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AN ASSESSMENT OF FIELD DATA FOR SCOUR AT OFFSHORE WIND TURBINE FOUNDATIONS

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A range of offshore wind farm projects has been built in recent years to help satisfy the increasing demand for 'clean energy' through renewable resources. The development of scour due to waves and currents around the installed foundations has been monitored and the data for five contrasting sites has been analysed in the present paper. The site specific nature of scour at the five sites is discussed and the results are presented in a comparative fashion. At one of the sites the seabed is underlain by a marine clay which has (to date) limited the development of scour at those turbines, whilst those sites with unconstrained depths of sandy sediments show a deeper scour depth develops. Based on the combined results from the five sites conclusions are drawn about the range of scour depth development that can be expected and a number of recommendations are made to improve the understanding of scour development at offshore wind farm foundations.

Key Words: *Foundations, offshore, wind farms, scour, scour protection.*

1. BACKGROUND TO STUDY

The new results from the study presented in this paper were obtained in order to evaluate the scour development observed at a range of completed offshore wind farm projects. The results provide a clearer picture of the scour that can be expected to develop at monopile foundations in the marine environment. This adds knowledge to the existing guidance available from DNV[1)] which, for scour caused by currents, recommends a scour depth S of 1.3 times the foundation diameter D is used (i.e. S/D= 1.3).

Scour around marine structures is well recognised as an engineering issue[2)]. Where scour is anticipated to be sufficiently severe to cause problems of structural stability or other related damage, scour protection is required [3,4,5)]. Also scour protection may be required to protect the cables that run between turbines where they pass from being buried under the seabed up into the transition piece on the foundation. 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.

The core aim of the research was to provide a higher level of understanding of the scour process and to inform the design and evaluation of wind farms. For a complete understanding of the bed level changes the variation over the design life of the wind farm needs to be considered; this may arise from regional or local changes due to migration of seabed features such as banks, sandwaves or channels as well as local scour.

2. INTRODUCING THE SCOUR DATASET

Data for scour development have been obtained from the five sites shown in Figure 1. A dataset with the key

Fig. 1 Location of offshore wind farm sites studied in this paper around the coast of England and Wales and Ireland [note: Scarweather Sands has a met mast which is referred to in the paper]

parameters for each foundation was created comprising of:

- Structure information – dimensions and installation date
- Environmental data – general information on water depth/variation, currents, waves, sediment type
- Depth of scour at structure – defined as depth of hole below surrounding local seabed level at the time of survey (see Figure 2)

For the present analysis only a broad categorisation of environmental conditions was required. The dataset for scour was based on analysis of the ambient and local scoured seabed level around the foundation – hence the scour depth is calculated directly – and the extent of scouring. 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.

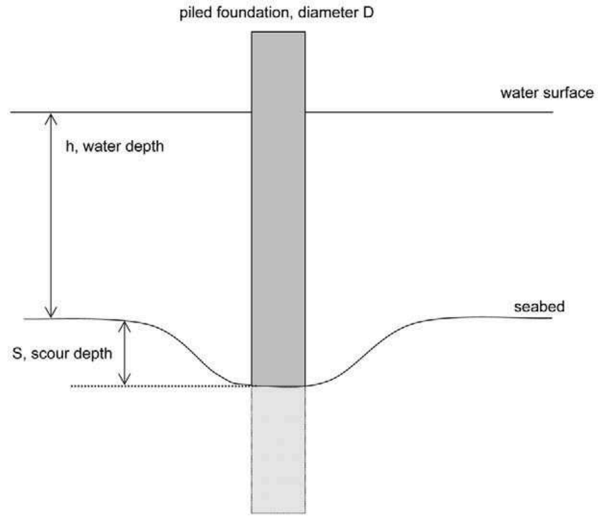

Fig. 2 Schematic diagram of parameters used in the analysis of scour depth

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) with the following characteristics:

- <u>Barrow, north east Irish Sea</u>
  moderately exposed to waves, moderate currents, gravelley sand, sand and sandy clay, stable seabed environment, deep water
- <u>Kentish Flats, outer Thames Estuary</u>
  moderately exposed to waves, moderate currents, superficial fine sand overlying stable seabed environment, shallow water
- <u>Scroby Sands, southern North Sea</u>
  exposed to waves, strong currents, sand, dynamic sandbank environment, shallow water, presence of mobile bedforms
- <u>North Hoyle, southern Irish Sea</u>
  moderately sheltered from waves, moderate currents, stable seabed environment, deep water
- <u>Arklow Bank, western St George's Channel, Ireland</u>
  exposed to waves, strong currents, sandy gravel, dynamic seabed environment, shallow water

Previously Harris, *et al.* [6)] described scour measurements around the met mast at the Scarweather Sands site which has the following characteristics.

- very exposed to waves, strong currents, medium sand, dynamic seabed environment, shallow water.

The sites studied, whilst sharing some characteristics, were all unique. This was both a benefit, as it allowed the study of different physical conditions in relation to scour, and also a problem as it made it more difficult to draw common conclusions based on the datasets. All sites used monopile foundations.

3. DISCUSSION OF SITE SPECIFIC DATASETS

Each of the sites has been analysed and observations have been made as follows:

(1) BARROW

Scour depths were measured at thirteen of the thirty 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. Depressions from the spudcans of the jack-up barge used for installation were visible in the seabed.

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 key parameters that determine the amount of scour are the composition and thickness of the surficial sediment layer. Figure 3(a) shows the measured scour depths for all 30 of the monopiles with respect to the thickness of the surficial sediment layer. Some of the turbines have well developed scour but at some of the turbines scour has been restricted by the thickness of the surficial layer. The turbines that have experienced the greatest seabed scour are those that lie to the west where the seabed consists of fine to medium sand and the thickness of the surficial layer is greatest. The depth limited cases generally lie to the east where the seabed consists of glacial till and the detail of this limiting effect is indicated in Figure 3(b).

The measured scour depths were overpredicted slightly by DNV guidelines [1] and to a greater extent by the Opti-Pile Design Tool [7]. The most likely

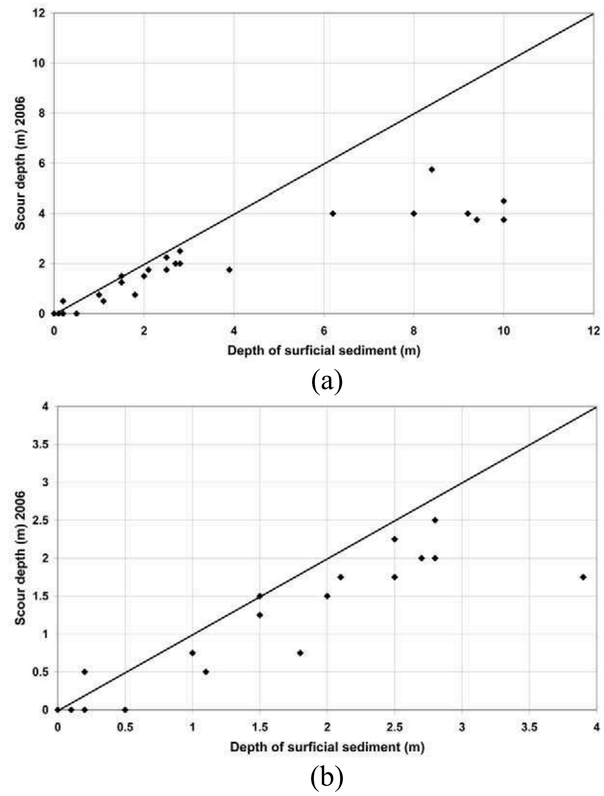

Fig. 3 Barrow data for 2006 survey showing the influence of clay on the scour depth formation: (a) complete dataset and (b) detail of scour depths less than 4m

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.

(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 thirty turbine foundations. The sites monitored were on the east side of the turbine array and the seabed had a surficial covering of fine sand and shell overlying clay, other than where there were greater thicknesses of sands and clays present in the infill deposits in a palaeo river channel running across the site.

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 was not clear how much of the initial "scour" depression around the turbines was 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 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 were 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.

(3) SCROBY SANDS

The scour depths at this site were measured in March 2004 following installation of the thirty foundation piles with diameter of 4.2m; the foundations were installed over the period November 2003 to February 2004. Therefore, the March 2004 survey contained 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 was expected to have resulted from spatial variations in water depth and wave-current exposure as well as the time elapsed since installation. Inevitably there will always also be some natural variability in the scour produced under similar prevailing conditions.

With the information presently to hand it was not known the minimum period of time that scour took to form to a significant proportion of its ultimate value. However, according to den Boon, *et al.*[7] scour at site was observed to form in a few tidal cycles before scour protection was installed in the scour holes. This rapid development of scour was also referred to by Høgedal and Hald [8]. Following development of the scour hole scour protection rock was installed.

(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 comprised of 4.0m diameter monopiles which were installed over the period April to July 2003. The seabed sediments were predominantly gravels and sandy gravels and below the top one metre of soil there was more compact gravelly clay.

The scour depths recorded in 2004 were no greater than 0.125D – although scour was recorded at only ten of the thirty 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.

(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 (unknown duration) delay between installation of the 5m diameter monopile foundations and the installation of scour protection rock. This was sufficient for scour holes to develop around the monopiles, due to the tidal current alone (Figure 4 – from [9]). Side scan sonar was used to measure the size of the scour holes and an example of a contour plot derived from side-scan sonar is shown in Figure 4. The scour hole was fairly symmetrical, with smooth sides and was about 4m deep (S/D = 0.8). It had a similar depth and shape to the scour hole measured in the laboratory current-only tests reported by Whitehouse, *et al.*[9].

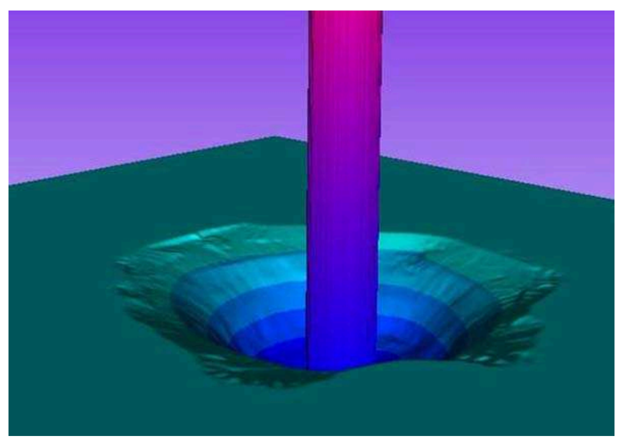

Fig. 4 Scour hole at Arklow (from Whitehouse, *et al.*[9])

4. OVERALL PRESENTATION OF RESULTS

The scour data available from the built sites have been brought together and plotted to show how the scour depths compare in terms of scour depth and ambient water depth, i.e. water depth away from the influence of scour (Figure 2). In the present analysis depth below

Chart Datum has been used to characterize the water depth.

The influence of ambient water depth has been investigated in Figure 5. This figure shows that the data from the different sites occupy a number of clusters. 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; both of these sites are on the top of offshore sandbanks. The Kentish Flats site has similar water depths to the lower depths at Scroby but smaller 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 controlling influence of sediment type highlighted in Figure 3 is evident in the Barrow data shown on Figure 5, 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 gravelly bed overlying more resistant gravelly clay, and at Kentish Flats where there is a layer of fine sand overlying clay. Scroby Sands and Arklow Bank both have thick mobile bed deposits, with the sediment being coarser at Arklow than at Scroby.

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

The data have been re-plotted in terms of the ratio of scour depth to pile diameter and water depth to pile diameter ratio (Figure 6). This is an accepted form of scaling for scour data[4,5]. The deepest scour equates to a ratio of S/D = 1.4 and the DNV guidance[1] 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 represented a case for which scour could have fully developed, although the influence of the flow and wave conditions just prior to the survey may have had an influence on the observed value of scour depth. It is possible that the scour at Barrow on the

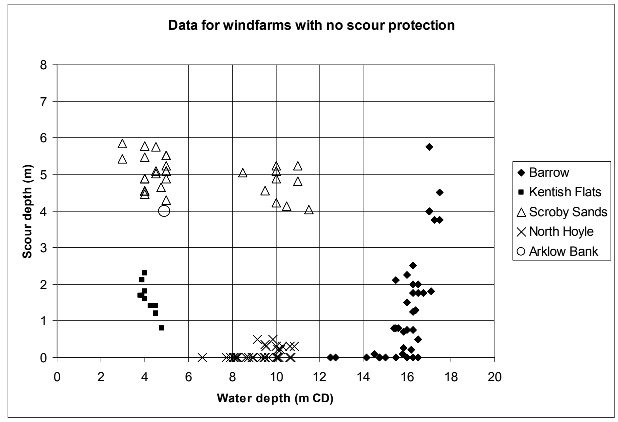

Fig. 5 Compilation of data for scour depth at the five sites shown in Figure 1

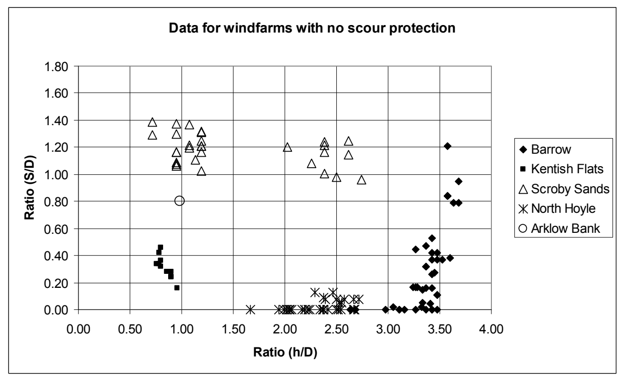

Fig. 6 Compilation of scour depths for the five sites shown in Figure 1 plotted in terms of non-dimensional parameters

sandy sediments may continue to get deeper with time, so it will be valuable to examine the monitoring data collected in future. The data from Scarweather[6] – 2.2m diameter foundation – indicates scour varies through the tide with Low Water and High Water values of S/D = 0.27 and 0.59 respectively. Comparing these results with Figure 6 for the water depth ratio h/D = 2.7 (ignoring tidal variation) it can be seen these values lie above the North Hoyle data and below Scroby Sands.

Finally, it is noted that empirical formulae for scour prediction[3,4,5] indicate a reduction in scour depth due to a reduction in water depth, for values of the ratio h/D which are less than 3 to 5. It is apparent from the Barrow and Scroby data that such a reduction in scour is not supported by the present dataset.

5. CONCLUSIONS

The available scour data for offshore wind farm sites have been collated and analysis of that data 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, for example where 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 to develop in a given time or limited in depth.

In comparison with the existing predictive formulae in guidance[1)] and the Opti-Pile method[7)] the following conclusions can be made. DNV guidance suggests that current-induced scour is S/D = 1.3 and the Opti-Pile method assumes the greatest scour depth that can be achieved is S/D = 1.75 but a reduction factor is applied in shallow water based on the h/D ratio. The wind farm 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 advised in DNV guidance but it is not clear whether that value (observed at Scroby Sands) was fully developed and what range of wave and current forcing had been experienced prior to the measurement being made.

Based on laboratory experience the stronger currents occurring under spring tides can be expected to produce deeper scour than under neap tides. There is some evidence for this from the measurements at Otzumer Balje inlet[10)]. Under more extreme conditions, e.g. storm surges, larger currents may be generated and wave action can become significantly more energetic producing a more mobile seabed. 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 and associated storm currents. Field data is required to answer this.

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. The time-series of scour from the Scarweather Sands met mast shows changes at tidal time-scale[6)], but for a smaller diameter pile than is used for the wind farm foundations and without a complete complimentary set of metocean data. Therefore, the data required to assess the range of scour responses at different time-scales is not available presently from any offshore wind farm site for a large diameter foundation.

The following recommendations arising from the research are proposed:

1. 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 need to be catalogued centrally in a consistent fashion so that future operational research can be facilitated.
2. Carry out analysis of the time variation of scour over the period of tides, spring-neap cycles and with the influence of storm events. There is evidence from existing analysis and modelling 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[11)].

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