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Scour Assessment and Design for Scour for Monopile Foundations for Offshore Wind Turbines

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Summary:

A number of design tools exist for predicting scour around off shore structures. In this paper some of these tools are described and validated by comparing their calculation of scour formation (depth and extent) around a monopile foundation with a large number of full scale measurements from the Scroby Sands Offshore Wind Farm. It is shown that especially the OptiPile design tool, developed by HR Wallingford for assessing scour risk and scour protection stability, predicts the scour depth very well.

Local scour is generally taken into account in the design of support structures for offshore wind turbine projects by assuming a design scour depth corresponding to the most likely extreme local scour depth both for fatigue and ultimate limit state design. Hence, the foundations for offshore wind farms in sandy areas are most often designed with a scour protection system.

Nevertheless, cost comparison on recent projects seems to indicate that a design without scour protection can be feasible in some areas. In addition it can be argued that always designing for the extreme local scour depth, which will for most locations be experienced for a current only situation, is too conservative as imposed wave actions will tend to reduce the scour depth.

In the paper this is demonstrated using the OptiPile design tool together with reported time scales for scour development and a suggestion for an alternative to the traditional design approach is presented for debate, as it is recognized that much more evidence supporting such a design approach will be needed.

Key words:

Scour predictive models, full scale measurements, scour adaptive design.

1 Scour Assessment

A number of tools exist for predicting the scour risk around offshore structures. See e.g. [1], [2], [3], [4] and [5]. In this chapter some of the most recent of these are, after a brief introduction to scour, described for calculating live bed scour around a wind-turbine monopile-type foundation in non-cohesive sediments.

Introduction to Scour

A flow encountering a cylindrical vertical pile speeds up around the periphery of the pile, producing a “horse-shoe vortex” and a highly turbulent wake in the region downstream of the pile. The combined effect is to carry sediment away from the foot of the pile in all directions, creating a scour pit roughly shaped like an inverted cone.

Scour occurs when the near bed shear stress exceeds the critical shear stress at which the bed material starts to move. If only critical shear stress is exceeded in the vicinity of the structure we term the scour clear water scour, whereas if the critical shear stress is exceeded everywhere we term it live-bed scour.

The depth and horizontal extent of the scour pit are found to scale with the diameter of the pile, the water depth at the site and the grading of the sediment around the foundation. In current the scour development is a function of the current speed U_c and in waves it is a function of the Keulegan-Carpenter number, KC, where scour does not occur if $KC<6$. In combined flows the scour development is a function of both U_c and KC, and scour may occur even for $KC<6$.

Sumer & Fredsøe and DNV

Based on the large number of experimental data from Breussers et. al. [8], Sumer et al. [9] worked out the mean value and standard deviation for the equilibrium scour depth for a vertical circular cylinder in steady current:

$$\frac{S}{D} = 1.3 \qquad and \qquad \sigma_{S/D} = 0.7$$

where S is the scour depth, D is the pile diameter and $\sigma_{S/D}$ the standard deviation of S/D.

Sumer et al. [9] conducted a large number of experiments with a cylinder exposed to waves and found the following expression for the equilibrium scour depth for a vertical circular cylinder exposed to waves:

$$\frac{S}{D} = 1.3\left(1 - e^{-0.03(KC-6)}\right) \qquad for \qquad KC > 6$$

where the Keulegan-Carpenter number KC is defined by

$$KC = \frac{U_m T_P}{D} \qquad with \qquad U_m = \sqrt{2}\sigma_U$$

where T_P is the wave peak period and σ_u is root mean square of the near bed orbital velocity U.

As can be seen the equilibrium scour depth approaches 1.3 D for large KC values, corresponding to the steady current situation, where the scour depth is largest.

S/D = 1.3 corresponds to the scour depth specified by DNV [10] to be used in fatigue and extreme load calculations when designing the support structure for offshore wind turbines.

Sumer and Fredsøe [6] conducted a large number of experiments with a cylinder exposed to waves and current and found the following expression for the equilibrium scour depth for a vertical circular cylinder in combined waves and current:

$$\frac{S}{D} = \frac{S_C}{D}\left(1 - e^{-A(KC-B)}\right) \qquad for \qquad KC \geq B$$

$$A = 0.03 + \frac{3}{4}U_{cw}^{2.6}$$

$$B = e^{-4.7U_{cw}}$$

where S_c is the scour depth in the case of steady current only and the relative near bed velocity U_{cw} is defined by

$$U_{cw} = \frac{U_c}{U_c + U_m}$$

where U_c is the near bed current velocity.

CSU/HEC-18

An equation for predicting scour depth around bridge piers in steady current was derived by Colorado State University (CSU) and has recently been revised by Richardson and Davis [11] and issued as Hydraulic Engineering Circular No. 18 (HEC-18).

The equation predicts the maximum scour depth as

$$\frac{S}{D} = 2.0K_1K_2K_3K_4\left(\frac{h}{D}\right)^{0.35} Fr^{0.43}$$

where h is the water depth and the Froude number, Fr is defined by

$$Fr = \frac{U_c}{(gh)^{0.5}}$$

where g is the gravitational acceleration.

The coefficients K_1, K_2, K_3, and K_4 are correction factors for pier shape, angle of attack, bed shape, and sediment dimensions.

For vertical circular cylinders on a sea bed without large sand dunes and with sediment where d_{50}<2mm or d_{95}<20mm the CSU/HEC-18 equation can be reduced to

$$\frac{S}{D} = 2.2\left(\frac{h}{D}\right)^{0.35} Fr^{0.43}$$

Breusers et al. and OptiPile

Breusers et al. [8] presented a simple equation for predicting the equilibrium scour depth around a circular cylinder in steady current

$$\frac{S}{D} = \alpha \tanh\left(\frac{h}{D}\right)$$

where α is the depth independent equilibrium scour depth.

Bruesers formulation was adopted by HR Wallingford and adjusted to physical experiments for the Q7 Offshore Wind Farm in The Netherlands, ref. [7].

The adjustments were introduced to account for depth limitation (K_1) and grading of the sediment (K_2):

$$\frac{S}{D} = \alpha K_1 \tanh\left(K_2 \frac{h}{D}\right)$$

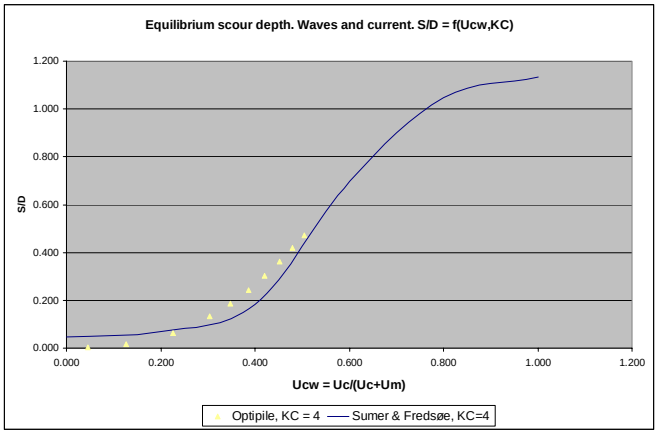
α was estimated at 1.75 for the Q7 project, which is consistent with [1] suggesting α to be within the range of 1.3 ± 0.7.

In general use of α = 1.3 is expected to lead to expected scour depths, whereas α = 1.75 probably will lead to more conservative design scour depths.

For scour caused by waves the formulations by Sumer and Fredsøe [1] were used and for combined current and waves a linear interpolation between the two formulations was used adopting the relative bed shear stress τcw for scaling:

$$\tau_{cw} = \frac{\tau_c}{\tau_c + \tau_m}$$

where τ_c and τ_m are the bed shear stresses due to current only and waves only, respectively.



Compared to Sumer and Fredsøes method for interpolating between the current only and waves only formulations, using the relative near bed velocity, U_{cw}, for scaling, the difference is small as can be seen from Figure 1 below.

The above formulations have by HR Wallingford been combined in the OptiPile tool, a versatile tool for calculating scour depth around a monopile type foundation on a non-cohesive sea-bed. Also the stability of either a static or dynamic type scour protection can be verified using the OptiPile tool. In [7] the OptiPile tool was validated on the installed scour protections for Scroby Sands, North Hoyle and Horns Rev.

Figure 1 Combining wave and current scour, OptiPile vs. Sumer and Fredsøe

Time scale for scour development

In [1] the development of scour follows the following expression:

$$S(t) = S(1 - e^{\frac{t}{T}})$$

where T is the time scale of the scour process.

For scour around a slender cylinder the normalized time scale for the scour process T^* is defined by

$$T^* = \frac{(g(s-1)d^3)^{1/2}}{D^2} T$$

where g is the gravitational acceleration, s the relative density of bed material and d the grain size for the bed material.

Sumer et al. [9] provided empirical expressions for the normalized scour time scale in steady current only, T_c^* and in waves only, T_w^*:

$$T_c^* = \frac{1}{2000} \frac{h}{D} \theta^{-2.2}$$

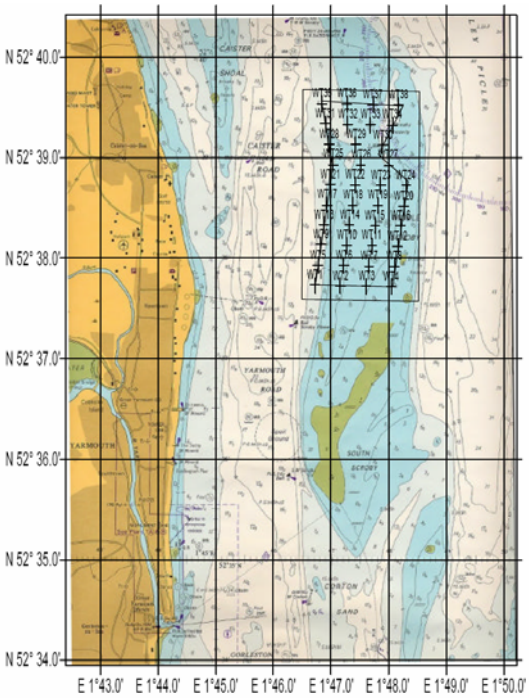
$$T_w^* = 10^{-6} \left(\frac{KC}{\theta} \right)^3$$

where θ is the near bed Shields parameter for the flow. In [9] KC>7 for all tests with waves only, as scour does not occur for KC<6. Hence, applying the above formulation for smaller KC numbers may be rather uncertain.

2 Scour Assessment Compared with Full-scale Measurements

In this chapter the predictive tools described in Chapter 1 above are validated against full scale measurements at the Scroby Sands Offshore Wind Farm.

Scroby Sand Offshore Wind Farm



The Scroby Sands Offshore Wind Farm was completed in 2004 and comprises 30 2 MW Vestas V80 wind turbines and is located on a large sand bank 3 km east of the Great Yarmouth Borough coastline in Norfolk, UK. See Figure 2 below.

The seabed mainly consists of sand, however, with some layers of clay or silt. The water depth at the turbines varies between 1 m and 11 m below LAT, with a maximum depth being 4 m below LAT across the bank. Consequently even moderate waves at the wind farm will be depth limited.

The tidal range is limited to app. 1.9 m (spring) but a strong tidal current runs across the bank driven by a North-South pressure gradient. During sea states with waves from North-East a strong wave induced current runs across the bank.

Figure 2 Scroby Sands Offshore Wind Farm

The foundation for the turbines is an OD 4.2 m monopile with a post installed dynamic scour protection, i.e. a widely graded scour protection with small diameter stones installed after a natural scour hole has been allowed to form around the installed monopile. [12] provides further reference to the functionality of the scour protection.

Prior to installing the dynamic scour protection surveys were carried out for all wind turbine locations: A pre-survey before installing the monopile (October 2003) and a post survey after the development of a scour hole around the monopile (February 2004). Based on these surveys the scour depth and the amount of eroded material have been determined. Two examples are shown in Figure 3 below.

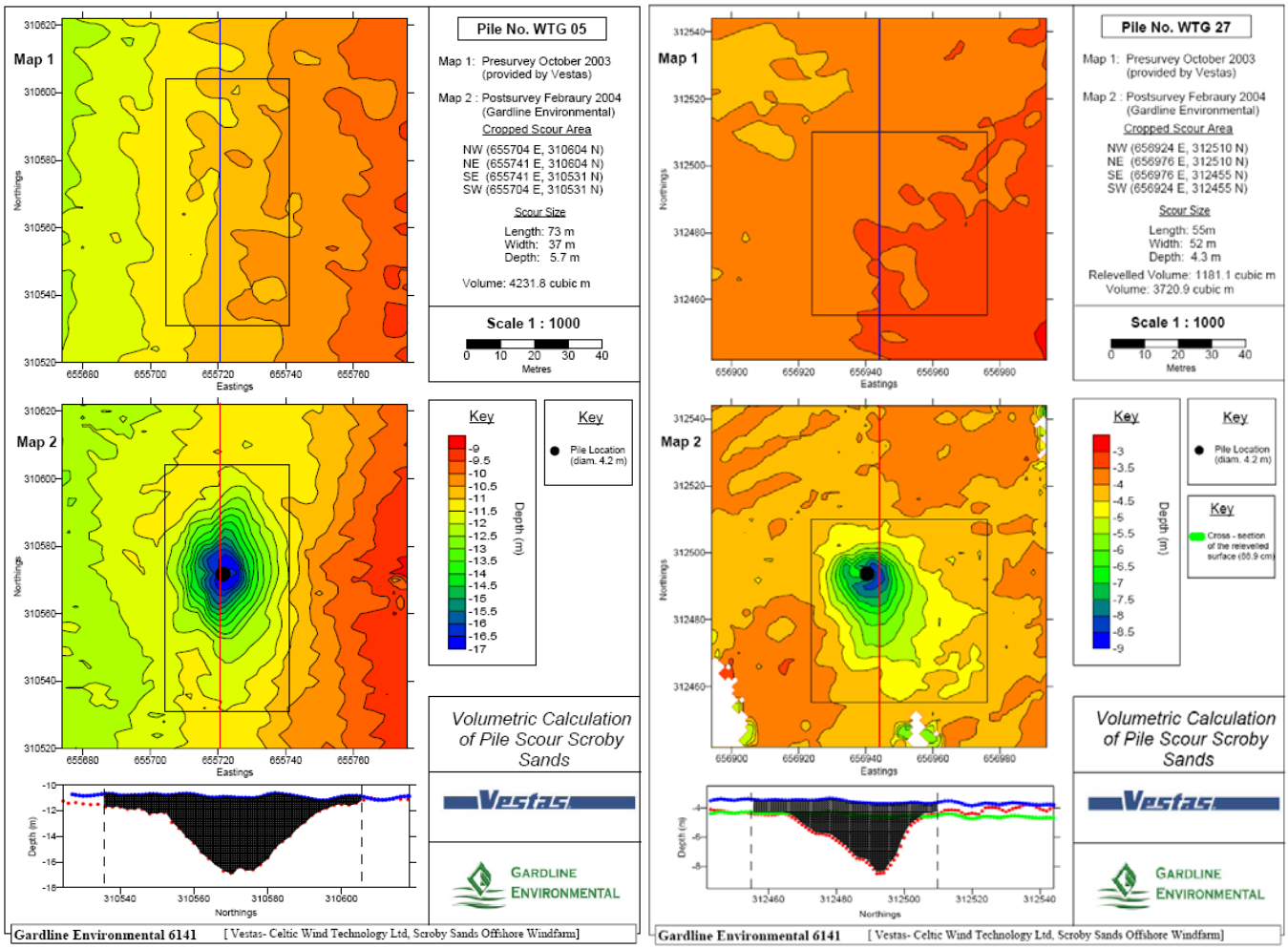


Figure 3 Seabed surveys at Scroby Sands prior to pile driving and prior to installation of scour protection

These surveys prove an excellent basis for evaluating the scour predictive tools described in the previous section.

Scour prediction comparison

In this section the scour depths measured at Scroby Sands – both the individual measurements and averaged values – are compared to predictions made using the below predictive tools together with the scour driving parameters in Table 1 as follows:

- Sumer and Fredsøe
- CSU/HEC 18 – using maximum tidal current with and without including maximum monthly wave induced current
- Breusers et al. – using $\alpha = 1.3$ and $\alpha = 1.75$
- OptiPile –current only and using $\alpha = 1.3$ and $\alpha = 1.75$, respectively.

Water Level		
MSL (Mean Sea Level)	1.48	m LAT
Average water depth across the wind farm	7.5	m LAT
Currents		
1 month wave driven current (S-going)	0.8	m/s
50 year wave driven current	1.2	m/s
Maximum tidal current at water depth 25 m MSL	1.68	m/s
Slack tidal current	0.35	m/s
(maximum tidal current - slack tidal current) ~ $depth^{½}$		
Waves		
50 year maximum wave height, Hmax	5.7	m
50 year associated period, Tass	8.1	s
Sea bed material		
10% fractile grain size diameter, d_{10}	0.1575	mm
50% fractile grain size diameter, d_{50}	0.2625	mm
84% fractile grain size diameter, d_{84}	0.34125	mm

Table 1 Scour driving parameters for Scroby Sands

The results of the comparison are shown on the figures overleaf, and the following observations are made:

Although the CSU/HEC 18 method fits well the Scroby Sands data – assuming that no wave induced current driven by waves from North East has contributed to the scour development, which is likely – it is not appealing that the predicted scour depth does not approach a constant value for increasing depth, as has been reported by several authors.

It is seen that both the Breusers et al. formulation and the OptiPile tool provide very good estimates, both when comparing design values calculated with $\alpha = 1.75$ to the individual measurements and when comparing expected values calculated with $\alpha = 1.30$ to averaged measurements.

It is also seen that the method suggested by DNV for calculating the expected scour depth, i.e. the Sumer and Fredsøe approach, tends to overestimate the actual expected scour depth for shallower water, as it neglects the effect of the relative water depth *h/D*.

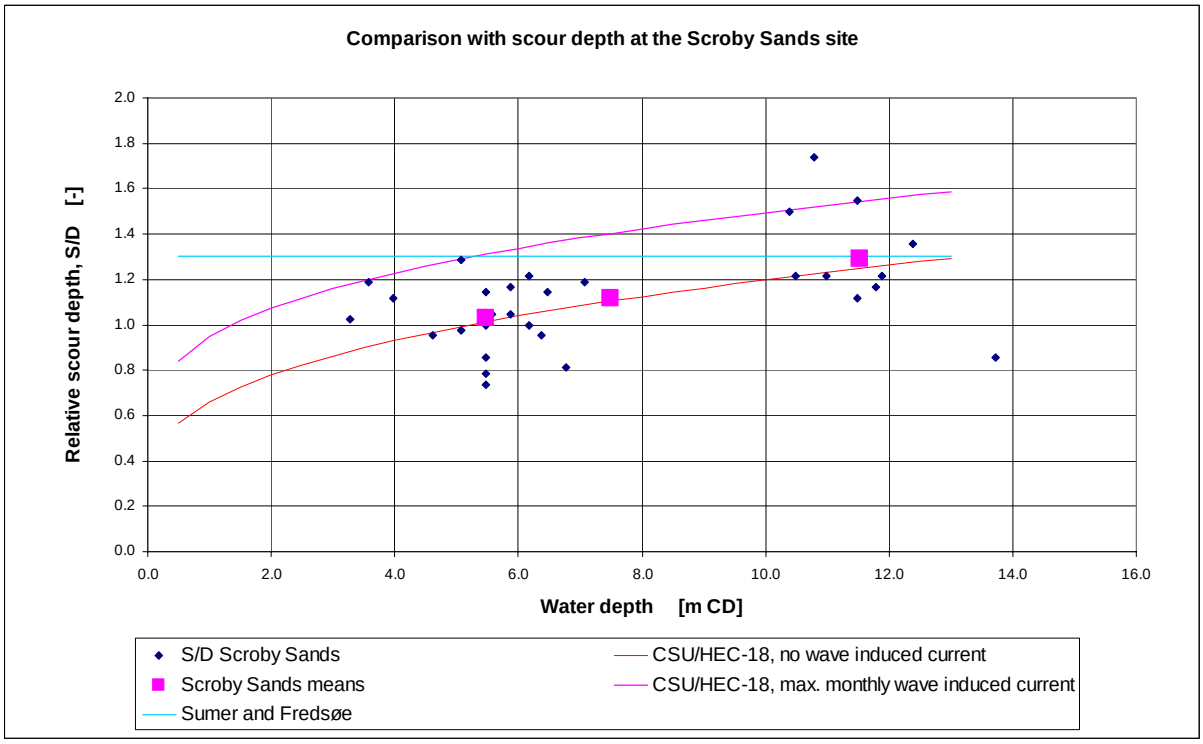


Figure 4 Scour prediction using the CSU/HEC-18 model on the Scroby Sands project site

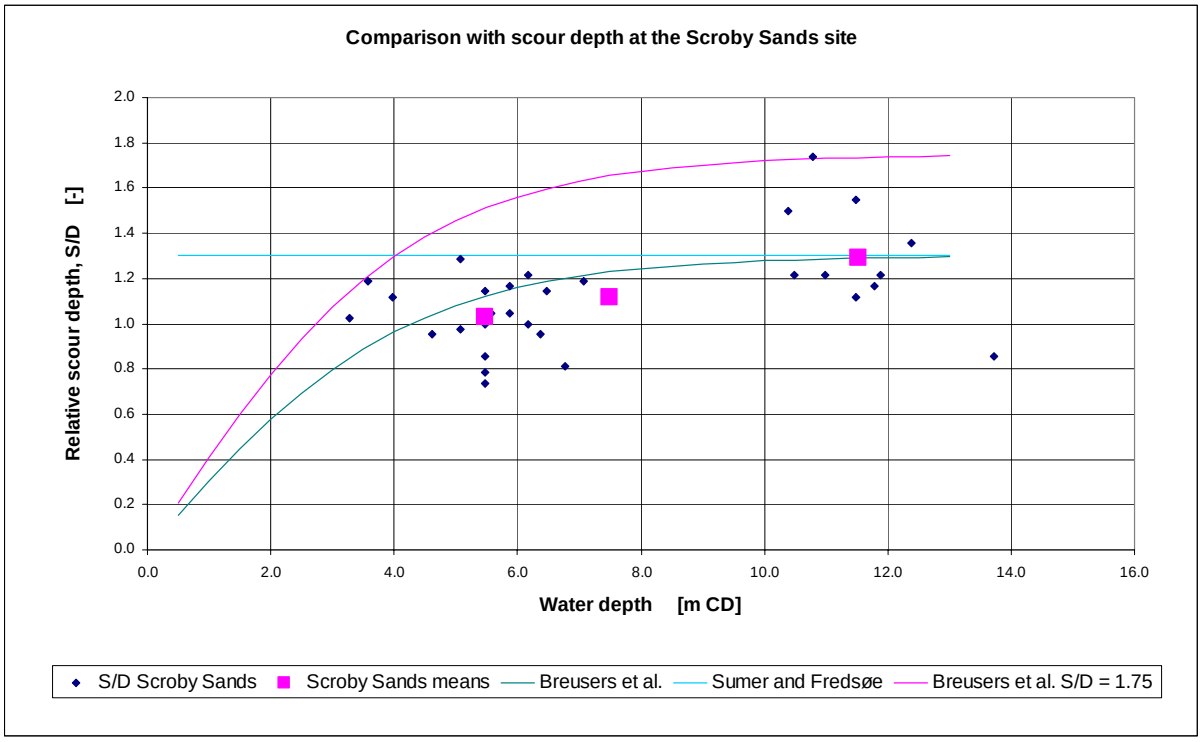


Figure 5 Scour prediction using the model of Breusers et al. on the Scroby Sands project site

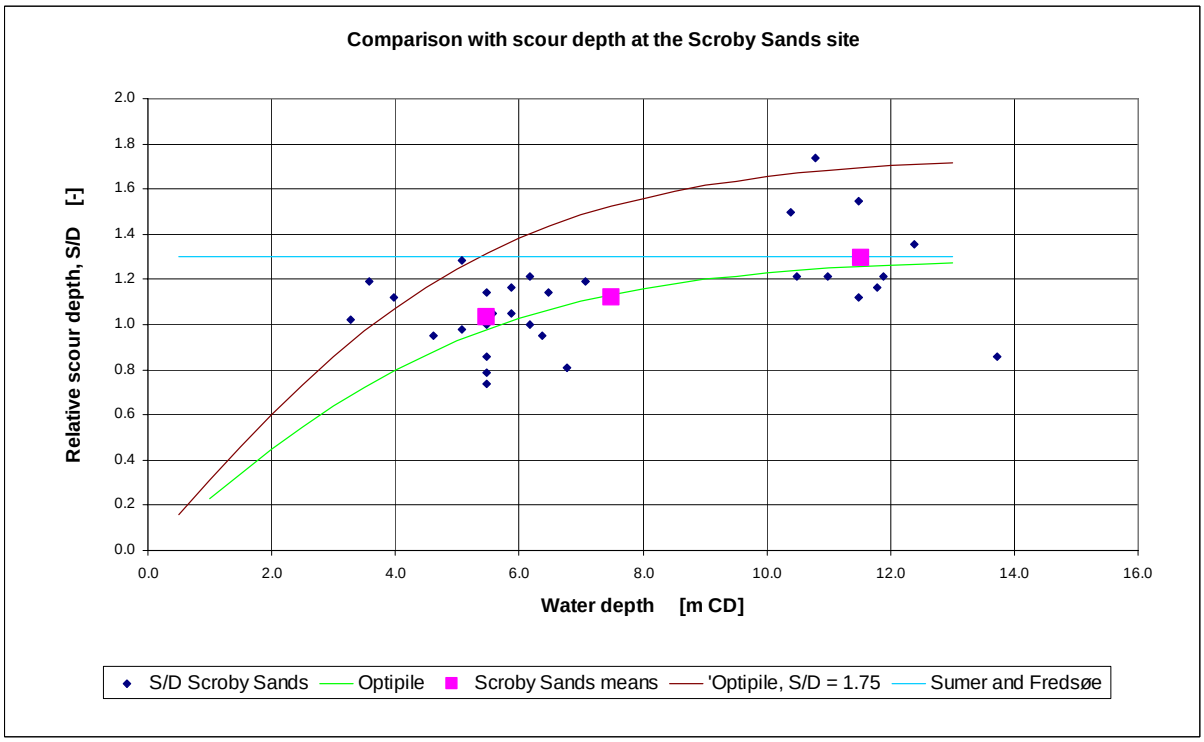


Figure 6 Scour prediction using the OptiPile tool on the Scroby Sands project site

3 *Proposal for scour adaptive design approach*

If no scour protection is installed around the foundation for an offshore wind turbine local scour is generally taken into account in the design of support structures for offshore wind turbine projects by adopting a design scour depth corresponding to the most likely extreme local scour depth. Ref. [10] where a local scour depth of 1.3 *D* – corresponding to the mean equilibrium scour depth from Sumer et al. [9] – in addition to any global scour shall be included in the fatigue limit state (FLS) and

ultimate limit state (ULS) load verifications. Scour depths larger than the most likely will combined with the FLS or ULS load verification increase the level of safety.

The impact on the foundation design of not installing a scour protection – using current practice for accounting for scour – is significant and probably the reason that most foundations for offshore wind farms in sandy areas are designed with a scour protection system, where the most common is layers of rock that are large enough to be stable (to an acceptable degree) under the largest design wave and current conditions.

Nevertheless, cost comparison on recent projects seems to indicate that a design without scour protection can be feasible in some areas, even when using current practise. In addition hereto it can be argued that this might be a too conservative approach, because:

- Extreme local scour normally occurs for a current only situation
- Combined waves and current or waves alone will normally lead to less scour depth than the current only situation
- It is normally the waves and not the current that governs the hydrodynamic loads in ULS and FLS

To exploit the possibility of suggesting more appropriate scour depth to be used in the ULS and FLS load analyses a desk study has been carried out.

The objective of the study has not been to provide specific methods for calculating a proper design scour depth, but merely to point out the relevance of further investigations into this, as the authors indeed realize that more sophisticated scour simulation tools combined with physical experiments are needed.

Desk study

As OptiPile is a simple and effective tool for estimating the scour depth in combined waves and current for a monopile foundation it has together with the estimation of scour time scales in [1] been used for the desk study and the Scroby Sands Offshore Wind Farm project is used as reference test case with the scour driving parameters listed in Table 1.

The calculated relative scour depths for various wave and current combinations are shown in Table 2. In Table 2 is also shown, based on the Scroby Sands background material, the discrete un-conditional probability, *p*, for each wave and current bin.

				Uc [m/s]										
Hs [m]	Tp [s]	Um [m/s]	KC	0.10	0.30	0.60	0.90	1.10	1.30	1.50	1.70	1.90	2.10	p(Um)
0.00	1.00	0.00	0.00	0.00	0.50	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	0.23
0.50	3.10	0.35	0.03	0.00	0.57	1.06	1.10	1.11	1.12	1.12	1.12	1.13	1.13	0.40
1.00	4.40	0.71	0.21	0.04	0.29	0.66	0.86	0.93	0.98	1.02	1.04	1.06	1.07	0.24
1.50	5.40	1.06	0.49	0.02	0.14	0.41	0.64	0.74	0.83	0.88	0.93	0.96	0.99	0.09
2.00	6.20	1.41	0.85	0.01	0.09	0.29	0.49	0.60	0.69	0.77	0.83	0.87	0.91	0.03
2.50	6.80	1.77	1.24	0.01	0.06	0.21	0.39	0.50	0.59	0.67	0.74	0.79	0.84	0.00
3.00	7.40	2.12	1.69	0.01	0.05	0.17	0.32	0.42	0.51	0.59	0.66	0.72	0.77	0.00
3.50	7.70	2.47	2.09	0.00	0.04	0.14	0.27	0.36	0.44	0.52	0.59	0.66	0.71	0.00
4.00	7.90	2.83	2.48	0.00	0.03	0.11	0.23	0.31	0.39	0.47	0.54	0.60	0.66	0.00
4.50	8.00	3.18	2.84	0.00	0.03	0.10	0.20	0.27	0.35	0.42	0.49	0.55	0.61	0.00
5.70	8.10	4.03	3.66	0.00	0.02	0.07	0.15	0.21	0.27	0.33	0.39	0.45	0.51	0.00
			p(Uc)	0.12	0.40	0.38	0.10	0.01	0.00	0.00	0.00	0.00	0.00	1.00

Table 2 Relative scour depth S/D vs. current speed and wave height

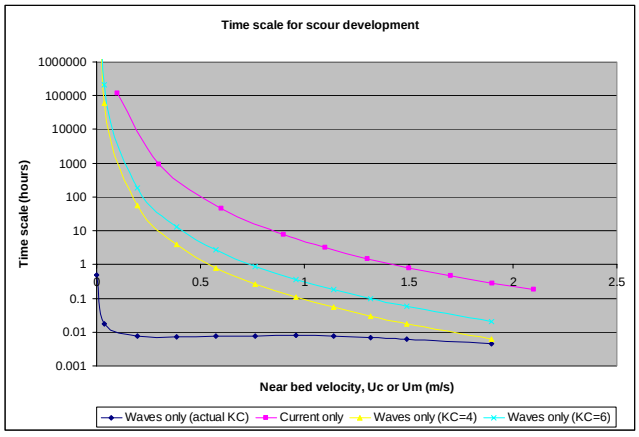


Figure 7 Time scale for scour development

In Figure 7 below the time scale for the scour process, *T* has been calculated for the current only or the waves only situations using the formulations in [1]. As *KC* probably is too small for the calculation of *T* during waves only to be reliable *T* has also been calculated for wave only situation with *KC* kept constant (4 and 6) but without changing the Shields parameter.

As shown by Figure 7 the time scale for the scour process during waves, where *KC* is small, is often more than 2 decades smaller than the scour process during current. To these authors this indicates that the scour process in combined current and waves will have a time scale corresponding to the one governing the scour process during waves, as it is the overlaying wave action that reduces the scour relative to the current only situation.

Consequently, and because the time scale for the scour process during waves is so small, it is an appealing assumption that statistics for equilibrium scour depths for combined current and waves as calculated using the OptiPile or any other tool, e.g. as shown in Table 2 above, will follow the joint statistics for waves and currents.

If this is correct the probability to assign to each occurrence of the relative scour depth, *S/D*, conditional on waves and current can be calculated as

$$p(S/D \mid U_m, U_c) = p(U_m)p(U_c)$$

assuming waves and current to be statistical independent (which is not fully correct due to the wave induced current caused by waves from North-East).

The unconditional mean relative scour depth, $\overline{S/D}$, can then be calculated by

$$\overline{S/D} = \sum_{Uc=0}^{\infty}\sum_{U_m=0}^{\infty} p(S/D \mid U_m, U_c) \cdot S/D(U_m, U_c)$$

The mean relative scour depth conditional on U_m, $\overline{S/D}(U_m)$, e.g. U_m corresponding to an extreme design wave, can be calculated by

$$\overline{S/D}(U_m) = \sum_{Uc=0}^{\infty} \frac{p(S/D \mid U_m, U_c) \cdot S/D(U_m, U_c)}{p(U_m)}$$

Design application

The extreme design driving bending moment for a monopile can often be assumed to be unaffected by the overall Eigen frequency of the structure, i.e. linear proportional to the fixture depth, which again is linear proportional to the scour depth. Hence, an increase in extreme bending moment due to scour will be linear proportional to the scour depth.

The above formulation for calculating $\overline{S/D}(U_m)$ can therefore be used directly to estimate a more appropriate scour depth to be used for extreme load calculations.

Also the fatigue design driving bending moment for a monopile will be linear proportional to the fixture depth but also inverse linear proportional to the overall Eigen frequency of the structure, which again is inverse linear proportional to the square root of the fixture depth. Hence, the increase in fatigue bending moment due to scour will be exponential proportional to the scour depth. In addition the accumulated fatigue damage or equivalent fatigue load also depends on the adopted Wöhler exponent, *m*.

The below formulation can therefore be used to estimate a more appropriate scour depth to be used for fatigue load calculations.

$$\overline{S/D}_{fatigue} = \left(\sqrt[m+3/2]{\sum_{Uc=0}^{\infty}\sum_{U_m=0}^{\infty} p(S/D \mid U_m, U_c) \cdot \left(L_0 + S(U_m, U_c)\right)^{m+3/2}} - L_0 \right) / D$$

where L_0 is pendulum length in the equivalent 1DOF inverted pendulum system. For simplicity L_0 can be set equal to the vertical distance between hub-height and fixture depth.

In Table 3 below more appropriate scour depths to be used in the above Scroby Sands example, calculated using the above formulations with $L_0 = 80$ m and $m = 5$, are compared to scour depths calculated using traditional design practice.

As can be seen from Table 3 the savings in using an adaptive approach are significant and will decrease both the required pile penetration length and the design driving sectional forces. This will have a significant impact on the foundation costs.

Description	S/D	S
Adaptive design scour depth to be used for fatigue loads calculations	0.63	2.67 m
Adaptive design scour depth to be used for extreme wave loads calculations	0.05	0.21 m
Adaptive design scour depth to be used other extreme loads calculations	0.61	2.56 m
OptiPile maximum scour depth	1.13	4.76 m
Current practise design scour depth for fatigue and extreme load calculations	1.3	5.46 m

Table 3 Adaptive design scour depths compared to current practise and the OptiPile calculated maximum scour depth

Consequently, it is the hope of the authors that this very simple desk study can be an inspiration and encouragement to further investigation into the possibility of applying more appropriate scour depth when performing load calculations for offshore wind turbines. This will contribute to more optimal foundation designs and help offshore wind to become more feasible.

4 Acknowledgement

Several contributors to the Scroby Sands Offshore Windfarm project are acknowledged for their documentation which has served as valuable background for this paper.

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