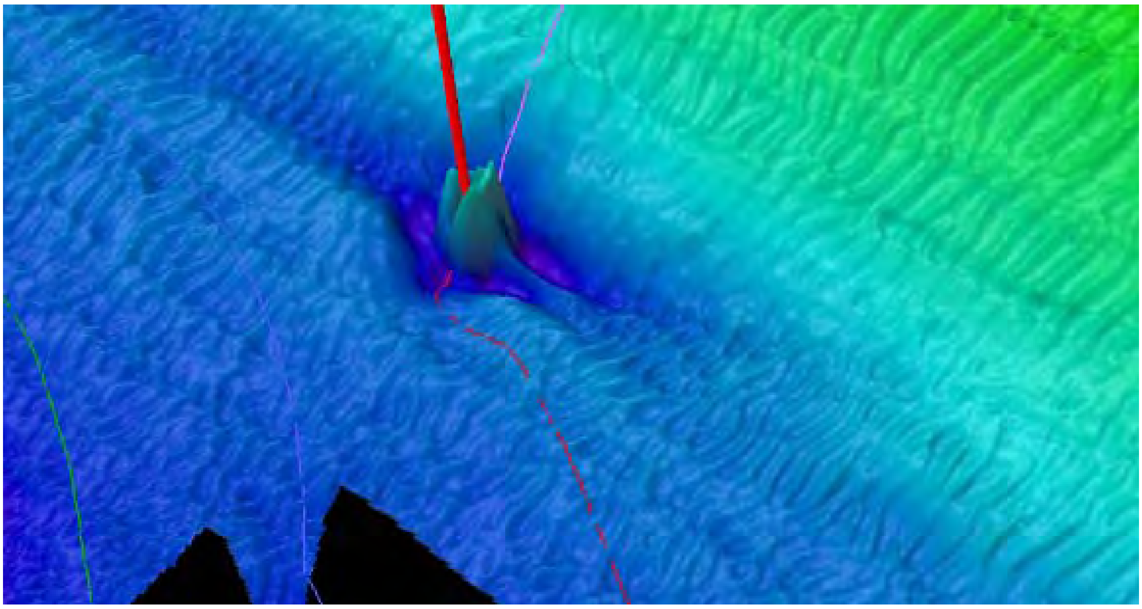

Figure 3: Fledermaus image showing the scour protection around the base of the monopile (red cylinder), along with the secondary scour pits and the "as laid" intra-array cable route (magenta) (CEFAS, 2006).

The main features that can be identified are (CEFAS, 2006):

Natural Features

(a) Large ridge running north-south along the OWF site
(b) Sandwave field in the NW corner of the site
(c) Megaripple sand fields across the site

Anthropogenic features

(a) Scour pits associated with the monopiles – typical depths up to 5m with a horizontal diameter of 60m (Figure 3)
(b) Scour tails extending from one monopile to the nearest down stream neighbour (Figure 4). The scour tails are orientated at approximately 30 degrees to the normal North-south tidal direction.
(c) “Scour pans” with a U- shaped profile in the NW corner within the sandwave field
(d) Reduction in bathymetry along the inshore line of Monopiles
(e) Impacts of jetting the intra-array cable close to the monopiles
(f) Traces of the ploughing of the intra-array cable across the OWF site
(g) Secondary scour pits associated with the scour protection deposited to stabilise the monopile
(h) Wrecks and associated scour pits

Some additional information and examples on observed behaviour of bed levels at the site are given in Annex 13.

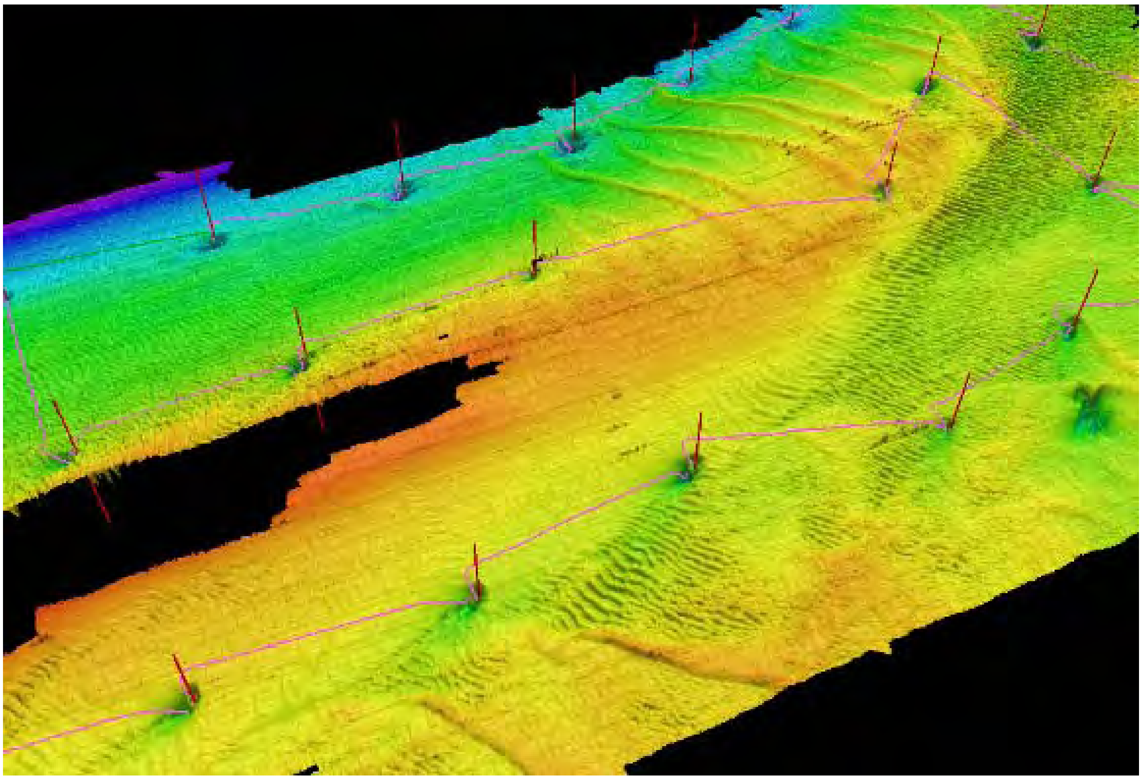

Figure 4: **Fledermaus image looking north-west showing the swathe bathymetry survey of February 2005 from the Scroby Sands OWF. Also shown are the monopiles (red cylinders) and intra-array cable route (magenta). In some cases a scour tail extends to the neighbouring monopile (CEFAS, 2006)**

1.4 Bedforms

An alternative assessment of the impact of the monopile on the sandwave field can be made by comparison of the positions of the crests of sandwaves from the four bathymetric surveys (the April 2002 survey is suitable for this type of analysis) and the sidescan sonar surveys. Figure 5 shows the position of the crests of the sandwaves digitised from the sources above. The crests of the sandwave field do not show any direct impact when compared with those pre-construction (other than within the scour pits). Similarly, between the monopiles, sandwave crests do not show any significant variations e.g. one sandwave between WTG-28 and WTG-29 only moves 18m over the three years of the comparison.

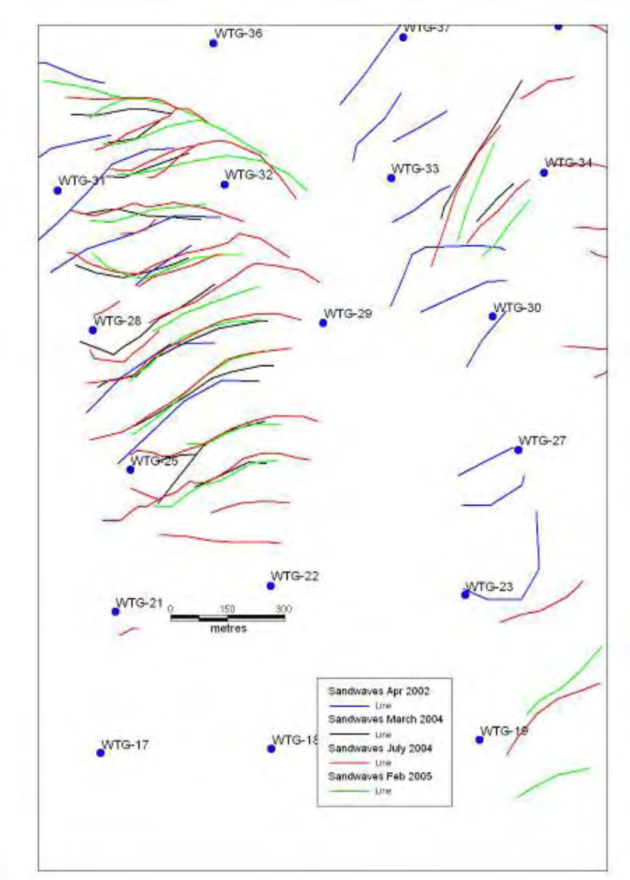

Figure 5: **Diagram showing the movement of sand wave crests in the north eastern sector of Scroby OWF between 2002 and 2005 (CEFAS, 2006).**

2 Conclusions

From the analysis of bathymetric data in the period March 2004 to November 2006 on the Scroby Sands Offshore Wind Farm it has been possible to evaluate the scour development around the installed monopile foundations and how this scour has developed since the installation of scour protection material. Also, troughs due to jetting from the end of the plough tracks to the sides of the scour pit have been observed.

Comparison of digital elevation models generated from swathe bathymetry surveys at approximately six monthly intervals has enabled detailed analysis of the impact of scour pits and scour tails (areas of deposition in the lee of the monopiles). Previously a comparison of the crests of sand waves in the north western part of the bank from surveys from 2002 to 2005 has shown no significant changes in the position, shape or orientation of the sand waves. Elsewhere the datasets do show some interaction between sand waves and the foundations.

The datasets have been used to illustrate the temporal and spatial variations in scour depth that has been observed at the monopiles and with scour protection material placed. The variation in scour depth with space and time has been analysed and is presented in Figure 6, based on the dataset in Table 4. Initially the scour depths were limited to the range 4 to 5.8m but the last dataset shows the spread of secondary scour pit depths with scour protection material in place has increased markedly to between 0.9m (WTG-13) and 6.97m (WTG-25). However, whilst some depths have changed some have not, as an example the scour depth at WTG-01 has remained quite similar between March 2004 (4.03m) and November 2006 (4.3m).

Figure 7 shows the relationship between water depth and scour depth. In March 2004 the data is clustered in two groups of water depth, 3m to 5m and 8.5m to 11.5m. The shallower water has scour depths clustered in the range 4.3m to 5.83m and the deeper water has scour depths clustered in the range 4.04m to 5.23m. Whether the differences are significant is unclear, as there will have been some differences in elapsed time between pile installation and the survey date. What is clear is that even assuming a mean sea level of 1m above charted depth, the scour depth in the shallower water was 1.02D to 1.39D and was of the same order of magnitude as the water depth.

The site moves between tidal and storm controlled environments, for example (CEFAS, 2006) the tidal surge of 11th March 2005, when combined with the strong waves reset the sediment transport environment on Scroby Bank from a tidally dominated regime to one of wave domination. Large volumes of sediment unfilled the northern edge of many of the scour pits and created scour tails on the outer (eastern) monopiles. The orientation of the scour tails was at approximately 30 degrees to the normal tidal direction due to the storm and surge generated currents when the resultant sediment transport direction is south east. The full effect of variations in tidal and wave energy on the scour development and infilling is not well understood at present.

In conclusion, the following features were observed based on an investigation of the time series of scour depths (Figure 6):

- Creation of scour pits with depths, initially in March 2004, in the range 4m to 5.8m with diameters up to 60m. The depths equate to 0.95D to 1.38D. Scour depths are not limited by sediment thickness at this site.
- Scour protection has been placed in the scour pits formed around the base of each monopile and secondary scour pits have been formed associated with the placed scour protection. The range of scour depths has increased with time and scour depths can be deeper than the absolute scour depth with the pile foundation only, but also shallower, depending on how the flow has interacted with the scour protection and local morphology of the bank surface.

Some further examples of sections are described in Annex 13 along with the method description for extracting the scour depths from the bathymetric data.

References

CEFAS (2006). Scroby Sands Offshore Wind Farm – Coastal Processes Monitoring. Final Report AEO262 prepared for Marine Environment Division, Defra and Department of Trade and Industry. April 2006.

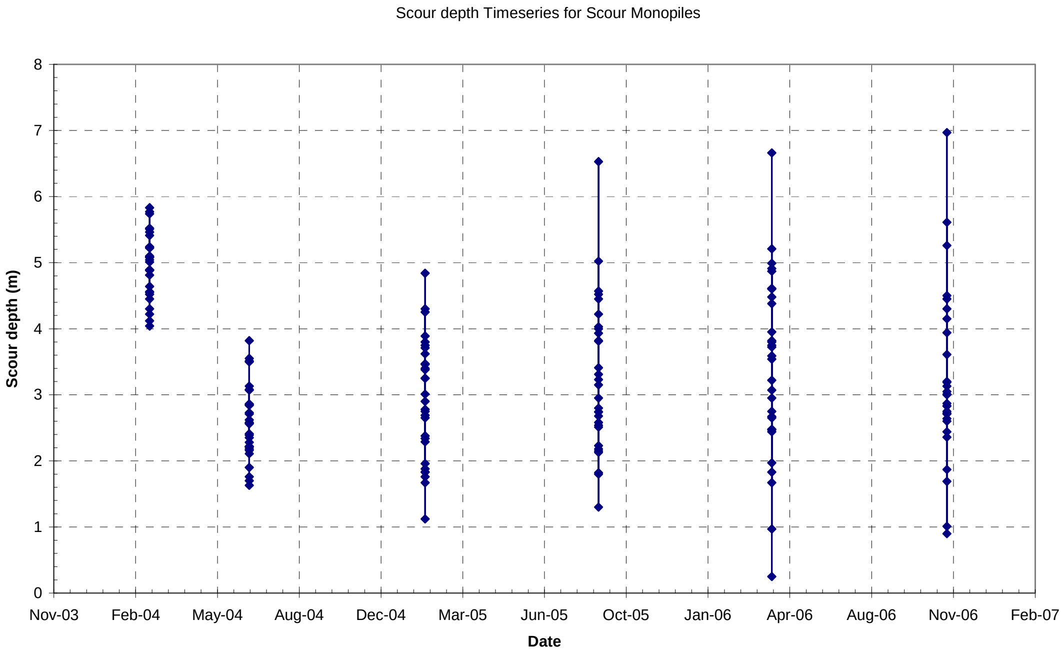

Figure 6: Variation of rang in scour depth in space and time at Scroby Sands Offshore Wind Farm. At each date the scour depths are plotted as a vertical spread of data points.

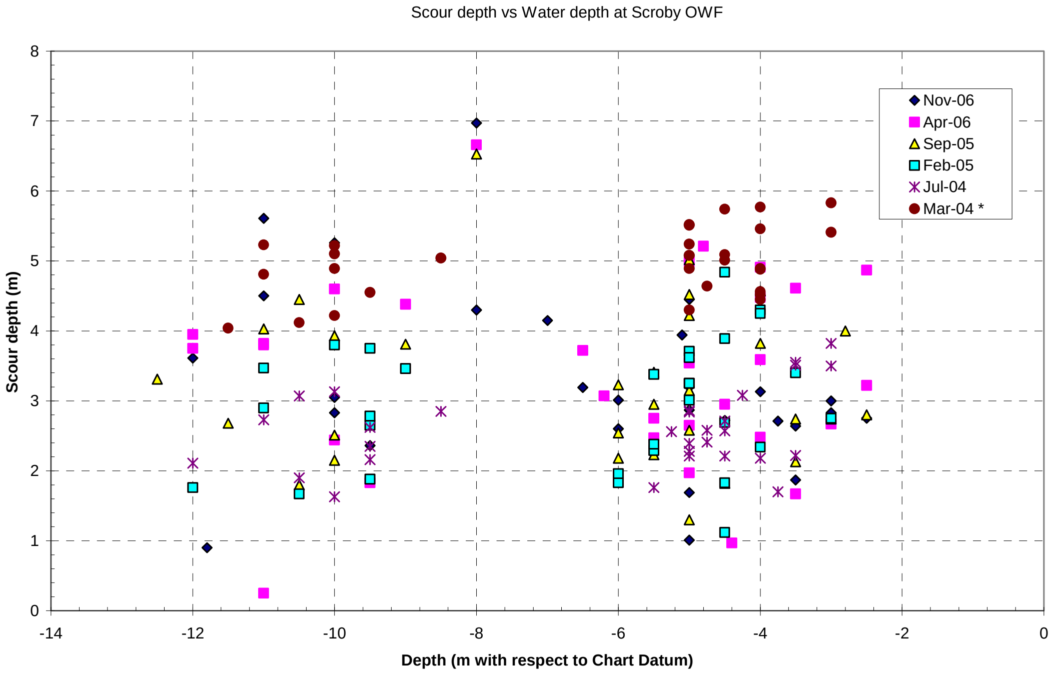

Figure 7: Plot showing how scour depths vary with water depth at Scroby Offshore Wind Farm.

Table 4: Scroby Sands scour dataset (2004 – 2006) (Mar 04 data is without scour protection in place and subsequent data is for post scour protection installation).

Survey date	Pile Nr/ID	Ambient bed level (m wrt chart datum)	Scour depth (m)	Maximum radius (m)	Minimum radius (m)
Mar-04	1	-11.5	4.04	20	20
Mar-04	2	-5	4.3	15	15
Mar-04	5	-11	5.23	25	16
Mar-04	6	-5	5.08	20	10
Mar-04	7	-4	4.52	20	20
Mar-04	9	-11	4.81	15	15
Mar-04	10	-5	4.89	15	25
Mar-04	11	-4	4.88	28	20
Mar-04	13	-10	4.89	20	20
Mar-04	14	-4	4.56	10	35
Mar-04	15	-3	5.83	18	25
Mar-04	17	-10	4.22	25	25
Mar-04	18	-4.5	5.09	25	25
Mar-04	19	-4	5.46	15	18
Mar-04	21	-9.5	4.55	12	12
Mar-04	22	-4	4.45	15	15
Mar-04	23	-4	5.77	17	18
Mar-04	25	-8.5	5.04	25	25
Mar-04	27	-4	4.89	25	25
Mar-04	28	-10.5	4.12	28	28
Mar-04	29	-3	5.41	20	20
Mar-04	30	-4.75	4.64	15	25
Mar-04	31	-10	5.22	16	16
Mar-04	32	-4.5	5.01	15	15
Mar-04	33	-5	5.51	20	22
Mar-04	34	-5	5.24	15	15
Mar-04	35	-10	5.1	33	23
Mar-04	36	-5	5.08	20	20
Mar-04	37	-5	5.52	20	20
Mar-04	38	-4.5	5.74	15	15
Jul-04	1	-12	2.11	25	29
Jul-04	2	-5	2.28	25	15
Jul-04	5	-11	2.73	20	10
Jul-04	6	-5.5	1.76	30	10
Jul-04	7	-3.5	2.22	30	25
Jul-04	9	-10.5	3.07	20	20
Jul-04	10	-4.75	2.41	70	10
Jul-04	11	-3.5	3.55	27	25
Jul-04	13	-10.5	1.9	25	25
Jul-04	14	-4.5	2.21	40	20
Jul-04	15	-3	3.82	40	30
Jul-04	17	-10	1.63	45	25
Jul-04	18	-4.5	2.71	20	20

Survey date	Pile Nr/ID	Ambient bed level (m wrt chart datum)	Scour depth (m)	Maximum radius (m)	Minimum radius (m)
Jul-04	19	-3	3.5	50	15
Jul-04	21	-9.5	2.62	35	30
Jul-04	22	-4	2.18	35	20
Jul-04	23	-4.25	3.08	30	20
Jul-04	25	-8.5	2.85	50	20
Jul-04	27	-3.75	1.7	30	20
Jul-04	28	-9.5	2.16	60	20
Jul-04	29	-3.5	3.51	15	12
Jul-04	30	-4.75	2.58	40	15
Jul-04	31	-9.5	2.35	80	30
Jul-04	32	-4.5	2.57	40	20
Jul-04	33	-5	2.39	20	20
Jul-04	34	-5	2.21	20	20
Jul-04	35	-10	3.13	60	50
Jul-04	36	-5.25	2.56	30	10
Jul-04	37	-5	2.86	40	30
Jul-04	38	-5	2.84	50	10
Feb-05	1	-11	3.47	50	50
Feb-05	2	-5.5	2.29	60	8
Feb-05	5	-12	1.76	40	30
Feb-05	6	-5.5	2.38	35	8
Feb-05	7	-4	4.3	60	12
Feb-05	9	-11	2.9	40	25
Feb-05	10	-6	1.83	40	8
Feb-05	11	-4	2.34	80	15
Feb-05	13	-10.5	1.67	25	13
Feb-05	14	-5	3.01	100	0
Feb-05	15	-3.5	3.4	300	10
Feb-05	17	-9.5	2.65	60	30
Feb-05	18	-4.5	4.84	60	15
Feb-05	19	-4.5	2.69	100	15
Feb-05	21	-9.5	2.78	40	25
Feb-05	22	-4.5	1.12	40	5
Feb-05	23	-4	4.25	350	15
Feb-05	25	-9	3.46	50	50
Feb-05	27	-4.5	1.83	130	6
Feb-05	28	-9.5	1.88	80	15
Feb-05	29	-3	2.75	70	0
Feb-05	30	-5	3.25	150	20
Feb-05	31	-10	3.8	125	100
Feb-05	32	-4.5	3.89	80	8
Feb-05	33	-5	3.25	45	10
Feb-05	34	-6	1.96	50	6
Feb-05	35	-9.5	3.75	100	50
Feb-05	36	-5.5	3.38	70	0
Feb-05	37	-5	3.71	50	25
Feb-05	38	-5	3.62	60	0

Survey date	Pile Nr/ID	Ambient bed level (m wrt chart datum)	Scour depth (m)	Maximum radius (m)	Minimum radius (m)
Sep-05	1	-11	4.03	140	50
Sep-05	2	-5	3.15	40	0
Sep-05	5	-12.5	3.31	60	30
Sep-05	6	-5	1.3	30	0
Sep-05	7	-2.5	2.8	200	0
Sep-05	9	-11.5	2.68	40	40
Sep-05	10	-6	2.18	100	0
Sep-05	11	-3	2.74	40	0
Sep-05	13	-10.5	1.8	80	30
Sep-05	14	-5.5	2.95	125	5
Sep-05	15	-3.5	2.13	75	5
Sep-05	17	-10	2.51	80	30
Sep-05	18	-5	5.02	150	30
Sep-05	19	-3.5	2.74	250	15
Sep-05	21	-10	3.93	60	40
Sep-05	22	-4.5	1.82	40	15
Sep-05	23	-4	3.82	400	10
Sep-05	25	-8	6.53	60	25
Sep-05	27	-5	2.58	80	10
Sep-05	28	-10	2.15	80	40
Sep-05	29	-2.8	4	60	0
Sep-05	30	-5.5	3.41	60	25
Sep-05	31	-10.5	4.45	60	30
Sep-05	32	-4	4.57	80	20
Sep-05	33	-5.5	2.23	50	10
Sep-05	34	-6	2.54	50	10
Sep-05	35	-9	3.81	60	30
Sep-05	36	-5	4.22	300	4
Sep-05	37	-5	4.52	50	35
Sep-05	38	-6	3.23	60	40
Apr-06	1	-11	3.82	150	50
Apr-06	2	-4	4.48	200	10
Apr-06	5	-12	3.95	60	55
Apr-06	6	-5	1.97	40	5
Apr-06	7	-2.5	3.22	250	10
Apr-06	9	-12	3.75	50	50
Apr-06	10	-5.5	2.47	100	8
Apr-06	11	-3	2.67	300	15
Apr-06	13	-11	0.25	30	30
Apr-06	14	-5	3.54	60	0
Apr-06	15	-3.5	1.67	120	10
Apr-06	17	-10	2.44	140	30
Apr-06	18	-5	4.99	250	10
Apr-06	19	-4	2.48	300	15
Apr-06	21	-9	4.38	120	30
Apr-06	22	-4.4	0.97	20	20
Apr-06	23	-3.5	4.61	425	15

Survey date	Pile Nr/ID	Ambient bed level (m wrt chart datum)	Scour depth (m)	Maximum radius (m)	Minimum radius (m)
Apr-06	25	-8	6.66	120	30
Apr-06	27	-5	2.65	200	0
Apr-06	28	-9.5	1.83	120	25
Apr-06	29	-2.5	4.87	60	0
Apr-06	30	-5.5	2.75	180	14
Apr-06	31	-11	3.8	40	40
Apr-06	32	-4	3.59	45	35
Apr-06	33	-4.5	2.95	40	15
Apr-06	34	-6.2	3.07	60	30
Apr-06	35	-10	4.6	45	30
Apr-06	36	-4.8	5.21	150	0
Apr-06	37	-4	4.91	45	45
Apr-06	38	-6.5	3.72	60	25
Nov-06	1	-8	4.3	55	25
Nov-06	2	-5	3.2	45	15
Nov-06	5	-11	5.61	80	40
Nov-06	6	-5	1.69	20	20
Nov-06	7	-2.5	2.75	50	20
Nov-06	9	-12	3.61	50	30
Nov-06	10	-5.5	2.44	70	10
Nov-06	11	-3	3	60	20
Nov-06	13	-11.8	0.9	N/A	N/A
Nov-06	14	-6	2.6	50	10
Nov-06	15	-3.5	1.87	50	10
Nov-06	17	-10	3.05	80	40
Nov-06	18	-5.1	3.94	90	30
Nov-06	19	-3.5	2.64	100	20
Nov-06	21	-10	2.83	100	50
Nov-06	22	-5	1.01	20	0
Nov-06	23	-3.75	2.71	100	20
Nov-06	25	-8	6.97	140	40
Nov-06	27	-5	2.87	50	5
Nov-06	28	-9.5	2.36	80	50
Nov-06	29	-3	2.83	50	0
Nov-06	30	-6	3.01	60	20
Nov-06	31	-11	4.5	140	60
Nov-06	32	-4.5	2.72	45	5
Nov-06	33	-4	3.13	20	20
Nov-06	34	-6.5	3.19	50	25
Nov-06	35	-10	5.26	50	50
Nov-06	36	-5	4.45	60	0
Nov-06	37	N/A	N/A	15	15
Nov-06	38	-7	4.15	70	20

Annex 8 North Hoyle dataset

The North Hoyle Offshore Wind Farm was the first completed Round 1 project in the UK. The site is located some 8 to 11km offshore of Rhyl, North Wales, and comprises of 30 wind turbines each rated at 2MW installed capacity. These turbines are arranged within a 10km^2 area of seabed licensed from The Crown Estate. The turbine array configuration is 5 columns and 6 rows, with respective separations of 800m and 350m, approximately, between foundations (see Figure 1).

The foundation units each comprise of 4.0m diameter monopiles, which were installed by Seacore Ltd. over the period April to July 2003. It is pertinent to note that the installation methodology required a combined drive and drill technique. Each pile was driven initially through upper sand and clay layers (nominally 10m thick) using a large hydraulic hammer to reach underlying bedrock. A slightly undersized hole was then drilled into the bedrock (layers of sandstone or mudstone) and the pile finally driven into this hole to the nominal design penetration of 33m (maximum) below seabed (LIC, 2004). Met masts have also been installed with foundation diameters of 3.2m (remains to be confirmed) for met mast 1, a tripod structure for met mast 2 (3 off 762mm raker piles angle 1 : 3 – driven 10m into the seabed) and another monopile at Rhyl Flats on Constable Bank (met mast 3) with a foundation diameter of 1.89m.

The dominant sediment types at the site fall into the categories of gravel and sandy gravel. The site investigation data identified the site as being strongly heterogeneous, with variability over very short distances, as well as being composed of very poorly sorted sediments with varying contributions of sands and gravels mainly. Therefore, the use of a single sediment size (e.g. 4mm) was not recognised to accurately represent the natural sediment conditions.

Thresholds for seabed mobility indicated that currents alone only create live bed conditions for the sandy material, with large storms required to exceed thresholds for both sands and gravels. The largest gravels were immobile and can be regarded as a lag deposit.

Current data from one of the met masts showed measured flow speeds in excess of 0.8m/s, with a maximum peak flow rate measured on 5 November 2002 of 1.17m/s. It is noted that this event occurred on the flood tide.

Table 1: Summary of Met ocean parameters.

Parameter	Unit	Value
Peak Wave Event		
Return Period	year	1 in 1
Wave Height, Hs	m	4.91
Wave Period, Tz	s	8.00
Water Levels, Z_0 (relative to MSL)	m	+0.50
Water Depth, h_{min}	m	12.16
Water Depth, h_{max}	m	16.76
Flows during peak waves, U_c	m/s	0.67
Peak Flow Event		
Velocity, U_c	m/s	1.17
Water Levels, Z_0 (relative to MSL)	m	-1.71
Water Depth, h_{min}	m	9.95
Water Depth, h_{max}	m	14.55
Waves during peak flows		Unknown. Assumed to be no wave activity

A high-resolution scour survey using a swathe bathymetry system was completed around each offshore structure over the period 12 August to 12 October 2004 (Osiris, 2005). This survey represented a period of 16 to 18 months post-installation. The surveys were carried out over 100m square boxes, centred at each monopile location and by running a series of parallel survey lines at 50m centres. In addition, 68 grab samples were taken at specific locations around each foundation. Of note in the survey report is the comment that rock dumping (armouring) operations were underway during the survey period which are understood to relate to protection around J-tubes.

A further survey was undertaken between 26 April and 2 May 2005.

A key observation from the scour survey is the presence of drill cutting mounds to the south of each pile, and where presently observed some minor scouring to the north of the piles (e.g. see Figure 2). The mounds are assumed to be related to armouring around the J-tubes. The mounds have variable volume and form and may also have variable sediment gradings. As yet there is no definite data to confirm sediment gradings on these mounds, or the permanency of these features. There also appears to be some anomalies between the 2004 and 2005 surveys with respect to these mounds.

Interpretation of scour around each foundation was based on a series of gridded datasets supplied by Osiris Projects. This data resolved seabed levels at 0.5m centres across the domain of each 100 by 100m survey area. However, it is noted that the 4.5m diameter monopile unit was not explicitly resolved (or blanked out) in this data. Therefore, the analysis of scour in the present report was interpreted as an observed distinct reduction in seabed level connecting to the location of the stated ‘as-built’ position for each monopile. The data has been summarised in Table 2 and it is interesting to note that scour was recorded at only 10 out of the 30 wind farm foundation piles at the time of that survey.

One limit on scour depths is the erodible property of the sub-soil sediment where this may be different to that of the surface sediments. Evidence of sub-soil property across North Hoyle indicate that the top sediment layers (0 to 1m, approximately) resolved by the boreholes generally confirm sandy gravels. Below this top layer (>1m) there is a more compact sediment comprised of gravely clay. The scour depths are plotted in Figure 2 and show depths of no greater than 0.5m in 2004 and no scour depths in 2005; whether this was due to rock dumping or natural infill is not clear. The maximum scour depth to pile diameter ratio recorded in 2004 was 0.125D.

The scour depths in 2004 at met mast 1 was (with some uncertainty) 0.3m equating to 0.094D and at met mast 2 the scour depth around each raker pile was 0.3m or 0.39D. However, the scour depth recorded in 2004 at met mast 3 on Constable Bank (see Figure 1 for location) was 1.5m. The pattern of scour in 2005 was different in detail but the scour depth was still around 1.5m. The 1.5m scour depth equates to 0.79D.

References

LIC. 2004. North Hoyle Wind Farm. Monopile Foundations. Offshore foundation series sheet 0019. LICengineering A/S. November 2004.

Osiris, 2005. North Hoyle Offshore Wind Farm. Scour Monitoring Surveys - 12 August - 12 October 2004. C4014a. January 2005.

Table 2: Scour parameters for North Hoyle (2004).

Pile Nr/ID	**Ambient bed level** (m wrt CD)	**Scour depth** (m)
1	-8.5 to -9.0	0
2	-8.7 to -9.2	0
3	-7.6 to -8.3	0
4	-7.2 to -8.3	0
5	-6.3 to -7.0	0
6	-9.2 to -9.8	0.35
7	-7.8 to -8.8	0
8	-7.8 to -8.3	0
9	-7.7 to -8.6	0
10	-7.7 to -8.8	0
11	-8.3 to -9.0	0
12	-8.8 to -9.0	0
13	-9.5 to -9.8	0
14	-9.0 to -9.3	0.5
15	-9.2 to -9.8	0
16	-9.2 to -9.5	0
17	-9.3 to -9.8	0.3
18	-9.7 to -10.0	0.5
19	-9.8 to -10.2	0.3
20	-9.9 to -10.3	0.2
21	-9.3 to -9.6	0
22	-10.1 to -10.3	>0.2
23	-10.1 to -10.5	0.3
24	-10.4 to -10.9	0.3
25	-10.4 to -10.8	0
26	-9.8 to -10.3	0
27	-10.0 to -10.3	0
28	-10.5 to -10.9	0
29	-10.7 to -11.0	0.3
30	-9.7 to -10.3	0
Met. Mast 1	-9.9 to -10.3	0.3?
Met. Mast 2	-8.7 to -9.6	0.3
Met. Mast 3	-5.73 to -6.65	1.5

Note: The piles numbered 1 to 30 are monopiles, the Met. Mast 1 is a monopile, Met. Mast 2 is a tripod structure and Met. Mast 3 is a monopile foundation situated on Constable Bank some distance away from the North Hoyle site, see text for more details.

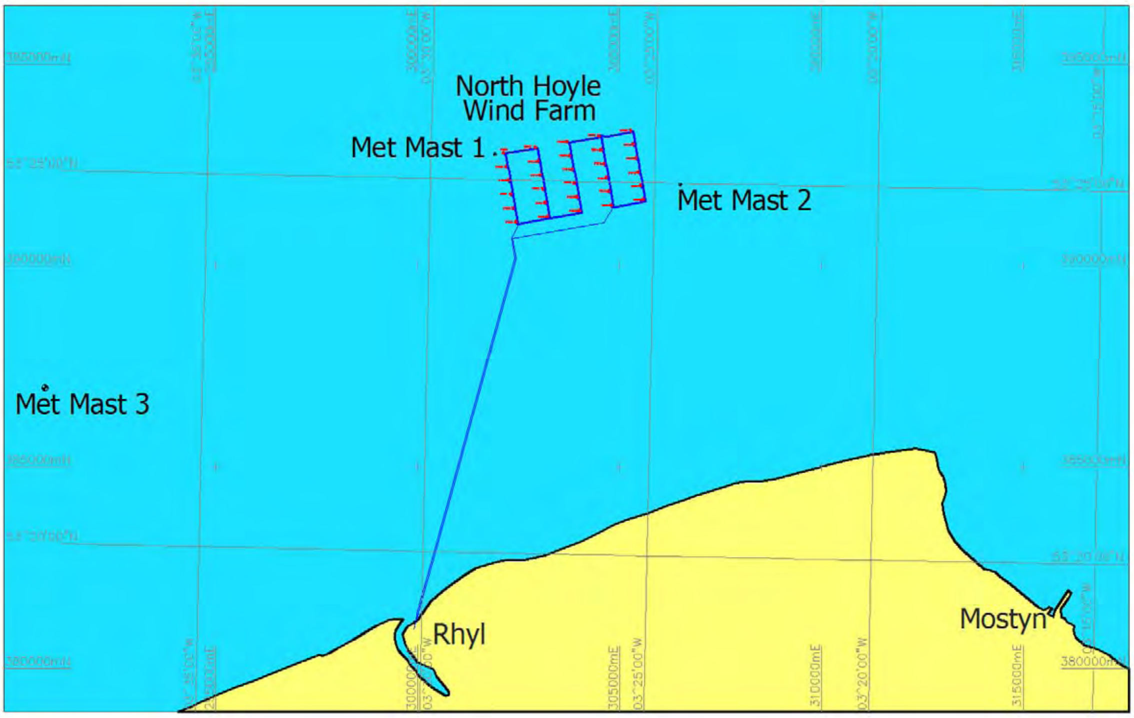

Figure 1: Location of North Hoyle Wind Farm turbines and export cable (from Osiris Projects, 2005, North Hoyle Windfarm - Post Construction Survey - Drawing C4014b-03).

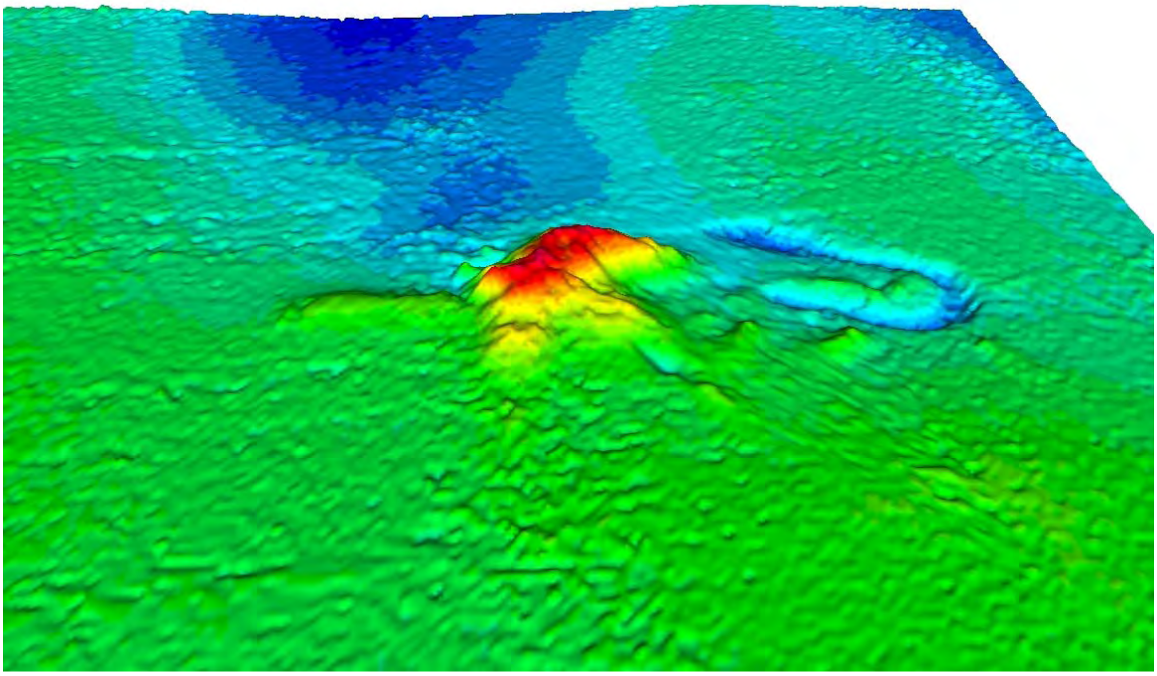

Figure 2: Turbine 4 looking from the south (2004 survey; Osiris Projects, 2005).

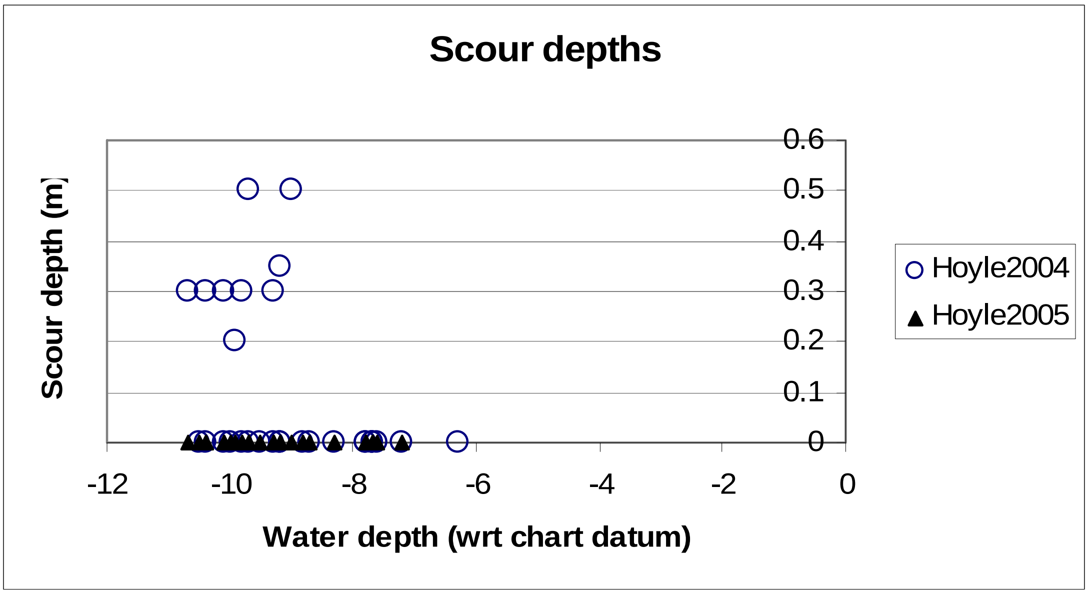

Figure 3: Scour depth data at North Hoyle plotted against the ambient water depth at each foundation.

Annex 9 Arklow Bank dataset

Arklow Bank Wind Farm Scour

Arklow Bank Wind Park

The Arklow Bank Wind Park consists of 7 of GE's 3.6MW wind turbines at locations shown on Figure 1. Arklow Bank is a shallow water sandbank situated between 10km and 12km offshore from the eastern coast of Ireland and has some of the best wind resources in the Irish Sea. The Bank is subject to overall seabed movement, such as movement of the sandbank, channel migration and overall erosion and accretion. In addition, the installation of the 5m diameter, D, monopile foundations for the wind turbines was predicted to (and did) cause local scour around the monopiles. Scour was caused by the strong currents that flow over the sandbank, often over 2m/s, and design wave heights of almost 6m on the offshore side. The water depth is as low as 5m over the crest of the bank so depth-limited wave breaking occurs during severe storms.

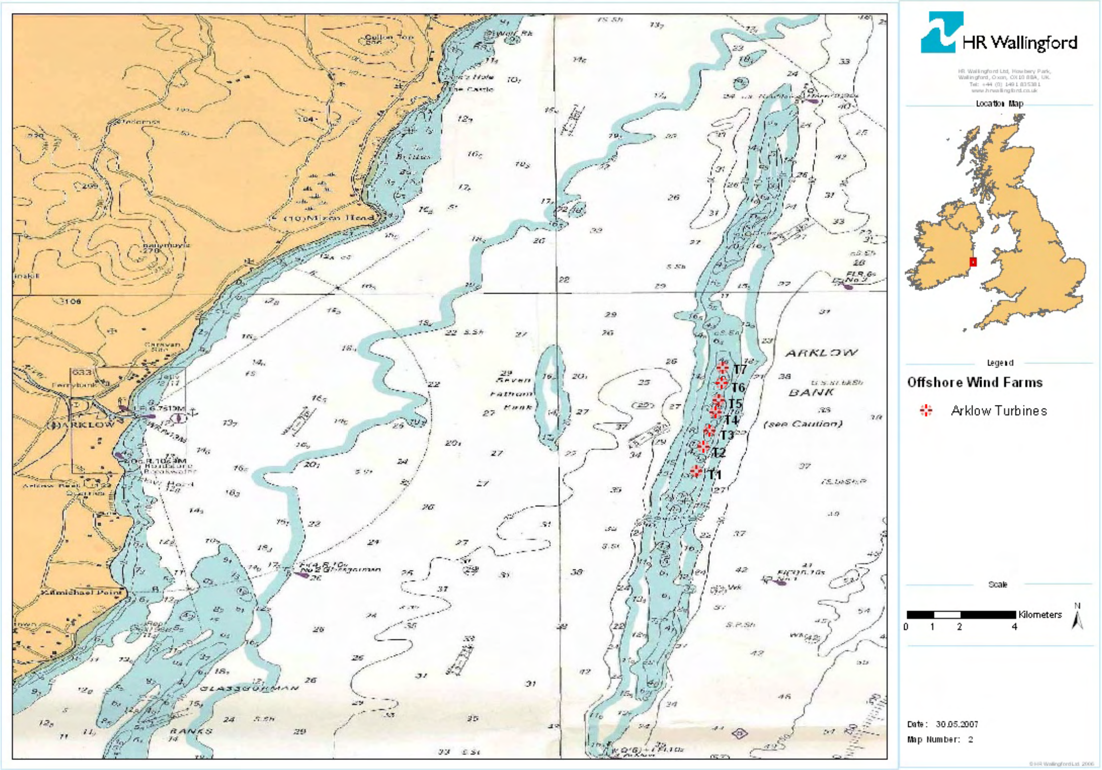

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Figure 1: Arklow Bank location.

Installation of the 7 wind turbines was achieved in only 9 weeks during late summer and early autumn in 2003 using a jackup barge fitted with a 1,200 tonne crane. There was a short delay between installation of the monopiles and the scour protection, which was sufficient for scour holes to develop around the monopiles, due to the tidal current alone. A survey was conducted to measure the size of the scour holes and an example of a contour plot derived from the survey is shown in Fig. 2. The scour hole is fairly symmetrical, with smooth sides and was about 4m deep. Scour protection design was optimised using physical model tests (Whitehouse *et al.*, 2006) and is shown in Figure 3.

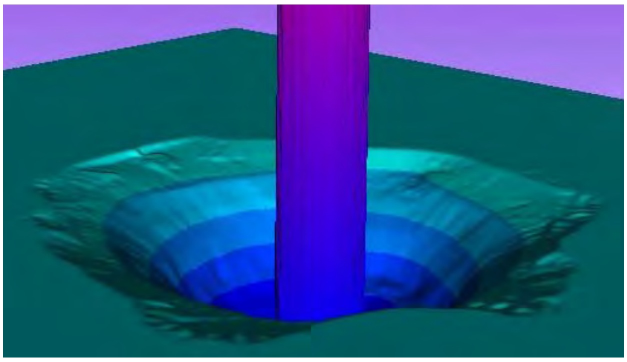

Figure 2: Scour hole observed after monopile installed.

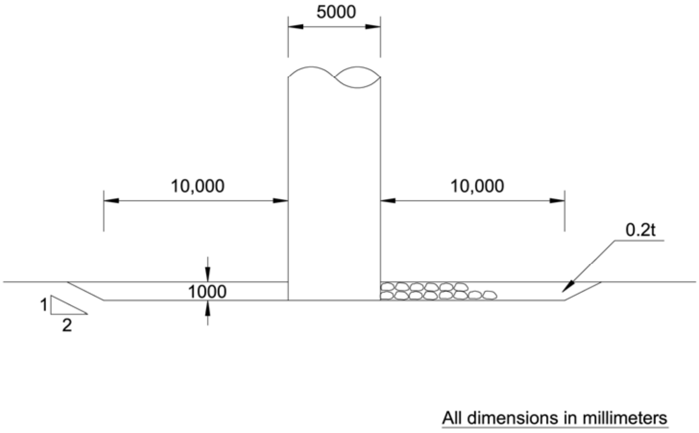

Figure 3: Scour protection design for Arklow Bank Wind Farm.

In the field the scour protection was installed into the naturally-occurring scour hole using a back-hoe on the side of a jackup barge. The quantities and size-distribution of the rock actually used are not known.

Measurements of scour protection

A pre-installation survey was performed by HydroServ in 2002 (a year before installation) although no information was made available from this survey. The monopiles were installed in Autumn 2003 and some survey data must have been collected at the time, but only Figure 2 has been supplied. Therefore, there is no record available to the present review of the pre-scour protection installation scour conditions or of the as-built scour protection.

After installation of the scour protection a further 4 surveys have been, or will be performed by HydroServ at approximately 6 monthly intervals. Information was provided from the first three post-installation surveys from 13 June 2004 (almost 9 months after installation) (HydroServ, 2004a), 26 September 2004 (only 3 months later) (HydroServ, 2004b) and 21 April 2005 (HydroServ, 2005). In each case 100m by 100m sidescan sonar bathymetries, centred on the monopiles, were collected. Charts were only supplied from the second and third survey. Bathymetry from the first survey was interpreted from the bathymetry from the second survey and a difference plot supplied with the second survey. In addition, diver surveys were performed, which included comments on the seabed / scour, J-tubes and cables.

The following observations about the bathymetry around the monopile are based on the September 2004 survey. The area within about 10m of turbine 1 was 0.25m to 0.50m higher than the surrounding seabed, except to the north-west, where it was 0.25m to 0.50m lower. The raised areas were probably due to the presence of rock armour. The lower area was around a J-tube, where free-spanning was observed.

The bed almost 10m south-west of turbine 2 had a mound of material up to 1m above the surrounding seabed level – quite possibly armour. There was also a slightly raised area to the north and north-east. There was a small area of scour immediately against the monopile on the north-west. The areas about 10m to 15m to the south-east and north-west were lower than the ambient level – possibly bed lowering had occurred due to flow acceleration round the monopile and rock armour.

Turbine 3 was in an area of seabed that slopes down from south-east to north-west. There were lower areas immediately to the south of the monopile and about 10m to 15m north north-east of the monopile. There was a raised area of bed 10m to 15m west of the monopile.

Turbine 4 had a 10m wide, relatively flat-bottomed scour hole to the east of the monopile, with a lower area about 10m north of the monopile. The highest area was about 20m south south-west of the monopile but it was not clear if this was a natural variation in bed or armour (probably the former). There were no obvious signs of armour in the bathymetry (although the original design had the top of the armour flush with the seabed so in a perfect placement this would be the case).

Turbine 5 had an asymmetrical scour hole around the monopile. The scour hole was deeper and had a smaller radius (so is steeper) to the west than the east. It had a slightly longer radii to the north-east and south-east, possibly due to vortex shedding from the monopile.

Turbine 6 had lower areas all round the monopile, particularly to the west and north-west where the maximum scour of 1.5m occurred.

Turbine 7 had a raised area up to 1m above the ambient seabed level immediately to the west of the monopile. It also had a lowered area to the north-east and east with a maximum scour depth of 1.5m occurring 10m east of the monopile.

Table 1 shows the date of survey, ambient bed level, maximum depth of scour, maximum and minimum radius of the scour hole and the average change in bed level for the two surveys that were available since the June 2004 survey. Ambient bed level was estimated from the general pattern of seabed contours away from the monopile and is measured relative to Chart Datum, Arklow (CDA) which is assumed to be close to LAT. Mean sea level is 1.3m above LAT. The maximum depth of scour was calculated by subtracting the lowest level close to the pile from the ambient bed level. The maximum radius was the maximum distance from the pile wall to the base of the scour hole, while the minimum radius is the smallest distance from the base of the scour hole to the pile. The average change in bed level since the June 2004 survey was calculated by HydroServ by calculating the volume of water between 0mCDA and the seabed over the entire 100m by 100m area of the survey. Differences in volume were then calculated between surveys and the average change in bed level was calculated by dividing this by the plan-shape area ($10^4 m^2$).

The seabeds were generally sloping with signs of bedforms, the most common of which had wavelengths of 3m to 6m, heights less than 0.25m and have their crests aligned NW-SE (more or less perpendicular to the prevailing peak flows). The difference plot of Pile 6 between June and September 2004 showed that a longer and higher sandwave was moving past the monopile. The maximum scour depths are plotted against ambient water depth in Figure 4, with time-series of scour depths being shown in Figure 5. The maximum scour depth was observed for Pile 5, in a scour hole on the west side of the monopile. This filled in between September 2004 and April 2005 when the deepest point was to the north-east of the monopile, at a depth that had not changed from the September 2004 survey.

The wide scatter in scour depths close to monopiles with similar environmental conditions occurs as the scour protection was installed with a different distribution at each site. There will also be variation in wave height as waves will be depth limited at the turbine locations. This will be discussed in the following section, where diver observations are referred to.

Table 1: Measured scour parameters at Arklow for the three surveys (post scour protection installation).

Survey date	Turbine Pile Nr	Ambient bed level (m CDA)	Scour depth (m)	Maximum radius (m)	Minimum radius (m)	Average change in bed level (m)
13/06/04	1	-5.4	0.6	4	3	
13/06/04	2	-5.7	0.8	2	0	
13/06/04	3	-5.4	1.0	15	8	
13/06/04	4	-4.5	2.0			
13/06/04	5	-2.1	4.0			
13/06/04	6	-4.3	0.6			
13/06/04	7	-5.9	0.6			
26/09/04	1	-5.6	0.4	4	3	-0.23
26/09/04	2	-6.0	0.5	2	0	-0.31
26/09/04	3	-5.9	0.7	15	8	-0.54
26/09/04	4	-5.0	2.3	8	6	-0.34
26/09/04	5	-2.3	4.3	2.5	0	-0.15
26/09/04	6	-4.0	1.5	2	0	0.28
26/09/04	7	-5.5	1.5	9	8	0.36
21/04/05	1	-5.8	0.5	8	0	-0.43
21/04/05	2	-6.0	0.8	22	7	-1.21
21/04/05	3	-5.3	0.8	10	3	-0.96
21/04/05	4	-5.0	1.8	12	1	-0.38
21/04/05	5	-3.6	1.9	13	2	-1.30
21/04/05	6	-4.5	1.0	11	0	-0.69
21/04/05	7	-4.5	1.5	11	0	1.35

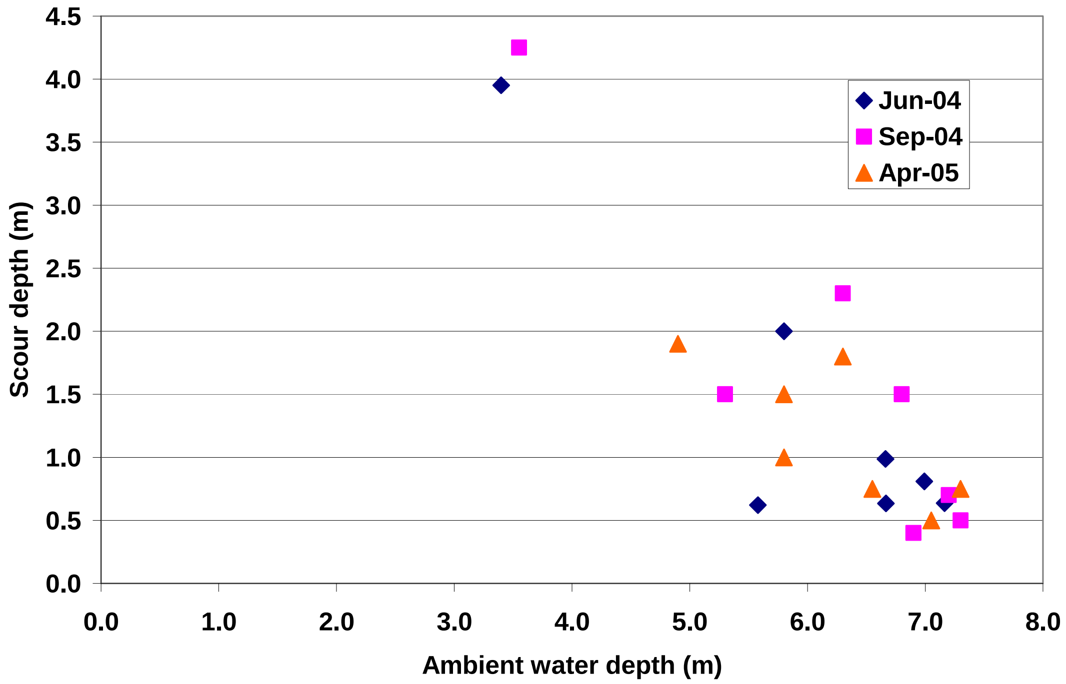

Figure 4: Scour depths post scour protection installation as a function of ambient water depth.

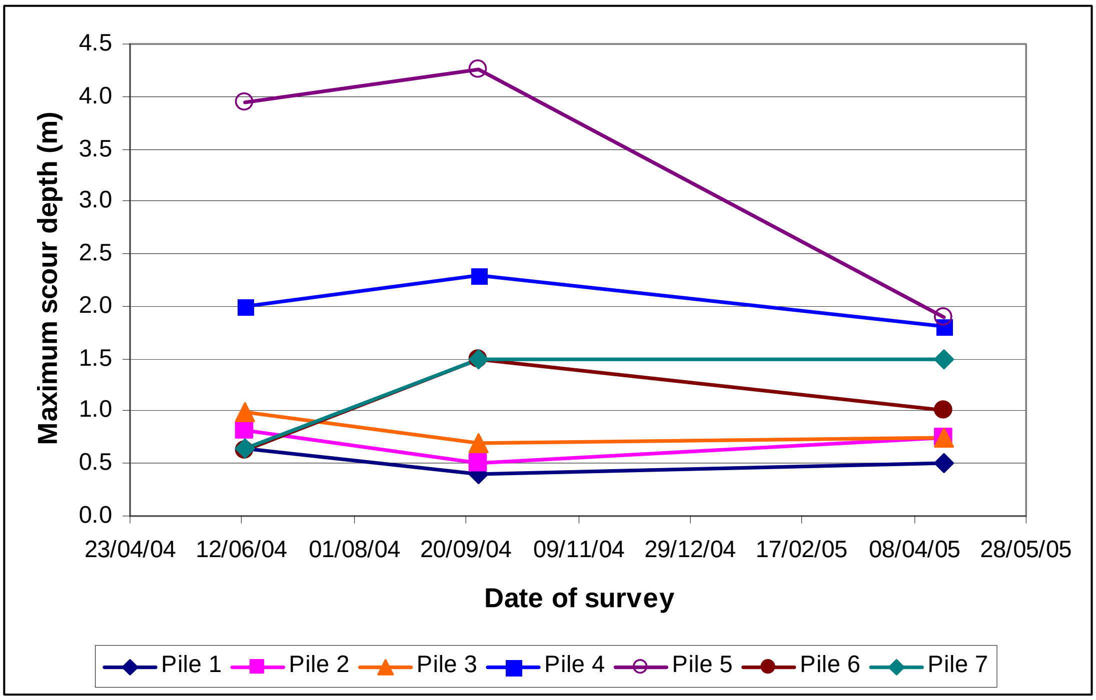

Figure 5: Time history of maximum scour depth post scour protection installation at each monopole.

Observations of scour protection

Divers made observations about the conditions of J-tubes, cables, scour and scour protection around the monopiles at similar times to the surveys. They also took photographs (HydroServ, 2004a, 2004b, 2005). An example is shown in Figure 6.

Figure 6: **Photograph of scour protection at pile 6 (Spring 2004, HydroServ).**

No rock armour was observed at Turbine 5. Only gravel was found within 8m of Turbine 5 during the June 2005 survey. In the other cases the distribution of armour stone was described as haphazard or sporadic. Other diver comments include “not much evidence of armour to N, S and E”, “rock armour thins out within 2m of pile”, “no armour was found to N or E” (Turbine 7) and “the rock rises away from the pile at a steep angle” (Turbine 3). It is apparent that in some cases the current-generated scour hole was not filled in by rock armour, but that some armour was dropped into the scour hole to form a loose falling-apron style layer of rock.

No data was available on the scour protection as it was built. Moreover, the seabed itself is relatively dynamic: sediment is observed in suspension in several of the photographs and the average bed levels change by as much as a metre between June 2005 and April 2005. Therefore, some of the rock armour may have been covered up by natural sand or gravel. It is noted, however, that average seabed levels fell at Turbines 1 to 6, indicating that armour is perhaps more likely to have been exposed than buried.

Cables were observed to free-span at most monopiles and this had caused damage to some of the cable cover as their movement in the current and waves has caused chaffing against J-tubes and rock armour. Rock armour was also observed to be lying on top, beside and under cables, indicating the possibility of damage.

Conclusions and recommendations

Other than for Figure 2 there was no data available to this project from the period immediately after installation of the piled foundations. The scour depth at that time, and prior to installation of rock, was about 4m or 0.8D, although it is not clear how long it took for this scour hole to form. The current only test in a physical model (Whitehouse et al, 2006) generated an equilibrium value of 4.8m or 0.96D, and more extreme wave and current conditions generated deeper scour depths. The non-availability of survey data meant that it was not possible to draw further conclusions about the scour depths at the monopiles without scour protection in place.

The three surveys that were available were for the situation for scour protection in place, although rock armour was not observed at Turbine 5. Scour has occurred around the rock armour that was placed, but a shortage of information about the rock armour scour protection as-built means that it is difficult to draw sound conclusions about the relationship between the armour configuration and the scour parameters. It is assumed that no filter layers or geotextile were laid and from the diver surveys it is apparent that the method of rock placement at Arklow has left irregular, and in some places (apparently) no armour around the monopiles. In some cases the placement of armour is associated with free-spanning of the cables, which were observed to have experienced some damage to their sheathing in several places due to abrasion between the cables and the J-tubes or rock. The irregular spacing of the armour is likely to mean that it will perform its function less well than compact, closely-fitting armour. There is more likely to be suffusion of bed material through the armour which may then sink into the seabed. Alternatively, at those sites were armour is not apparent, this may be because the seabed has risen in general to cover over the armour that was placed.

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Whitehouse, R.J.S., Sutherland, J. and O’Brien, D. 2006. Seabed scour assessment for offshore windfarm. Proceedings Third International Conference on Scour and Erosion, November 1-3, 2006. © CURNET, Gouda, The Netherlands, 2006.

Annex 10 Review of Scarweather Sands met mast scour

Two reviews of the Scarweather site are included in this Annex. They have not been compared for consistency.

Review 1

Scour at offshore foundations
Note prepared for SED02

This is an interesting dataset that has been reported in the literature from Scarweather Sands in the Bristol Channel (Harris *et al*., 2004).

Scour at Scarweather Sands (Bristol Channel)
Harris *et al*. (2004) looked at scour depths at the met mast on Scarweather and also made a time-series prediction of scour through tidal cycles.

For scour in slender pile in currents they used Sumer et al (1992) with S/D = 1.3 + standard deviation with standard deviation given as 0.7; i.e. $0.95 \le S/D \le 1.65$. They also tied in with some of the USA HEC 18 approach (HEC RAS, 2001). The data from Scarweather (United Utilities Green Energy Ltd) relates to the following structure:

- The met mast was installed at Scarweather in May 2003
- The pile OD is 2.2 m
- The position coincided with the 6 m depth contour

Shortly after installation a multi-beam sonar survey was completed in an area 300 m by 300 m centred on the mast. The survey was undertaken on the flood tide from around low water up to high water, two days after lowest neap tide – tidal range on the day of survey (25/6/2003) was about 4.8 m at Port Talbot.

The following observations were made:

- Scour effects were limited to the immediate area around the mast
- The seabed responded to changes in flow over a half-cycle of tide

At low water the scour hole was elongated in one direction, with the steepest scour hole slope about 29 deg and the shallower “downstream” slope about 14 degrees. At high water the bed all around was rougher (bedforms) and scour was more symmetrical.

From the survey data plotted it was shown that there were no bedforms in the immediate vicinity of the met mast in the scour hole.

The average scour hole depths were:

- Low water 1.3 m
- High water 0.6 m

It was considered that wave action was not significant during the period of measurements.

Harris et al noted that Sumer *et al*. would predict 3.6 m maximum equilibrium scour depth (including standard deviation). They then applied a time-varying prediction of scour using the HEC RAS (2001) version with Sumer and Fredsøe (2002) scour depth S(t) and timescale T* predictor functions, and worked out the dimensional time scale. The equations used were similar to the ones included in the DNV guidance (DNV, 2004). The predicted timeseries was somewhat spikey with scour development varying between 0.7m and 2.5m at the top of the spikes.

To make comparison with the field observations the values for Low and High water have been extracted. The predicted values were 0.69 m and 0.83 m which are of the same order as the average scour holes but the deepest value was not predicted and the predicted value was larger on High water than Low water, which is the opposite to that seen in the observations.

They recommend that continual (through tide) measurements of scour should be made along with area surveys to provide the dataset to validate a time-series type approach.

Review 2

United Utilities Green Energy Ltd. (UUGEL) pre-qualified for a 25 year-lease of a 10km^2 area of the seabed from the Crown Estate for the development of an offshore windfarm. The allocated site is in the lee of a sandbank known as Scarweather Sands, located towards the south-east of Swansea Bay in the Bristol Channel (Figure 1). The development site also extends across parts of the adjacent Hugo Bank. The Bristol channel is a macro tidal environment with some of the largest tidal ranges in the world.

A meteorological mast was installed at the Scarweather Sands offshore wind farm site in May 2003. The mast consisted of a 2.2m diameter mono-pile without scour protection. The position of the met mast coincided with the 6m depth contour (relative to Chart Datum, Port Talbot).

Shortly after installation, monitoring was undertaken using multi-beam sonar to assess the bathymetry in the immediate vicinity of the mast. The survey area was 300m by 300m centred on the mast location. The survey was undertaken over a flood tide from around low water up to high water two days after the lowest neap tide in the particular spring-neap cycle (Figure 2). Tidal corrections for the survey depths were undertaken automatically with reference to Chart Datum at Port Talbot.

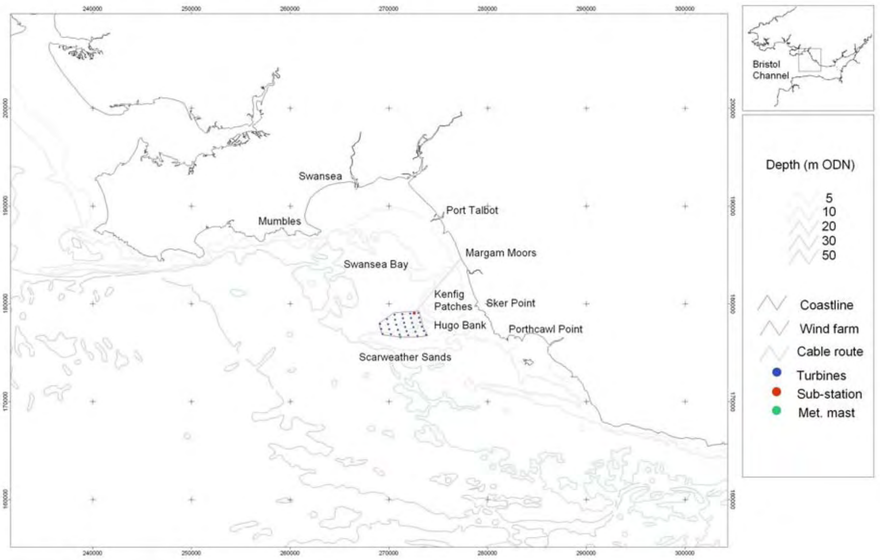

Figure 1: Location of Scarweather Offshore Wind Farm.

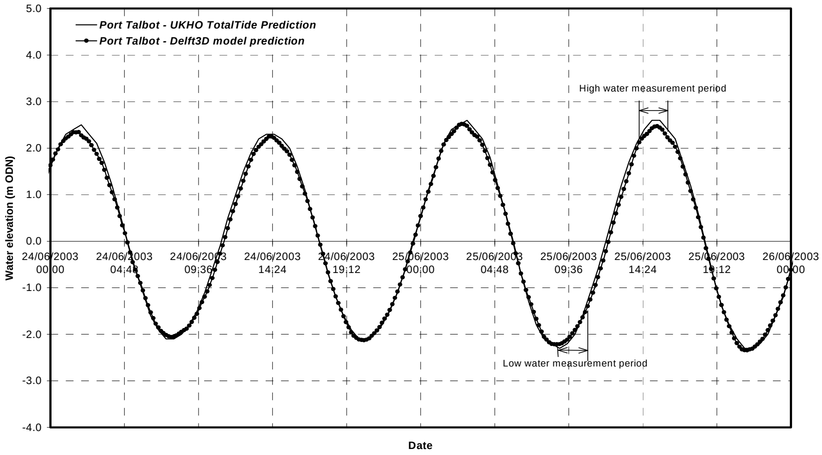

Figure 2: Predicted water level at Port Talbot.

Harris *et al.* (2004) looked at scour depths at the met. mast on Scarweather and also made a time-series prediction of scour through a spring-neap tidal cycle.

Table 1: Typical physical parameters at met mast site.

H_s (m)	2.8 – 4.4	Significant wave height
T_{mean} (s)	6.0	Mean wave period
d (m, msl)	9.9	Depth to mean sea level
$u_{c(max)}$ (m/s)	1.0 – 1.1	Maximum current
$u_{0m(rms)}$ (m/s)	0.2 – 1.4	Maximum root-mean-square wave orbital velocity
L (m)	23.1 – 52.3	Wave length

The seabed of the windfarm survey site is dominated by medium sand, which is fine grained and shelly on the large prominent sandbanks. More pebbly sands are located in the centre of the area; these patches were probably derived from the underlying glacial drift. Across the sand there are numerous ripples, mega-ripples and small sand waves with their crests in a generally north to south orientation indicating east/west current flow. In the location of the windfarm area these features are predominantly symmetrical and have wavelengths of less than 12m. On Scarweather Sands several larger asymmetrical features have been identified. These features infer a north-easterly direction of sediment transport.

The thickness of medium to fine grained shelly sand varies from approximately 9m on the north side of Scarweather Sands and 17m on the Hugo Bank to being very thin to absent (<2m) over much of the site, particularly in the northeast and southeast sections. The thickness of the sand is controlled primarily by the presence of sandbanks but is also thicker where the drift is infilling erosive features in the top of the bedrock.

The results from the multi-beam survey show that scour effects are limited to the immediate area around the mast. However, it is also evident that the seabed around the met. mast responds to changes in the flow even over a half tidal cycle (Figure 3).

Table 2: Angle of repose for different soils (from Hoffmans and Verheij, 1997).

Sediment type	Soil type	**Angle of repose ϕ (°)**
Coarse sand	Compact Firm Loose	45 38 32
Medium sand	Compact Firm Loose	40 34 30
Fine sand	Compact Firm Loose	30-34 28-30 26-28

Also evident in Figure 3 are the tidal effects on scour development. From the 'low water' plot, which corresponds to an incoming flood tide, the scour hole is elongated along the path of the tide with a steeper profile on the upstream side of the mast (≈ 29°). This is of the order of the angle of internal friction (30°) for loose medium sand (Table 2). The downstream slope is much less steep (≈ 14°). The scour hole corresponding to around high water shows a more symmetrical profile with a slightly elongated scour hole in the direction of the ebbing tide.

Around Low Water:

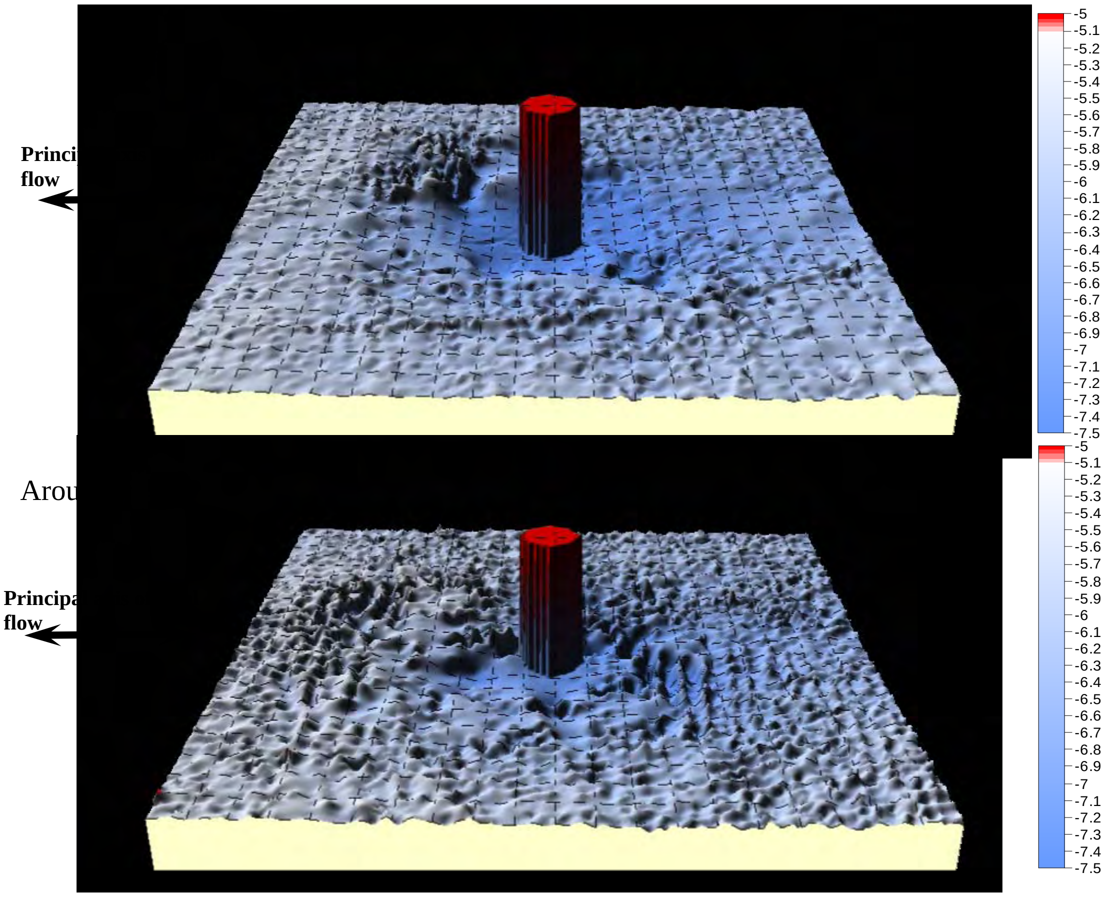

Figure 3: Surface plots showing evidence of scour around the met mast. Depths are in m relative to chart Datum (Port Talbot).

In order to assess the extent of the scoured hole, the bathymetry was divided into two perpendicular transects: one running north-south (NS) and one running east-west (EW). The orientation of the EW axis is close to the principal direction of tidal flow, and the NS axis is perpendicular to this approximated axis of flow. Separate transects were created for LW and HW (Figure 4). The estimated scour hole dimension is the mean of those derived from the NS and EW transects.

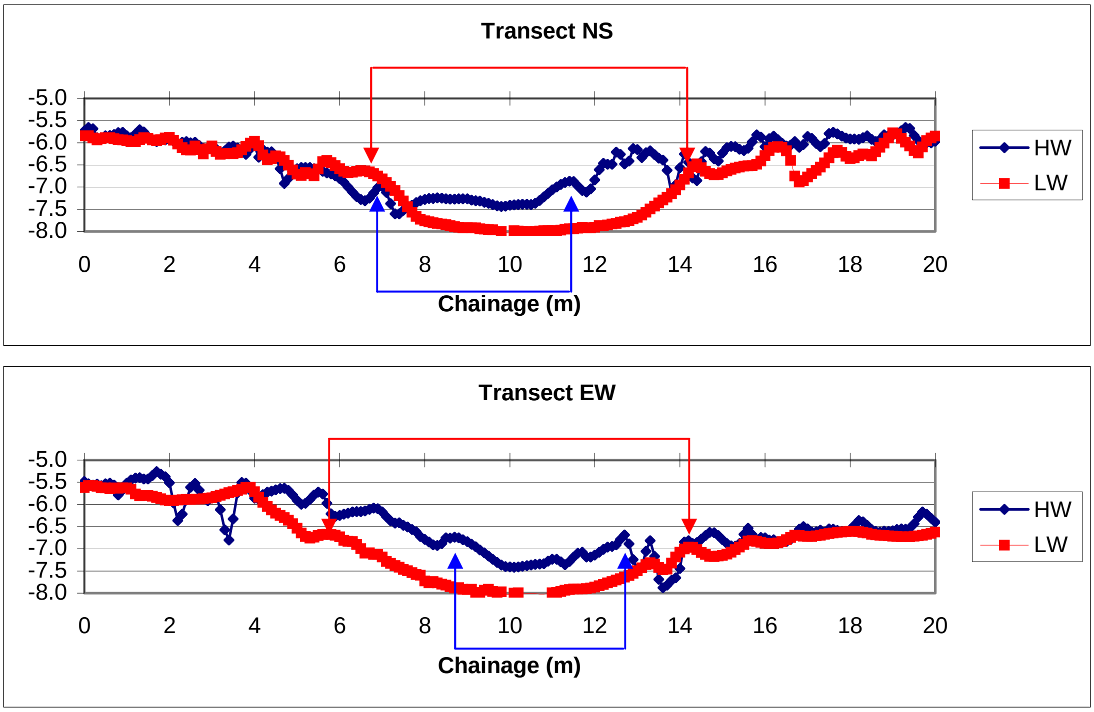

Figure 4: **Extent of scour at Transect NS (North-South through mast location) and Transect EW (East-West through the mast location).**

Table 3: **Summary of scour dimensions (shown in Figure 4).**

Tide	**Width (m)**			**Depth (m)**		
	NS	EW	Mean	NS	EW	Mean
LW	7.4	8.5	**8.0**	1.3	1.3	**1.3**
HW	4.5	4.0	**4.3**	0.4	0.7	**0.6**

The average scour hole depths for the low water and high water measurement periods are 1.3m and 0.6m, respectively. Using Sumer *et al.* (1992) and ignoring the effects of waves Harris *et al.* estimated the equilibrium scour depth to be 4.4m assuming a standard deviation of 0.7. However, to make an assessment of the scour depth through a tidal cycle they adopted a different approach. Using the HEC 18 formula of HEC RAS (2001) Harris *et al.* generated a time-varying depth of scour using an empirical expression to place the scour hole development within a time-frame (see Sumer and Fredsøe, 2002). The equations used were similar to the ones included in the DNV guidance (DNV, 2004). The predicted time-series was somewhat spikey with scour development varying scour between 0.7m and 2.5m at the top of the spikes.

To make comparison with the field observations the values for Low and High Water have been extracted. The predicted values are 0.69 m and 0.83 m which are of the same order as the average scour holes but the deepest value is not predicted and the predicted value is larger on High Water than Low Water, which is the opposite to that seen in the observations.

Harris et al (2004) recommend that continual (through tide) measurements of scour should be made along with area surveys to provide the dataset to validate a time-series type approach.

The dimensions of the scoured hole adjacent to Scarweather meteorological mast has been estimated in terms of a mean width and depth during LW and HW tidal stages (during neaps only). The greatest differences between LW and HW transects are found in the south-west quadrant of the scoured hole, whereas least vertical change appears north-east of the mast. From Table 3 it can be deduced that the width of the scoured hole in relation to the mast diameter, D ranges between 2.0D (LW) and 3.6D (HW). The depth of the scoured hole in relation to the mast diameter, D, ranges between 0.3D (LW) and 0.6 (HW).

The evidence for temporal variations in scour is expected to indicate that similar temporal variations can be expected at other sites such as Arklow and Scroby Sands. It also indicates that monitoring data to determine long-term scour development may include variation due to tidal scale scour processes, and in particular the differences in scour that might occur between spring and neap tide periods.

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Annex 11 Review of N7 monopile scour

Scour at offshore foundations
Note prepared for SED02
10 November 2006

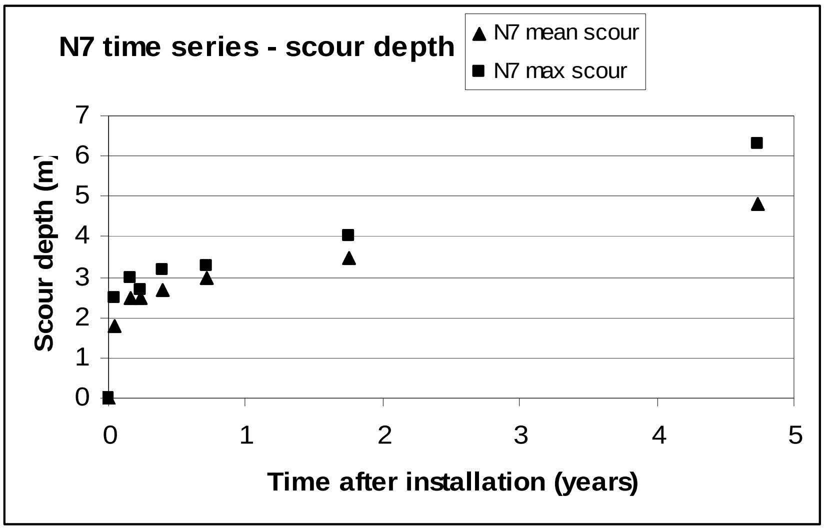
This is an interesting dataset from the Netherlands sector of the North Sea with measured scour depths taken at a number of discrete intervals over a period of nearly five years (Rudolph *et al*, 2005).

Scour at N7 (North Sea)
The paper by Rudolph *et al.* presents data for scour around a monopile at location N7 in the North Sea. The key parameters were as follows:

- Monopile OD = 6.0 m installed summer 1997
- Located in "coastal zone" at about MSL –7 m water depth
- Absolute water depth variation 5.2 m at LAT to 11 m at HAT
- Depth averaged current velocity of tide in range 0.25 to 0.75m/s
- The 100 yr storm has H_s = 4.6m, T_p = 16.1 s and an associated depth average current =1.3 m/s
- Since installation measurements have indicated H_s =4.4 m, T_p=14.0 s and u = 1.2 m/s
- Seabed consists of fine to medium dense sand
- No scour protection - however patches of gravel were detected in the area around the monopile

Time after installation (yrs)	Mean scour depth (m)	Maximum scour depth (m)
0.0	0.0	0.0
0.05	1.8	2.5
0.16	2.5	3.0
0.24	2.5	2.7
0.39	2.7	3.2
0.72	3.0	3.3
1.76	3.5	4.0
4.73	4.8	6.3

Here the terms “mean” and “maximum” appear to indicate the mean (i.e. averaged around the pile) and maximum values found in the scour pit. The time series is shown in the following figure.



Analysis of the Digital Terrain Model in the paper showing bed levels around the pile indicated that after nearly two years the scour hole locally had an extent from the edge of the pile to ambient bed level of about 30m associated with the maximum depth of 4.0 m on the south-west side. However, the scour depression had an overall extent of about 200 m according to Rudolph *et al*.

After a duration of nearly 5 years the scour depth had increased to 6.3 m, equivalent to the pile diameter – actual value of scour depth 1.05D. The mean scour depth was 4.8m or 0.8D.

References

Rudolph, D., Bos, K.J., Luijendijk, A.P., Rietema, K. and Out, J.M.M. (2004). Scour around offshore structures – analysis of field measurements. Proceedings 2nd International Conference on Scour and Erosion, 14-17 November , Singapore, eds. Chiew, Y-M, Lim, S-Y and Cheng, N-S. Volume 1, pp. 400-407.

Definitions

OD – Outside Diameter of foundation pile
MSL – Mean Sea Level
LAT – Lowest Astronomical Tide
HAT – Highest Astronomical Tide
H_s – Significant wave height
T_p – Peak period of waves
u – depth-averaged current speed

Annex 12 Review of Otzumer Balje monopile scour

Pile structure in Otzumer Balje tidal inlet (Noormets et al, 2003).

A single steel pile was installed in August 2002 in the 500m wide channel of the East Frisian Wadden Sea on the Northwest coast of Germany. The D = 1.5m diameter pile was of plain steel driven into the bed of the tidal channel connecting the North Sea to the backbarrier area. The water depth in the inlet was between 7 and 13m deep below Chart Datum, and the mean depth at the pile was 13.3m. The sediments at the site comprised a mean grain size of 0.3mm.

The mean semi-diurnal tidal range was 2.6m and the maximum depth averaged flow velocity was 1.4m/s.

The pile was installed on 20 August 2002 and surveys were made on 20 January 2003 and 27 February 2003. A scour pit was recorded within the high resolution multibeam echo sounder dataset, which also indicated the presence of sandwaves and an apparent area of deposition of sediment lying to seawards of the pile. This was described as a sand bar with height 1m and length 60m. The scour pit was recorded to have a depth of about 2.2m and a lateral extent (diameter) of 14 to 20m. The scour depth to pile diameter ratio was 1.47D.

Data collected on spring and neap tides indicated that there was some fluctuation in the scour hole parameters, with there being some evidence for part of the scour hole being deeper by 0.4m on neap tides than on flood tides. Noormets et al (2003) compared predictions from Richardson and Davis (2001) and Jones and Sheppard (2000) with the data and found the former overpredicted the depth by 28% and the latter underpredicted by 43%. They concluded that an equation for predicting scour in tidal flow environments is required.

References

Jones, J.S. and Sheppard, D.M. (2000). Scour at wide bridge piers. ASCE, US Department of Transportation, Federal Highway Administration, Turner-Fairbank Highway Research Center. 10pp.

Noormets, R., Ernsten, V.B., Bartholamä, A., Flemming, B. and Hebbeln, D. (2003). Local scour in a tidal environment: a case study from the Otzumer Balje tidal inlet, southern North Sea – preliminary results. Poster reproduced in report on Offshore Wind Turbines Situated in Areas with Strong Tidal Currents. Offshore Center Danmark DOC. NO. 6004RE01ER1, February 2006. Esbjerg, Denmark.

Richardson, E.W. and Davis, S.R. (2001). Evaluating scour at bridges. Hydraulic Engineering Circular No. 18. Fourth Edition, National Highway Institute, Federal Highway Administration, U.S. Department of Transportation.

Annex 13 Example method of calculating scour depth from bathymetric datasets

SED02 calculation of scour depths

a) At Scroby the digital datasets were used to extract the observed scour depths in a five stage process:

1) From swathe bathymetry a Digital Elevation Model based on 1m cells was created in Fledermaus ©.
2) Two orthogonal sections were analysed in order to assess the ambient water depth at the pile location; this was found to be especially important on sloping areas of seabed.
3) The deepest location of scour was identified and the scour depth automatically calculated.
4) The maximum and minimum width of the scour hole was estimated by circling around the pile with the Fledermaus "Section" tool.
5) Some sections were also taken for identification of background bedforms that could be picked up in the survey.

When investigating the data it was necessary to bear in mind the vertical and horizontal accuracies and the resolution. The sounding accuracy near monopiles can be affected by multiple echoes from the structure and the data processing will have been carried out to remove some of these artefacts.

Four timeseries of sections were produced as examples.

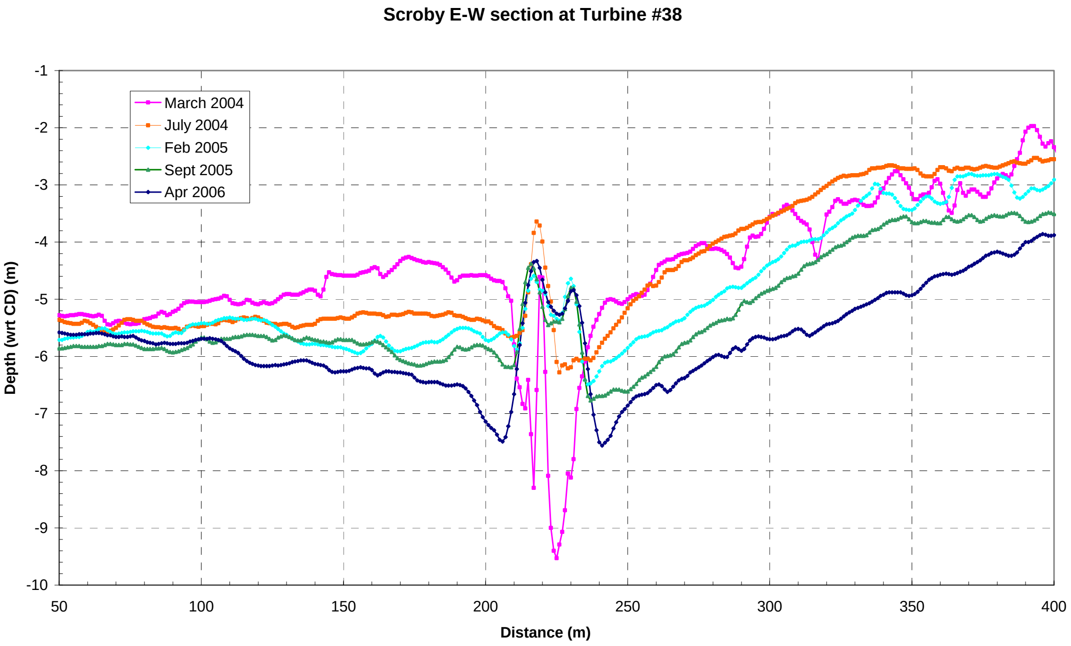


Figure 1: Dropping bed case at turbine #38 (2004-2006).

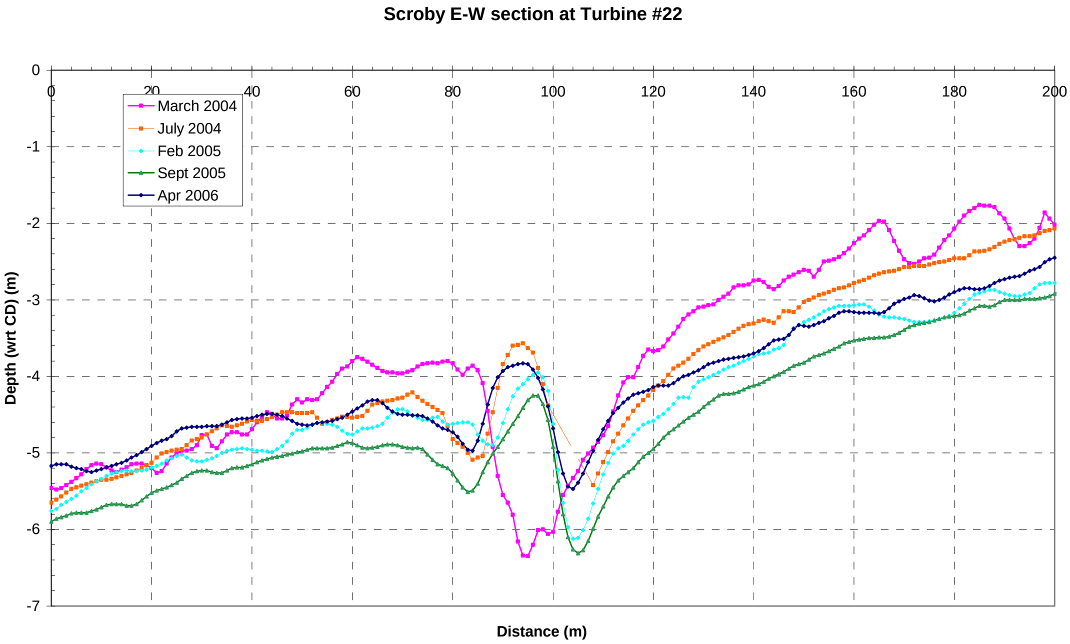


Figure 2: Accreting case at turbine #22 (2005-2006).

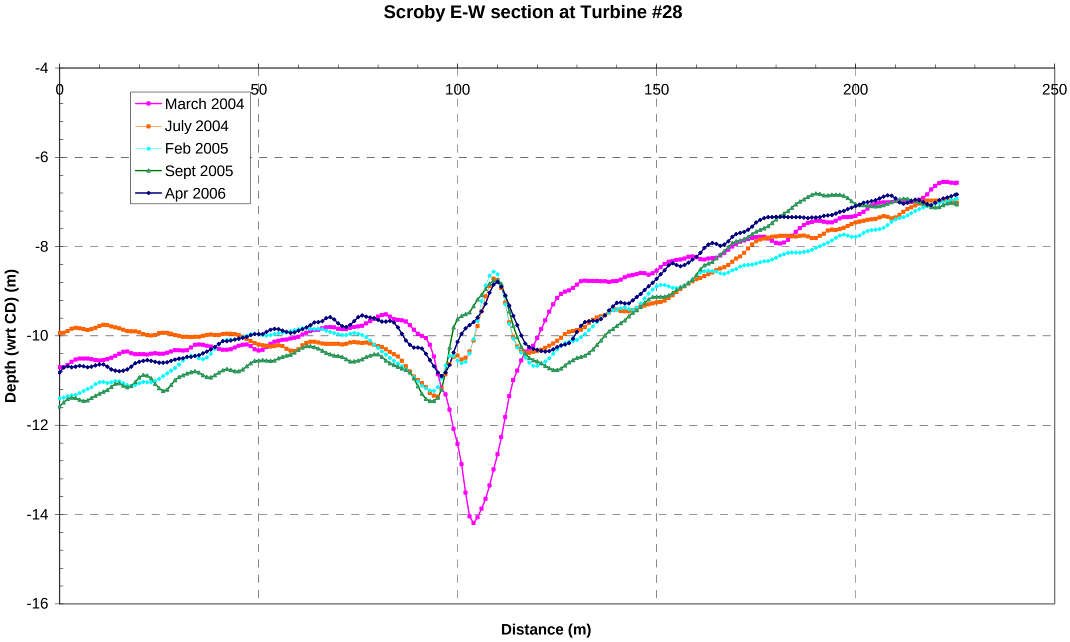


Figure 3: Complex case at turbine #28 where the bed level dropped and accreted (2004-2006).

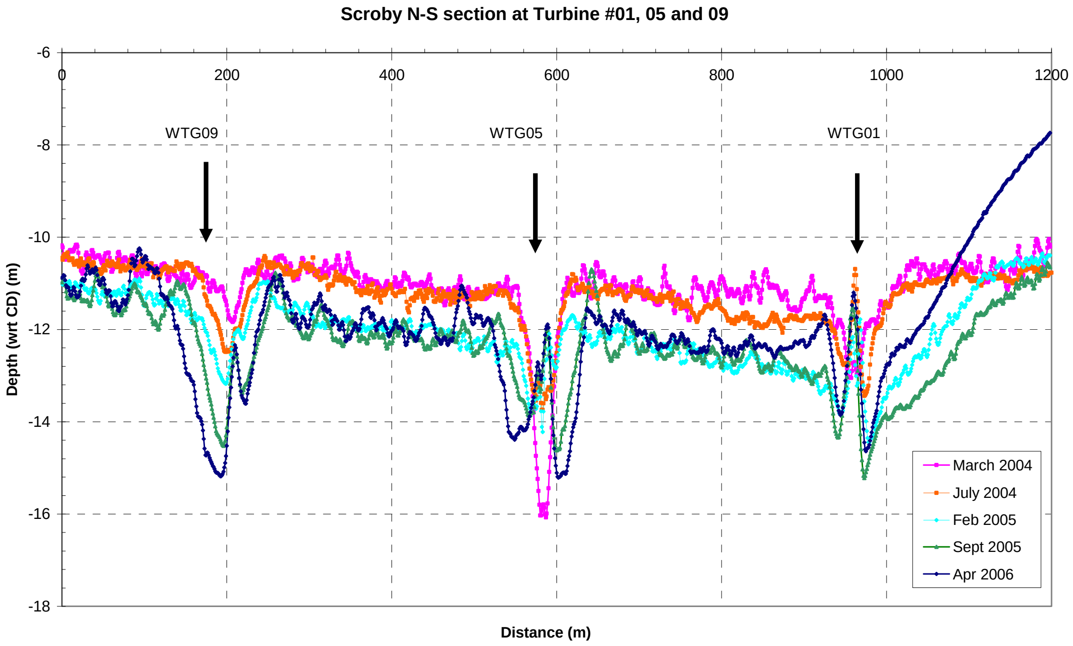


Figure 4: **Section shown the bed dropping between monopiles along a north-south section at turbines #9, #5 and #1 (2004-2006).**

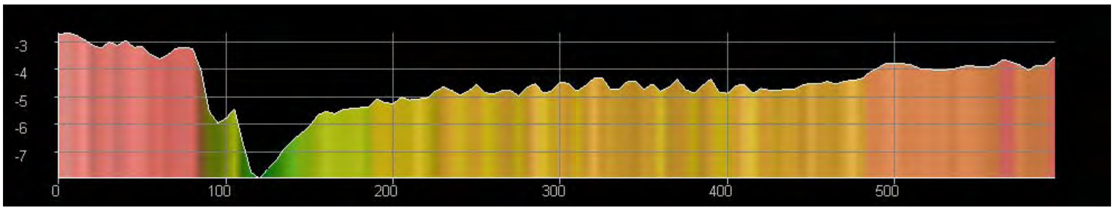


Figure 5: **Long section example at turbine #23 from April 2006.**

The section in Figure 5 along the scour wake from turbine # 23 shows an upstream depth of 3m, the scour pit at 120m reaching near to 8 m depth and a scour wake approximately 2m below the upstream (background) level. The bed level returns to background elevation at approximately 500m chainage, i.e. approx 380m from the monopile.

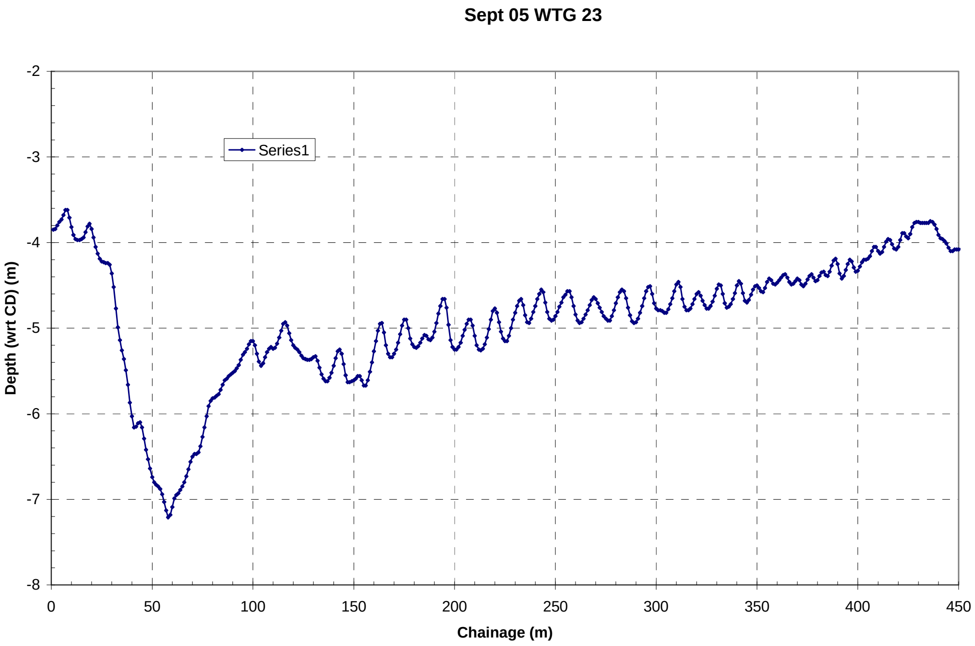


Figure 6: **The same north-south section as was shown in Figure 5 but from September 2005.**

b) At Kentish Flats the PDFs of pre-construction were compared with three post construction surveys. The estimate of depth was probably to the nearest ± 0.25m at best and distance ±5m.

c) At other sites the scour depths and extents were derived manually from the various charts produced by the survey companies.

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