Marine scour: lessons from Nature's laboratory

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Abstract

Scour associated with anthropogenic activities in the marine environment has exercised the minds of scientists and engineers for decades. Despite the advances in understanding there remain areas of uncertainty which require further examination and challenges that require further research. Whilst real-life scour problems often help formulate the questions for detailed laboratory experiments, the associated information is less often used to answer some of those questions and yet the available data can offer the chance of exploring the scour at full-scale using real marine soils, albeit with all the inherent uncertainty associated with measurements obtained in the field. It can be argued that through the interpretation of these data, it forces the scientist and engineer to not only explore in more detail the limitations of the measurements but to engage in the full range of processes, whether physical (e.g. hydrodynamics and meteorological forcing) or biological (e.g. marine growth, benthic organisms) that impact on structures placed in what are often, very challenging environments.

1. Introduction

As engineers and scientists, investigating scour associated with anthropogenic activities in the marine environment continues to be governed by uncertainty related to the complexity of marine soils and different foundations as well as the performance of placed scour protection measures. With growing sea trade and our continued exploitation of marine resources, scour associated with these anthropogenic activities continues to be of importance. Research into scour development associated with the placement of foundation structures, cables and pipelines or vessel movement in the marine environment is a fruitful area of study and combined with all the research conducted into bridge scour amounts to a significant level of knowledge that has been gained over the years.

Numerous studies have been undertaken for the offshore oil and gas industry, although despite the rapid growth in the 1970's in oil and gas developments the wealth of knowledge and data obtained from them has not always been openly available either due to commercial sensitivity or because there was no formal framework for capturing the results of any monitoring undertaken.

The continuing expansion of port facilities and advances in ship design, including larger vessels, have resulted in a requirement to assess further the impact of vessels on the stability of port structures as well as the need for navigation and sea defence structures to protect coastal areas and port facilities from the dynamic and energetic environments in which they are located under a changing climate.

Over the last two decades the drive for developing offshore renewables resources (wind, tides, waves) has led to specific needs for scour hazard assessment relating to the associated foundation structures and cabling necessary for in-field transmission and power export. These developments have been central to driving further research into obtaining a better understanding of the scour processes related to placing structures in coastal and offshore regions. Indeed, the results obtained from offshore wind developments have not only helped to drive many of the recent research questions in marine scour they have also started to provide some insight into the behaviour of seabed/ structure interaction in a range of environments, in what we term "Nature's laboratory".

2. Monitoring programmes

Within the European offshore wind industry there is a requirement as part of the consents and licensing process for routine monitoring to be carried out. Two of the physical processes routinely monitored are scour development and general morphological change. The management of scour or scour protection measures through monitoring for comparison with pre-defined bed level design or threshold criteria allows a risk based approach to make decisions regarding remedial or mitigation measures to be adopted (Whitehouse *et al*., 2011b, Harris and Whitehouse, 2012). The requirement for undertaking monitoring during the operational life of a project is not only considered to be good practice it is described as a requirement under Det Norkse Veritas's (DNV) Offshore Standard "Design of Offshore Wind Turbine Structures", DNV-OS-J201 (2014).

Within the UK's offshore renewable industry, the importance of monitoring was recognised very early on. In 2005, a Research Advisory Group (RAG) was established by the Department for Trade and Industry (DTI) to consider research priorities in relation to the potential environmental impacts of offshore wind farm (OWF) developments and their impacts on other users of the sea. Three priority research projects were taken forward:

- Review of Round 1 sediment process monitoring data – lessons learnt (SED01);
- Dynamics of scour pits and scour protection (SED02); and
- Review of channel migration (SED06) – not covered in this paper.

The aim of SED01 was to draw together the sediment process monitoring work carried out on Round 1 offshore wind farm developments and review the methods, data, results and impacts in order to identify lessons learnt and to provide relevant recommendations for monitoring of Round 2 developments (DECC, 2008a), whilst establishing a coherent evidence base. SED02 dealt specifically with those aspects of sediment monitoring related to scouring around wind turbine foundations (DECC, 2008b) with the aim of examining scour patterns and identifying lessons learnt. A further study covering both SED01 and SED02 topics was reported on in COWRIE (2010), drawing upon available new data at OWF sites in UK and European waters.

Since then there has been a further Round of offshore wind projects in the UK, Round 3, which will involve the construction of thousands of foundations in deeper water depths, which will generate new challenges for construction, operation and maintenance.

3. Uniform sandy sediments

A substantial amount of research has been conducted into scour in uniform sandy soils over many decades and this has resulted in a large number of approaches being proposed to estimate scouring in such non-cohesive soils. Summaries of many of these studies are presented by Herbich (1981), Herbich *et al*. (1984), Breusers and Raudkivi (1991), Hoffmans and Verheij (1997), Whitehouse (1998), Melville and Coleman (2000) and Sumer and Fredsøe (2002).

A large number of predictive formulae have been proposed over the years to determine equilibrium local scour. Some of these formula are valid for clearwater conditions or live-bed conditions only, whilst other formulae are able to be applied over both conditions (see for example Sheppard *et al*., 2011).

Clearwater scour is defined as occurring when the bed material upstream of the scouring location remains at rest, whilst live-bed scour conditions exist when there is general sediment transport taking place across the bed. Under tidal conditions at a given site both clearwater and live-bed conditions can exist over a tidal cycle or even over a single tide.

Commonly, when predicting scour in the marine environment two general forms of predictive formulae are applied. The first type follow the form as proposed by Breusers *et al*. (1977), whilst the second type tend to follow the form of that proposed by Richardson and Davis (2001).

Breusers *et al*. developed an empirical relationship for scour based on various observations including measurements of scouring under tidal flow and which can be expressed as:

$$S_C = 2.0 K_1 K_2 K_3 D_p \tanh\left(\frac{h}{D}\right) \tag{1}$$

in which:

D = the pile diameter or pier width (m)

h = total water depth (m)

K_1 = correction factor for pile nose shape

K_2 = correction factor for angle of attack of flow

K_3 = correction factor for bed condition

where:

$$K_3 = 0 \qquad \text{If} \quad \frac{U_c}{U_{cr}} < 0.5$$

$$K_3 = 2\left(\frac{U_c}{U_{cr}}\right)\text{-}1 \qquad \text{If} \quad 0.5 \le \frac{U_c}{U_{cr}} < 1$$

$$K_3 = 1 \qquad \text{If} \quad \frac{U_c}{U_{cr}} \ge 1$$

U_c is the ambient depth-averaged current speed and U_{cr} is the threshold depth-averaged current speed for sediment motion to be initiated on the open seabed. Therefore, K_3 allows for both clearwater and live-bed scour to be taken into account. S_C = equilibrium scour depth under steady flow conditions.

Breusers *et al*. recommended a value of 2.0 for the leading coefficient rather than 1.5, "to be on the safe side".

The empirical approach of Richardson and Davis (2001) is the formulation used in the previous release of the US Department of Transport, Federal Highway Administration (FHWA) Hydraulic Engineering Circular (HEC) No.18 for determining scour at bridges.

$$S_C = 2.0 K_1 K_2 K_3 K_4 h F_r^{0.43} \left(\frac{D}{h}\right)^{0.65} \tag{2}$$

where:

D = the pile diameter (m)

h = flow depth (m)

K_1 = correction factor for pile nose shape

K_2 = correction factor for angle of attack of flow

K_3 = correction factor for bed condition

K_4 = correction factor for size of bed material

F_r = Froude number

S_C = Equilibrium scour depth under steady flow

From some of the early laboratory studies Breusers and Raudkivi (1991) suggested that a first order estimate of the local equilibrium scour depth is $2.3K_2D$ in relatively deep flow. K_2 is the correction factor for angle of attack of flow on a non-cylindrical structure, taking a value of 1 for a single cylindrical foundation pile. In addition, even where refinement is warranted, the effect of the shape factor (K_1) is eclipsed by a small angularity in the approach flow (for non-circular piles). In addition, if $U_{cr} < U_c < 4U_{cr}$ the leading coefficient can be determined graphically. This is comparable with the studies summarised in Sumer and Fredsøe (2002) where the mean value of $S = 1.3\ D$ omits the standard deviation term of 0.7. Including this term would give a value of $S/D = 2.0$, hence of the same magnitude as Equations (1) and (2).

It should be noted that these two predictive formulae are fundamentally different. The use of the Froude number in the approach of Richardson and Davis implies that increasing velocities give increasing scour depth, whilst the threshold criteria in Breusers *et al*. limits scour development above the value of $U/U_{cr} \geq 1$. The Froude number, F_r is used as a determination of the nature of the flow, that is, whether it is critical, super-critical or sub-critical and is defined as:

$$F_r = \frac{U_c}{\sqrt{gh}} \tag{3}$$

g is the gravitational acceleration, and all other terms are as defined previously.

In both methods, they fail to respond correctly to scour formation in deeper water. The processes behind scour in shallow and deep water are fundamentally different. In shallow water, that part of the total energy at the front of the pile that is due to the hydrostatic component is small relative to the kinetic part. This gives a stagnation point close to the water surface and a significant down-flow down the face of the pile. In deeper water, the hydrostatic component is larger, which combined with the kinetic component, leads to a more even pressure field at the face of the pile, typically, and the stagnation point is located closer to the seabed with corresponding weaker down-flows.

Therefore, whilst neither approach is ideal for estimating scour in the marine environment they are used frequently with some success. In fact good practise is to use a variety of predictive equations and evaluate the most likely result and spread in predictions. A range of input conditions for hydrodynamics and sediment properties should also be included in a sensitivity analysis.

With very few experimental studies having been conducted under tidal conditions, evidence from the field allows extrapolation to uni-directional flow experiments. The work of Escarameia and May (1999) investigated scouring under tidal conditions. This laboratory study showed that the scour depth continues to increase after the first half cycle (i.e. a change in flow direction) and equilibrium scour depth would be reached after about 4 to 5 half tidal cycles. Jensen (2006) presented recommendations for the prediction of local scour for piles under tidal conditions. The most recently published study to assess scour development under tidal conditions is that of McGovern *et al*. (2014). They concluded that scour time development is slower under tidal conditions than that under uni-directional currents and the magnitude of scour development was shallower compared with that obtained in their uni-directional test. However, this second conclusion may be a function of the short test durations used as well as the approach adopted for analysis of their measurements. Evidence from the field does not support this latter conclusion (see Section 3.1). Further, laboratory experiments of Porter *et al*. (2014) would also support this view.

For those environments where sandy sediments dominate and the depth of this sandy sediment can be taken as being unlimited, the deepest scour is of the order of S/D = 1.8 based on field measurements to date.

It is noteworthy that the methods given in DNV (2014), which are applicable to scour prediction in an unlimited thickness of mobile sandy soil, would give scour depth predictions in the range of 0.1 pile diameters (lower end of wave dominated regime) to 1.3 pile diameters (current regime). Therefore, the approach as stated in DNV guidance would under-predict the scour occurring at tidal sites with mobile seabed sediment. However, it should be noted, that the original studies upon which this guidance is based suggest that the scour depth for live-bed current scour conditions is $S/D = 1.3 + \sigma_{S/D}$ where $\sigma_{S/D}$ is 0.7 (Sumer and Fredsøe, 2002) and that for design purposes the maximum scour depth is $S/D = 1.3 + 2\sigma_{S/D}$, i.e. $2.7D$. This additional information has been omitted from the DNV document.

3.1. Tidally dominant offshore sites

Exploring the evidence base for scour development in relatively uniform sandy offshore environments, it is possible to assess a number of basic parameters with respect to scour development. Figure 1 shows a plot of relative water depth versus relative scour depth. Normalizing the scour depth S with water depth, h, is consistent with the empirical approach of Richardson and Davis (2001). The data shown in Figure 1 relates to two shallow, intermediate and deeper water with depths h to mean tide level (MTL) in the range 4 to 27 m. There is a gap in the data for h/D values of about 5, but in general the data appear to show a trend with respect to relative scour depth normalized using water depth and relative water depth (h/D). This latter term can be considered as describing the interaction of the surface "bow wave", the downflow into the seabed and the associated horseshoe vortex.

Some of the scatter in the data presented in Figure 1 is due to the scour at some locations still developing to equilibrium conditions or the scour hole infilling during wave events or lower magnitude tidal flows. The envelope curve on Figure 1 has h/D limits of $e^{-0.24}$ and e^{-4} giving S in the range $2.7h$ to $0.05h$. At the limit of $h/D = 0$ the value of S would be $3.4h$.

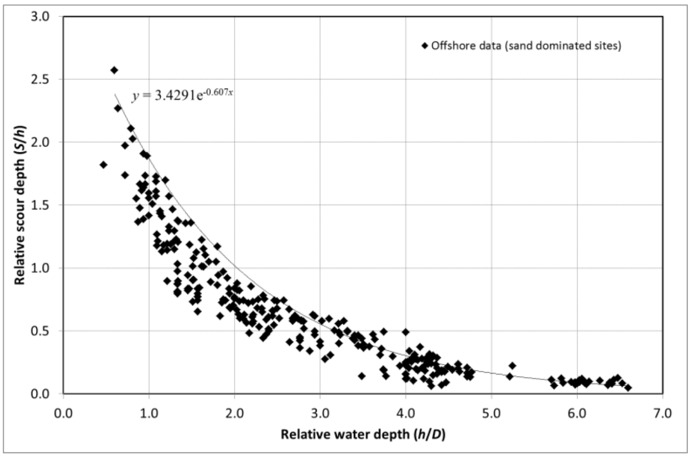

Figure 1: Plot of relative water depth against relative scour depth for offshore data

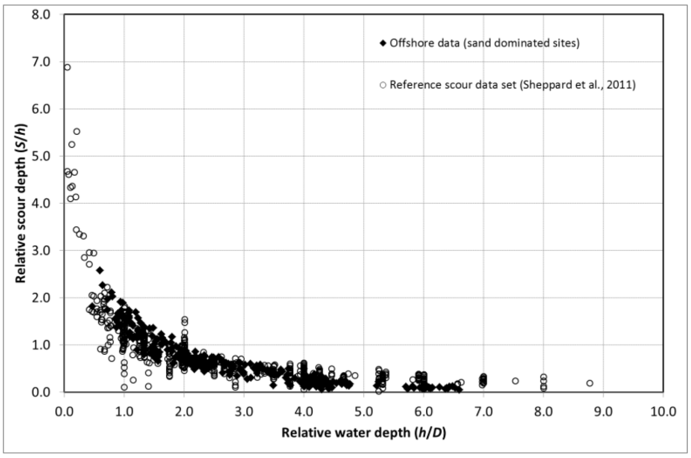

Figure 2: Plot of relative water depth against relative scour depth for offshore and laboratory data

If we now combine this field data with the laboratory reference data set presented in Sheppard *et al*. (2011) then Figure 2 is obtained. It is interesting to note that the field data relates to tidal induced flows whilst the laboratory data represents unidirectional flow conditions. Both data sets appear to fit within the same population, although again there is clearly some scatter. The laboratory data contain values of S/h at higher h/D which confirms the asymptotic behaviour of the scour envelope. As h/D tends to zero the value of S/h increases above the limit of $3.4h$ obtained from the envelope curve in Figure 1. This suggests the ability to create and maintain values higher than the field in very shallow unidirectional flow in the laboratory.

3.2. Time-scale of scour

Scour development under waves and time-varying currents around coastal and offshore structures is a time varying process. The response of the seabed around a structure and whether a scour hole will form, continue to develop, remain at some equilibrium or fill in is a function of both the geotechnical conditions and the hydrodynamic processes existing at any given time. Therefore, scour development is analogous to the growth and decay of seabed ripples. Under tidal flows the current reverses direction with the tidal phase, consequently the scour development will take place in two directions. In addition, the magnitude of the current will vary through the period of the spring-neap tidal cycle. As suggested in Section 3 it is anticipated that local scour depth can be estimated using the same approach as for unidirectional flow (e.g. in rivers), although it is expected that scour development is reduced due to sediment eroded during the first phase of the tide being deposited on the reversing part of the tidal cycle. Wind waves will also cause a time-varying hydrodynamic field and the combined effect of currents and waves will lead to a time-varying depth and extent of scour around an offshore structure.

The time-scale of the scour process can be defined in various ways. The scour depth develops to equilibrium conditions through a transitional period, which is generally asymptotic in form. In the case of live bed scour the equilibrium scour depth is achieved more rapidly than for the clear-water case. Figure 3 shows results from monitoring studies for a number of offshore wind farms in relatively uniform sandy soils. The data represents scour depth measured at the time of the survey relative to the time since the pile was installed. Whilst there is scatter in the data the field measurements demonstrate the asymptotic nature of scour development. The scatter is likely to be due to a combination of parameters, including varying soil conditions at different sites, variation in hydrodynamic conditions and water depth.

The variability in scour hole morphology was noted by Noormets *et al*. (2006) in their study of bedforms and local scour at the base of a 1.65 m cylindrical pile located within a tidal inlet in the Wadden Sea, southern North Sea. They observed changes in scour and bedform dimensions over a number of different time-scales (Figure 4). They noted that one area of subjectivity when determining the scour depth under mobile seabed conditions was where to take the existing seabed level from. In addition to variations in the scour depth, they noted considerable variability in the lateral dimensions of the scour hole at seabed level (varying from about 10.5 m to 22.7 m). At an intermediate level about 1.5 m above the bottom of the scour hole they recorded much less variation in diameter. Therefore, it is important to note that scour development in the marine environment in morphologically dynamic areas may be highly variable depending on the hydrodynamic conditions experienced at a given site.

The study site used by Noormets *et al*. was located in Otzumer Balje tidal inlet: the inlet was about 500 m wide and 8 – 15 m deep with peak depth-averaged currents of about 1.4 m/s. The site was sheltered from wave action. The sediment within the inlet varied from coarse gravel and packed shell mixtures to medium sands (0.26 – 0.33 mm) (Noormets *et al*., 2006).

Rudolph *et al*. (2004) presented field measurements at the N7 site in the North Sea. The monopile, with an outer diameter of 6.0 m, was installed in the summer of 1997. The water depth at the location was about 7 m (MTL) and the depth-average current varied between about 0.25 m/s – 0.75 m/s. The 100 years return period wave conditions are given as a significant wave height, H_s, of 4.6 m and peak period, T_p, of 16.1 s. The 100 years return period depth-average current is 1.3 m/s. Rudolph *et al*. report that the actual extreme conditions experienced since pile installation, based on an adjacent location were estimated as: H_s = 4.4 m; T_p = 14.0 s, and U_c = 1.2 m/s.

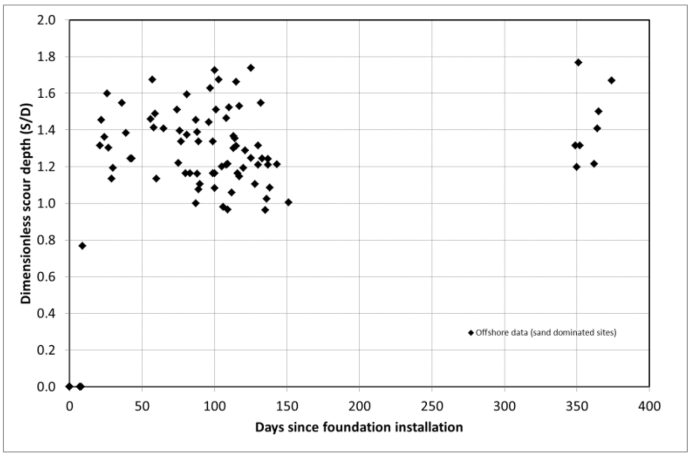

Figure 3: Scour evolution around monopiles for tidally dominated uniform sandy offshore environments

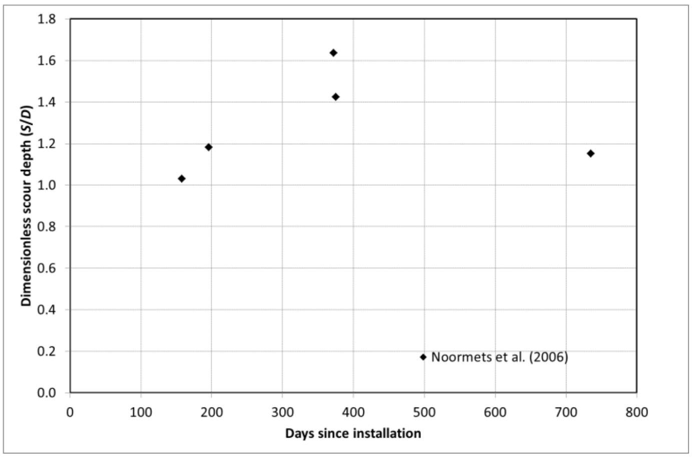

Figure 4: Variation in scour depth at a monopile in the Otzumer Balje tidal inlet (data from Noormets *et al.*, 2006)

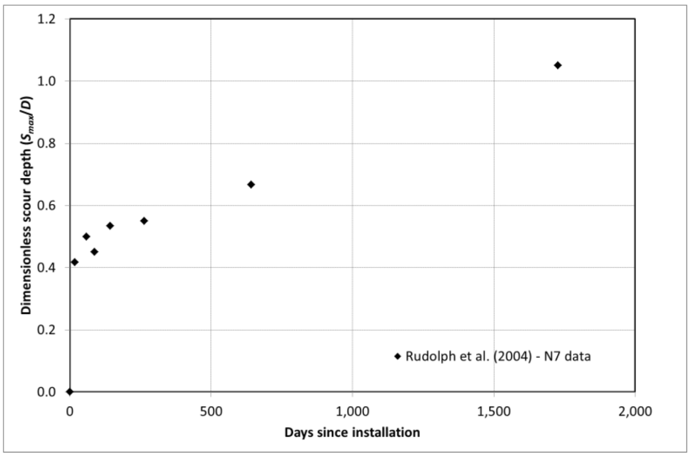

Figure 5: Scour evolution around the monopile at N7, North Sea (data from Rudolph *et al.*, 2004)

The seabed is described as fine to medium dense sand, although gravel patches were observed in the area local to the monopile.

Rudolph *et al*. present the mean and maximum scour depths measured over a period of almost five years. Figure 5 shows the measured maximum scour depth since installation of the pile. After almost two years Rudolph *et al*. state that the scour hole had an extent of about 200 m. It is assumed this is the total extent although this is not stated explicitly.

The data appears to indicate a progressive increase in scour although it provides snapshots on a time-varying process and it is not known whether the scour depths were deeper or shallower periodically during the between survey periods, for example as a result of storms, and the role of antecedent hydrodynamic conditions on the scour development at the time of the surveys.

Walker (1995) investigated the scour development at a bridge pier in a tidal inlet at Destin, in northwest Florida on the Gulf of Mexico. Similar to the Otzumer Balje study the site was sheltered from waves. The bridge pier was square in cross-section with a width of 0.61 m with an observed maximum scour depth of about 1.1 m over the study period. The sediment was non-cohesive sand with a median grain size (d_{50}) of 0.28 mm. The pier was skewed to the flow as illustrated in Figure 6. The pre-existing scour hole was filled with sand from the adjacent area and then the scour process was monitored continuously through a spring tidal cycle. The monitoring equipment deployed included a video camera for time-lapse imaging of the scour hole, two underwater lights for night time operations, an acoustic transponder to measure the scour depth at the base of the pile and an electromagnetic current meter. The equipment was mounted onto the bridge pier after removing marine fouling using an aluminium frame to form a stable and non-obtrusive measurement platform.

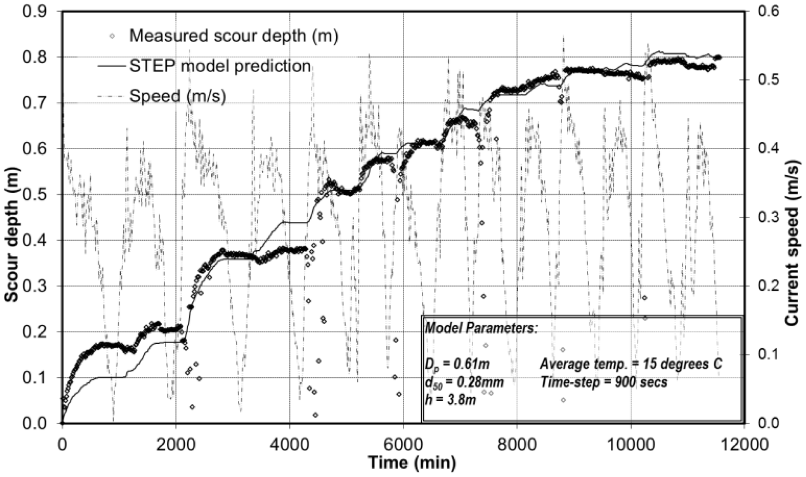

Figure 6: Schematic of bridge pier showing flow orientation (after Walker, 1995).

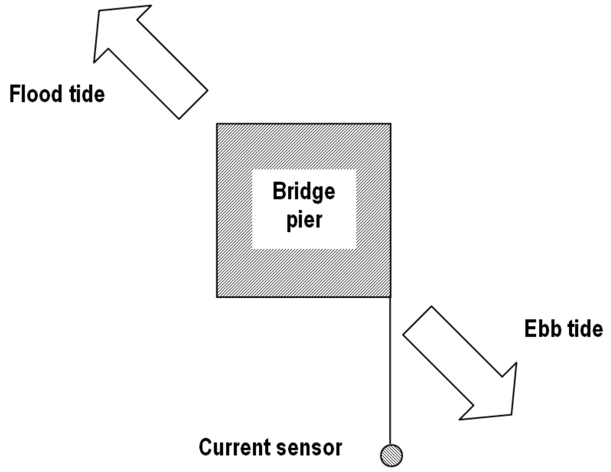

Figure 7: Time variation of current speed and scour depth at a bridge pier, Destin, Florida, over an 8 day period together with the results of a model simulation (Harris *et al.*, 2013).

Figure 7 presents the results from Walker's experiments. The scour hole scoured to its previous depth over the duration of the experiments (*S/D* of about 1.3 in 8 days). The scour measurements show a continual growth in depth over each tide although there is periodic infilling due to the reversing tide at the bridge pier site. The results presented in Figure 7 also show signal drop out corresponding with periods of turbulent flow with high suspended sediment concentrations which mask the acoustic signal. Also shown in the figure are results from an engineering model presented previously by Harris *et al*. (2010; 2013). The was used to investigate scour development under a range of hydrodynamic conditions within different water depths. The results from the model indicated that the scour depth can vary significantly under combined current and wave conditions through time. The need to develop time-series methods for scour development and, in particular, using the results from such methods to investigate the probability of exceedance of scour around the foundations of offshore structures was previously highlighted by Whitehouse (2006) and Harris and Whitehouse (2012).

Rudolph *et al*. (2008) carried out an analysis of the scour data for the Princess Amalia OWF. Their results indicated that the lower scour depths (compared to the typically expected 1.5*D*) observed were a response to the balance between the scour and backfilling process. They determined that during 10% of the time scour development took place and during about 90% of the time backfilling. This result implies that both the scouring and backfilling processes are equally important in a scour assessment. Laboratory analysis of backfilling has been studied (Hartvig *et al*., 2010 Sumer *et al*., 2013) and those results need to be compared with field data.

Dixen *et al.* (2012) presented results of a monitoring programme conducted at a monopile turbine foundation at Gunfleet Sands offshore wind farm in the outer Thames Estuary. The turbine foundation had a diameter of 4.7 m and was installed in November 2008. The study was designed to investigate how much variation in scour depth can be expected, although the measurement programme was carried out 1.5 years after foundation installation.

The measurements were collected over the period from June - December 2010. 122 days of scour data were collected together with 39 days of co-incident metocean data. Unfortunately, the Acoustic Doppler Current Profiler (ADCP) used to collect the metocean data ADCP stopped working after two months and, therefore, a hindcast model was used to supplement the missing ADCP data (wave and current data) over the period of interest. The site is tidally dominated with a maximum measured depth-averaged tidal current during the spring tide of 1.1 m/s, approximately. The water depth is 11.4 m MTL and the peak wave period is 8.3 s. The seabed sediment consists, predominantly, of medium sand (d_{50} = 0.2 mm).

Dixen *et al*. state that the local scour depth varied between 1.53*D* - 1.7*D* during the measurement period. The deepest and widest scour hole was observed to form in the main tidal direction.

3.3. Scour hole dimensions

In sandy sediments the extents of a scour hole can be approximated based on the angle of repose, also termed angle of friction, of the sediment (e.g. Harris *et al*., 2010). Under uni-directional flow conditions the upstream slope of the hole is the angle of repose, whilst the downstream slope is about half this angle ±2°, approximately. The side slopes of the scour hole are about 5/6 of the angle of repose. Typical values for the angle of repose in sands are in the range of 26° to 45° (Hoffmans and Verheij, 1997).

From the monitoring data obtained from built offshore wind farms, the scour extents for foundation structures placed in morphologically dynamic tidal areas within predominantly sand environments indicate slope angles lower than those based on sediment angle of repose. However, this is not unexpected as under reversing tidal conditions the downstream/ upstream positions will reverse and, therefore, the lower slope angles associated with the wake vortices are likely to prevail over the longer-term. Some examples of scour extents are presented in Figures 8 and 9 with the low angles of slope identified.

Interestingly, McGovern *et al*. (2014) also found lower mean slope angles (11 - 12°) from their tidal scour experiments, although their conclusion of lower scour depths under tidal conditions compared to those obtained under uni-directional flows is not supported by the field evidence.

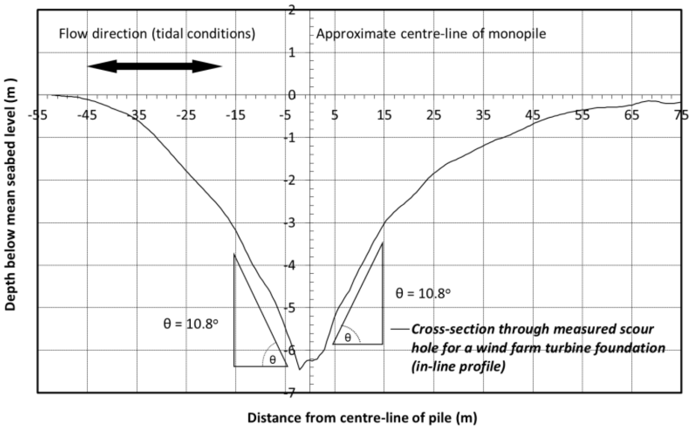

Figure 8: An example of scour hole extents around a monopile in a sand dominated environment. The extents are along the principal flow (scour) axis

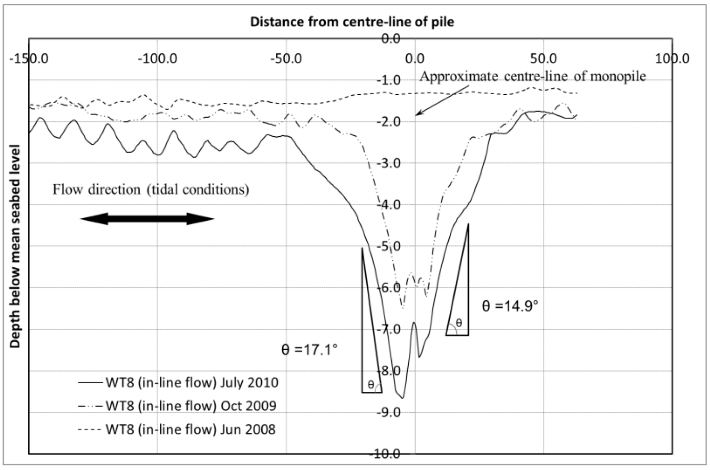

Figure 9: An example of scour hole extents around a monopile in a sand dominated environment under tidal conditions.

The smaller scour hole slope angles obtained under tidal conditions also implies larger overall scour extents than would be expected based on angle of repose.

3.4. Scour wakes

One of the features observed at Scroby Sands offshore wind farm (OWF) was the development of extensive scour wakes which consist of larger bedform features than observed in the surrounding seabed along the scour axis (Figure 10).

A possible analogy from experimental tests is where under clearwater conditions the sediment deposited downstream of a scour hole 'trips' the flow into live-bed conditions and bedforms start to develop. This would also imply a sediment dependency.

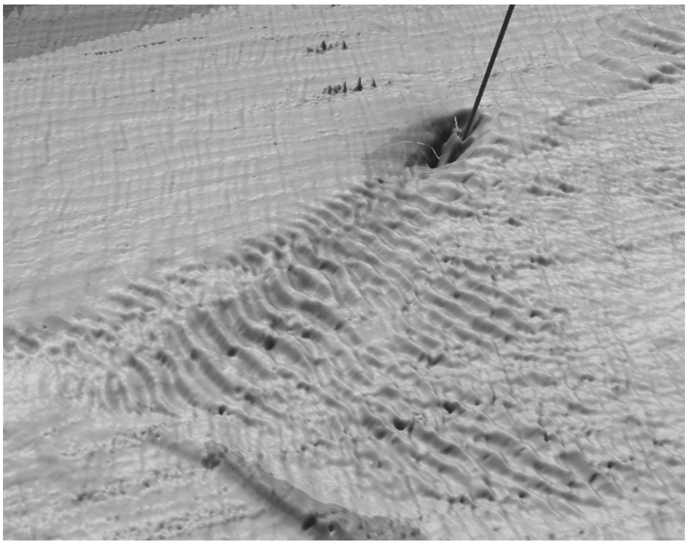

Figure 10: An example of a scour wake at Scroby Sands. Image courtesy of Dr Jon Rees, CEFAS, 2006

4. Non-Uniform Marine soils

Relatively few scour studies have been undertaken using heterogeneous marine soils, which are often variable in their make-up. Seabed sediments often consist of some combination of silts, clays, sands and gravels, which will not respond in the same way as a uniform sand. Their resistance to erosion and rate of erosion is still an area of uncertainty and requires further examination so that a clearer understanding of scour within multi-modal sediment distributions can be achieved (Whitehouse and Harris, 2014).

The prediction of scour in cohesive or multi-modal soils is more complex. Typically the scour process is much slower; as a result the effect of scour is very much dependent on the period of time that the structure will remain at the site. The principal body of work on scour in cohesive soils and clays is related to scouring around bridge piers.

Briaud *et al*. (1999) proposed an approach to predicting the scour depth and rate of scour in cohesive soils around a cylindrical bridge pier involving taking site specific samples and testing them in an erosion function apparatus to obtain the rate of scour against the applied hydraulic shear stress. The SRICOS method (**S**cour **R**ate **I**n **CO**hesive **S**oils) takes that rate of scour and combines this information with the maximum possible shear stress for the flow conditions prior to scour developing. Briaud *et al*. proposed a simple relationship for the maximum scour depth, S_{max}, based on the pier Reynolds number R_D:

$$S_{\max} = 0.00018 R_D^{0.635} \tag{4}$$

where,

$$R_D = \frac{VD}{\nu} \tag{5}$$

and V is the mean flow velocity, D is the pier diameter and ν is the kinematic viscosity of the water.

4.1. Scour potential

Evidence from the field particularly related to offshore structures is relatively limited. Three of the wind farm sites where monitoring data is available for seabed sediments influenced or underlain by clay are Barrow, Kentish Flats and North Hoyle in UK waters. In all three cases the foundations consist of circular monopiles.

4.1.1. Barrow OWF

Barrow OWF consists of 30, 4.75 m diameter monopile foundations, situated about 8 km southwest of Walney Island in the Irish Sea. Scour was measured at thirteen of the foundations over a number of years. The first scour survey was undertaken in 2005 and in the glacial till to the eastern part of the site, low scour depths (up to S/D = 0.04) were measured. There was some indication that scour depths in the glacial till increased slowly with time following installation (DECC, 2008b). Depressions from the spudcan footings of the jack-up barge used for installation were also visible in the seabed.

All thirty foundations were re-surveyed in September 2006. In those areas covered with a thin veneer of sand the short-term scour depths were limited by the thickness of that layer to scour depths of up to and around 0.5 m or 0.1D in clay sites.

The key parameters which determine the amount of scour are the composition and thickness of the surficial and sub-surface sediment layers as well as the prevailing hydrodynamic conditions. The monitoring data from Barrow OWF demonstrated that for the clay dominated sites scour had been restricted by the thickness of the surficial layer and the resistant properties of the underlying soils (Whitehouse *et al*., 2011a).

4.1.2. Kentish Flats OWF

Kentish Flats OWF is located in the outer Thames Estuary, approximately 9 km off the north Kent coast. The seabed is generally flat and subtly varied comprising mainly coarse sand, but with varying amounts of shell gravel and small exposures of the underlying clay. Geotechnical surveys also showed the seabed to consist of variable thickness of sand underlain by soft to firm clays overlying London Clay formation. From the last available monitoring data at the wind farm site S/D values of up to 0.4 were obtained. In the initial monitoring surveys, depressions were measured at four of the thirty 5 m diameter turbine foundations in January 2005, some three months after completion. It is uncertain whether 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 or a combination of the two processes. The monitoring data also revealed depressions in the seabed in response to where the jack-up barge legs had been present during installation, most probably mainly due to penetration of the legs into the soil rather than through scour processes (see Figure 11).

Assuming the scouring is the principal cause of the depressions at the foundations, the maximum measured 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. The picture of change was complex as the scour at one location increased with time during the three surveys whereas the scour at the other three locations increased in the first two surveys and then decreased in the last survey. Assuming consistency of the surveys, and the time variations were not an artefact arising from survey error, this suggested that seabed sediment transport processes were able to produce fluctuations in the depth of the scour around the foundations at this site. Figure 10 shows the scour development at Turbine E2 as measured in January 2005. The scour depth is around 0.8 m giving an S/D ratio of 0.16. In comparison the spudcan depressions to the southwest of the monopile location have a maximum depth of about 1.4 m.

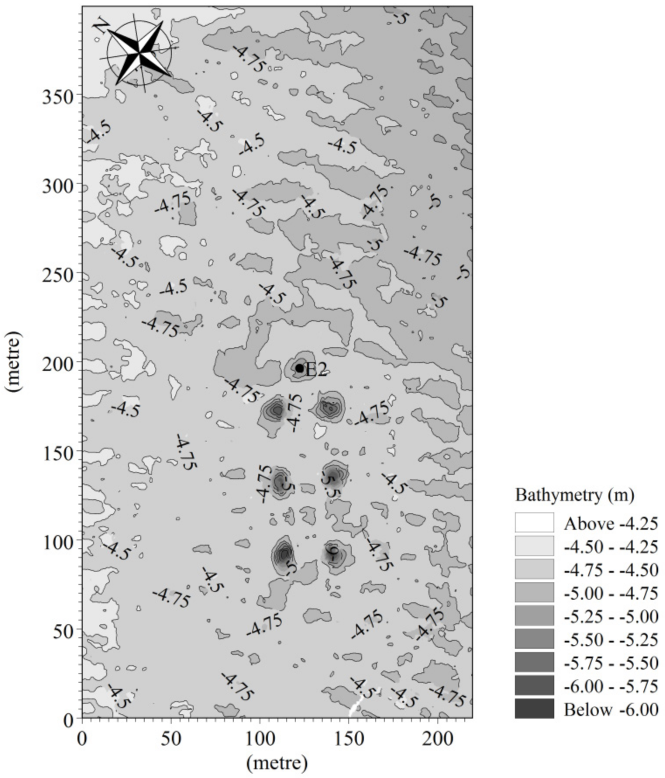

Figure 11: Scour development at turbine E2, Kentish Flats OWF survey, January 2005. Note jack-up spudcan depressions to southwest of monopile. (Data collected by EMU Ltd)

The footprints left behind by jack-up legs, with or without spudcans, may have the potential to destabilize scour holes rapidly if captured by the growing scour around the foundation. The effect is long-lasting, even where the surface expression of the jack-up legs may have reduced or disappeared through sedimentation or sidewall collapse. The effect is most likely to occur where legs have been placed within the scour hole extents, perhaps during the site investigation or installation phases of a project. More analysis of this interaction is required.

4.1.3. North Hoyle OWF

North Hoyle OWF is located about 7.5 km from the north Wales coast offshore of Rhyl. Within the wind farm site the seabed sediments generally consist of sandy gravel or gravelly sand with larger patches of gravel found further offshore. Within these areas the gravels tend to exist as thin veneer overlying sand or boulder clay. Results from various surveys shows the site as being strongly heterogeneous, having var-iability over very short distances and composed of very poorly sorted sediments. The thirty turbine foundations were installed over the period April to July 2003. Monitoring of the seabed post-installation was carried out over the period August to October 2004.

Some limited scour (less than 0.125*D*) was recorded in the 2004 survey at ten of the thirty foundations. In a survey conducted in April-May 2005 no scour was recorded at any of the foundations. No scour protection material was placed around the foundations although there was some redistribution of drill cuttings on the seabed which had arisen during the drill-drive process used to install the foundations. Burial of the inter-array cables was successful with target burial depths achieved in all but about 3 % of the total cable runs. Where full burial was not achieved, rock protection was placed during 2004.

Figure 12 shows an example of the survey data for North Hoyle OWF. A mound of drill arisings can be observed to the southeast of the monopile. There is little evidence of scour development at the foundation.

4.2. Scour evolution through time

Scour development around offshore structures is primarily a function of the hydrodynamics, sedimentology and geotechnical properties at a site. Under tidal flows the current reverses direction with the phase of the tide and, therefore, scour development will take place, typically, in two directions. The time variation in scour depth corresponding to the time of installation of the foundation structure and the monitoring survey(s) is important as there will be a general increase in the scour depth to some equilibrium condition over a time-scale that is site specific. In non-uniform soils it is possible that the equilibrium condition is not achieved over the (design) life of the project and, hence, having a reliable estimate of the time-scale in these type of soils is, arguably, of more importance than that in uniform non-cohesive soils. The time evolution of scour in offshore sites with non-uniform soils is more difficult to ascertain from available data due to the limited number of surveys available in time and the more gradual scour development. From the monitoring data for Round 1 wind farm sites (Barrow and Kentish Flats) the evidence base suggests a scour depth that is both variable in time and space between different locations (Figure 13). The results show a general growth in scour but also reductions in scour depth from one survey to the next. However, inferring a general reduction in scour depth over time from this data should be cautioned against as this may just be a function of the prevailing conditions at the time of the survey rather than some longer-term trend.

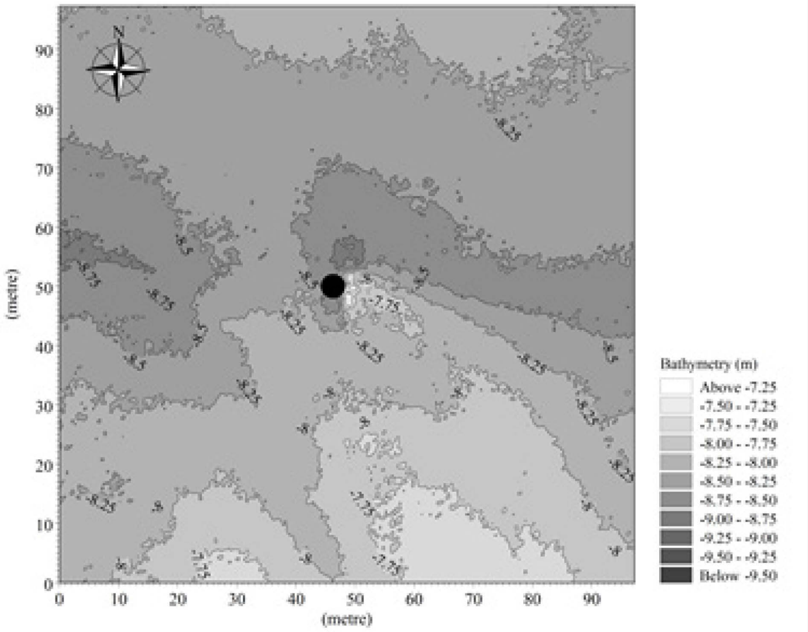

Figure 12: North Hoyle OWF measured bathymetry at turbine 10, survey 2005

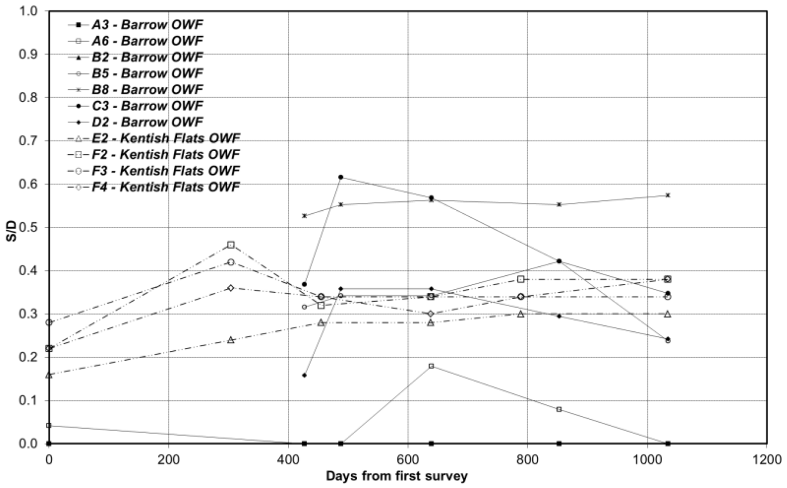

Figure 13: Variation of dimensionless scour depth with time at Barrow and Kentish Flats offshore wind farms

4.3. Scour prediction in marine soils

The requirement to undertake a scour hazard assessment for offshore projects that involve large volume installation of foundations, such as those related to offshore wind farm developments, will inevitably mean that there is a limit to the amount of detailed geotechnical information that can be collected as part of the project beyond the key requirements for foundation design and in cable corridors. Therefore, there is a need to have a reliable scour predictor for a range of ground conditions.

Annandale (1995; 2006) proposed an approach to assess the scour potential using the Erodibility Index method. The principal attraction of the Erodibility Index method is that it allows for the physical properties of the soil to be considered and although the method does not directly take into account the chemical properties of the material, the mass strength number, M_S, represents the relative influence of chemical bonding properties of the soil through the unconfined compressive strength. In principal, the method represents an engineering methodology that can be applied using information obtained during geotechnical site investigations. However, to apply the approach to a given location requires a number of key considerations which include:

- The requirement for good information on the soil properties with depth through the seabed, including grain size distributions, density, undrained shear strength, internal angle of friction, etc from the seabed surface to the depth (at least) of S_{max}, the maximum anticipated scour depth; and,
- Knowledge of the metocean conditions for both typical and extreme events.

Furthermore, the method relies on previously calibrated formulae for the stream power at the seabed and its variation with depth into the scour hole. There is still a requirement to determine the development of scour through time in complex marine soils and this requires further research, especially for soils with multi-modal grading distributions and with distinct layering. It is also important to determine any adjustment to soil properties that might occur during foundation installation that could affect resistance to scouring and the effects of abrasion by granular sediments is still not well understood.

The key assumption in the Erodibility Index approach is that undrained shear strength can be used as a proxy for the erodibility of soil.

Using available data from a range of offshore sites and laboratory test data where suitable geotechnical properties are available, it is possible to assess whether the data supports the hypothesis that undrained shear strength can be used as a proxy for the erodibility of soil. Figure 14 presents an initial review of the various data shown as dimensionless scour depth (S/D) against undrained shear strength.

The curve plotted in Figure 14 represents an envelope encompassing all the data only and is not intended to represent a curve fit. There is a significant amount of scatter within the data. There is an inherent limitation with the laboratory data as these data represent relatively low strength soils compared with those obtained from the majority of the field sites. The exception is the bridge scour data presented by Straub and Over (2010), which is in a similar range of soil strengths to those of the laboratory tests.

Revisiting Equation (4) for scour in clay with current speeds of 0.5 and 1.0 m/s, a pile diameter of 5 m and viscosity of seawater at 10 degrees Centigrade and 35 salinity, we arrive at S/D values of 0.4 and 0.6 which are not out of line as order of estimate values compared to the range of data on Figure 14.

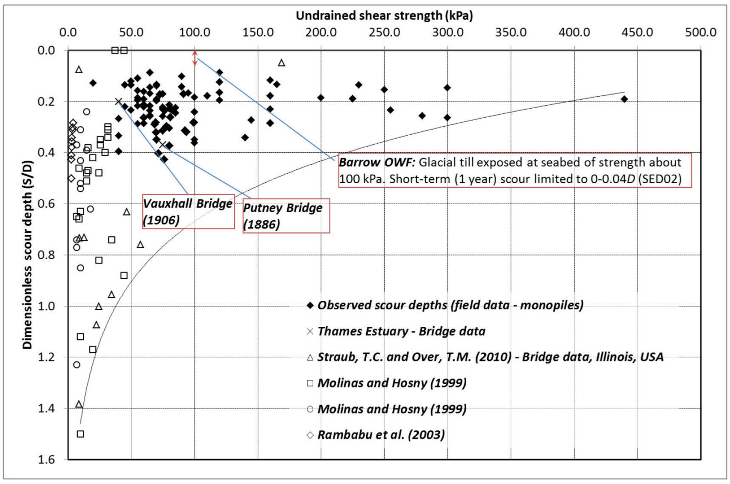

Figure 14. Field and laboratory evidence base of scour depth against undrained shear strength (Harris and Whitehouse, 2014)

There are a number of difficulties with analysing the field data to determine an undrained shear strength, including the representation of the layering effect of the marine soils. By this we mean that in the majority of cases the depth at which the scour has currently developed to has been achieved by eroding through a number of different soil strata with different properties. A decision was made to take the properties of the soil strata to which scour-ing has currently reached, but this may be somewhat arbitrary given the possible effects that the overlying layer(s) may have on the erodibility of the underly-ing soil layer. It is also not possible to determine whether abrasion has contributed to the scour development. Also, the values of undrained shear strength represent a pre-construction state and it is unknown what, if any change in soil properties may have oc-curred during and post-installation of the structure, for example due to piling. In addition, the results do not have any temporal element and, therefore, may only be representative of a transient state, and the equilibrium scour depth has yet to be achieved. The exception is for the two bridge sites in the tidal Riv-er Thames (Vauxhall and Putney Bridges in London, UK). These bridges have been in place for 100 years and the scour depths lie within the scatter of other data. However, it should be noted that the scour depths at these bridge locations may be inhibited by scour protection or the effect of bed armouring, although it is not possible to determine this from the data available to us.

5. Field data for other structure types

Whitehouse *et al*. (2011b) reviewed scour development around gravity base foundations (GBF), the behaviour of scour predictions as well as scour protection performance. They noted a general scarcity in published information on scour from oil and gas developments. Whitehouse *et al*. also note that more research is required to provide the data for developing improved and more versatile prediction methods including the effect of skirts on offshore structures.

Dahlberg (1983) discussed scour development at the Frigg TP1 GBF located in the North Sea in 104 m water depth. The foundation design consisted of a concrete cellular caisson, 72 m square and 44 m high with two 12 m columns supporting the topsides. A number of precast concrete skirts penetrating 2 m into the seabed were attached to the caisson (Burland *et al*., 1978). The surface seabed soil comprised fine sand in the range 0.1-0.2 mm. Observations showed scour had developed at two corners of the caisson about 2 m depth, which had developed during the summer months, predominantly. Remedial measures using gravel bags and gravel fill proved effective to remove further scour problems.

Bos *et al*. (2002) investigated the scour around a rectangular GBF (75 m by 80 m by 16 m high) in 42.3 m of water in the North Sea. Field observations showed scour at the structure had developed to depths around 2.5-3.5 m in 0.15 mm sand.

Monitoring data for vertical foundation structure types other than monopiles in the marine environment have been presented by Bolle *et al*. (2010; 2012), Stuyts *et al*. (2013) and Rudolph *et al*. (2004).

Bolle *et al*. (2010) describe some of the early monitoring results at the six gravity base foundations installed on Thornton Bank off the Belgian Coast in 2009. Scour protection has been installed at the foundations and whilst initial concerns were related to secondary scour around the protection, the early results indicated sedimentation occurring over the protection.

Bolle *et al*. (2012) describe scour development at the Thornton Bank wind farm, focusing, primarily, on scour around the jacket foundations. The wind farm is located about 30 km off the Belgian Coast, and the jackets are situated in water depths of about 12 – 30 m. The scour development has two phases, that due to pre-piling (prior to jacket installation) and then the second phase related to the foundation completion with the jacket in place.

At the pre-piling stage four pin-piles are installed having a length above the seabed of about 1.5 m. Scour development around these truncated piles was about 1.3 m on average (0.65D), whilst the maximum observed depth was 2.4 m (1.2D). After installation of the jacket structures, the average scour depth ranges between 1.4 and 1.9 m. The largest scour depth at each foundation (maximum of the four legs) varies between 1.7 and 2.7 m. Bolle et al. note that the measurements of scour magnitude at the jacket foundations support the use of maximum expected scour depth for design purposes.

Stuyts *et al*. (2013) present an engineering scour prediction model, which they compare against scour measurements obtained at the Alpha Ventus wind farm in the German sector of the North Sea. Scour was measured around the piles of the tripod at location AV7, with echosounders fixed on the pile sleeves and underneath the central column. They note that scour was most severe at the sensor most exposed to the dominant current direction. From the data presented scour at the piles varies between about 3 m to 4.3 m, whilst under the central column the scour varies from about 5 m to 6.5 m. It should be noted though that the larger scour depth correspond to a sudden change in scour depth between the end of August and end of October, 2010. At around 150 – 200 days after installation Stuyts et al. note that the scour depth at the piles appears to have reached an equilibrium state with depths between 3 – 3.5 m.

In addition to analyzing the data for N7 (Figure 5) Rudolph *et al*. (2004) also present results of measurements of scour around a jacket structure at location L9 (North Sea). They investigated the scour development at the wellhead and production platforms at block L9, which were installed in the summer of 1997.

The wellhead consists of a jacket structure with four legs (leg diameter = 1.1 m) with a spacing between the legs of 20 m and 17 m, whilst the support structure of the production platform comprises six legs (leg diameter = 1.5 m) with a spacing between the legs of 16 m and 20 m.

At the seabed, all legs are connected to skirt piles having a diameter at the seabed of 1.2 m and 1.5 m, for the wellhead and production platform structures, respectively.

Typical depth-averaged peak flow velocities at the site are 0.5 m/s during spring tides and 0.35 m/s during neap tides. The estimated depth-averaged mean flow velocity is u = 0.25 m/s. 100 year return period design conditions are estimated as: H_s = 8.8 m; T_p = 10.1 s and U_c = 1.2 m/s. Rudolph *et al*. report that the actual conditions experienced since installation were estimated at: H_s = 7.8 m; T_p = 9.8 s and U_c = 1.0 m/s. The seabed sediment is described as consisting of dense fine to medium grained sand (d_{50} = 0.2mm).

From the bathymetric survey data local scour was shown to be present at the majority of the legs of the jacket structures. Typical scour depths were in the range 2.0 to 3.5 m, with maximum scour depths in the range of 1.5 to 5.0 m.

The data also showed that a wide area around the platforms was affected by scour, with the extent of the global scour hole in the order of 50 m in all directions. Rudolph *et al*. noted that the extent of scour-induced seabed change relative to the undisturbed seabed had a radius approximately forty times the pile diameter, similar in magnitude to that observed at the monopile at N7.

6. Conclusions

There still remain a number of challenges related to scour in the marine environment which are required to improve the certainty with which engineering analysis is conducted. This paper has highlighted the importance of field data in developing a better understanding of these processes. Field data provides an opportunity to test both our theoretical understanding and our experimental and numerical predictions, albeit within the inherent limitations of the data, as well as explore hidden complexity of the processes encapsulated within the data. Moreover, field measurements in combination with laboratory and numerical data provides a powerful evidence base which will help underpin our understanding of both scour processes and the performance of scour countermeasures.

From the data analysed we are beginning to gain a better understanding of scour development for sandy seabeds in tidal flows as well as the scour potential within non-uniform marine soils, although it may be argued that the field data we have presented also raises further questions and uncertainty about the overall process that has taken place. It is certainly the case we require further investigation of substrate variability and the control it exerts on scour hole depth, shape and volume based on analysis of field data. We also require more information on the impact that the legs of jack-up barges have on the seabed and scour development.

Therefore, as well as further analysis of existing data, one of the key challenges for the future is to develop better methods for measuring and collecting data in the field including not only related to the associated changes in seabed levels, but the corresponding hydrodynamic processes linked to the seabed changes.

Further, not only do we require better tools, we require a better framework to capture the information and greater openness to allow the data to be shared across the community.

Developing better engineering models to provide the reliable prediction of scour at more complex foundation structures such as jackets, tripods and gravity base foundations also needs to be addressed. This can only be achieved through combining field data with laboratory and numerical data, although, ultimately, it may not be possible to develop simple empirical type models that are capable of capturing all scenarios. With increasing computer power, in the future it may be the case that numerical simulations become the norm rather than the exception.

Scour protection and mitigation measures, not fully discussed in this paper, are a key component in the design process. The industry still lacks any full understanding of comparative performance of different measures offshore. In respect of streams and rivers Lagasse *et al*. (2009) presented a matrix for scour countermeasures suitability for given applications and environments in relation to bridge scour. A similar joint-industry research project would be timely for offshore applications to inform future designs.

Ultimately, the work must lead to the design of more efficient and cost effective foundations that are to be built in the challenging environments that offshore development entails. This will require further collection and analysis of field data combined with large-scale laboratory testing.

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