The effects of Scour on the design of Offshore Wind Turbines

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SYNOPSIS

Offshore structures on a sandy seabed are susceptible to scour. Scour affects the required foundation length and stiffness, has an effect on the structure's natural frequency and may cause free-spanning of the J-tubes. Although preventive measures can be taken against scour, knowledge and understanding of the phenomenon can aid the designer in making a more tailored design for a specific location. A resume is given to show the impact of different design parameters on the occurrence of scour: waves, current, structure diameter and soil characteristics. Within the lifetime of a structure both extreme and long-time mean scour levels can be determined.

To test the effect of these varying scour depths, a typical design for a 2.75MW turbine is used for a location off the Dutch coast in 20m of water. Pile designs were made for different extreme scour depths. These designs were then checked for natural frequency and fatigue variation for zero to the maximum design scour depth. It can be concluded that varying the scour depth from 0 to 13m does require more steel (longer pile) but does not seriously affect the dynamics and fatigue of the structure in this case. The reader should be reminded that care was taken to avoid direct interference between natural and excitation frequencies, reducing the risk of large dynamic amplification and unwanted exponential increase of fatigue.

INTRODUCTION

The seabed of most of the North Sea consists of sandy soil. This sand is constantly moving due to waves and current. When a structure is placed offshore, the structure causes local increase of the current and wave motions. This fast flowing water stirs sand particles, picks them up and transports them away from the structure, creating a hole around the structure. This phenomenon is called scour.

The majority of offshore oil & gas structures are jackets: four or more legged structures. Because their main transfer of forces is through axial loading of the legs, a scour hole will not have large effects on the foundation. Offshore wind turbines on the other hand are currently being built on monopile support structures that transfer their loads mainly laterally. Because a large portion of these loads is transferred in the upper part of the soil, a scour hole will have great effect on the design. A second characteristic of offshore wind turbines is their dynamic sensitivity. The tall structure with a large top mass (the turbine) makes the structure relatively flexible with a natural frequency near the wave excitation frequencies. Fatigue of the structure can therefore become a design driver. When scour occurs around such a structure, the overall length will increase, further lowering the natural frequency and probably influence fatigue. The remedy against scour is scour protection: the dumping of large quantities of crushed rock around to the structure to fix the seabed to its original level. The method is expensive and requires regular inspection and occasional maintenance.

This paper explores the effect of scour on the design of offshore wind turbines. First the general background of scour is summarized: the basics behind the occurrence of scour and the empirical calculation methods to determine the extent of it. Then different scour depths are used to design the dimensions of the foundation. For these different designs the mean scour depth is varied to determine the effect on the natural frequency of the structure and the fatigue.

Reference location and turbine

First, a site off the coast of The Netherlands has been selected for which soil, wind, wave and current data was readily available. This site has been the focus point of the Opti-OWECS study [1] and is the target area for the first demonstration offshore wind farm in the Netherlands, NSW, which will be installed in 2005. The NSW farm will consist of 36 turbines with a rated power of 2.75MW. For this study, a preliminary design for these particular turbines is used as shown in figure 1.

· **First author's Biography**

Jan van der Tempel is in his last year of his PhD on "Integrated Design of Support Structures for Offshore Wind Turbines" at the Delft University of Technology. After his MSc. in Civil Engineering (2000) he worked for 1 year with the engineering department of Boskalis, mainly focussing on a tender for the installation of Horns Rev and the engineering of rock dump projects.

Figure 1. Location and sketch of offshore wind turbine off the Dutch coast

The Opti-OWECS report gives an extensive description of the site data. The wave scatter diagram and the design wave and current are given in figure 2. From Admiralty Chart 1083, the tidal current velocity for neap and spring tide is also plotted in figure 2.

H_s [m] \ T_z [s]	0 - 1	1 - 2	2 – 3	3 – 4	4 – 5	5 - 6	6 - 7	7 - 8	Sum:
6.5 - 7.0									0
6.0 - 6.5								0.1	0.1
5.5 - 6.0							0.1	0.1	0.2
5.0 - 5.5							0.1	0.1	0.2
4.5 - 5.0							1		1
4.0 - 4.5							4		4
3.5 - 4.0						4	5		9
3.0 - 3.5						19	0.1		19.1
2.5 - 3.0					0.1	38			38.1
2.0 - 2.5					27	43			70
1.5 - 2.0				0.1	115	5			120.1
1.0 - 1.5				6	220	1			227
0.5 - 1.0				236	145	1			382
0.0 - 0.5	1		1	113	14	0.1	0.1		129.2
Sum:	1	0	1	355.1	521.1	111.1	10.4	0.3	1000

Maximum wave height	12.8 m
Associated period	9.5 s
Maximum surface current	1.1 m/s
Maximum seabed current	0.7 m/s

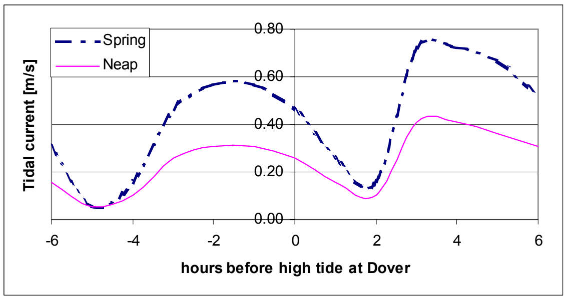

Figure 2. Scatter diagram of significant wave height and zero crossing period for reference site; design wave and current parameters; tidal current velocities

BACKGROUND

Development of scour

The disturbance of the flow by the structure is visualised in the left-hand drawing of figure 3. The oncoming flow is forced around the structure creating a down flow in front of the structure and a horseshoe vortex near the seabed. Behind the structure the flow is still turbulent. The horseshoe vortex is the main driver of the scour. The turbulent flow behind the structure has a lower velocity, which causes the floating sediment to settle again, creating a zone of deposition higher than the unscoured seabed as shown in the right-hand drawing of figure 3.

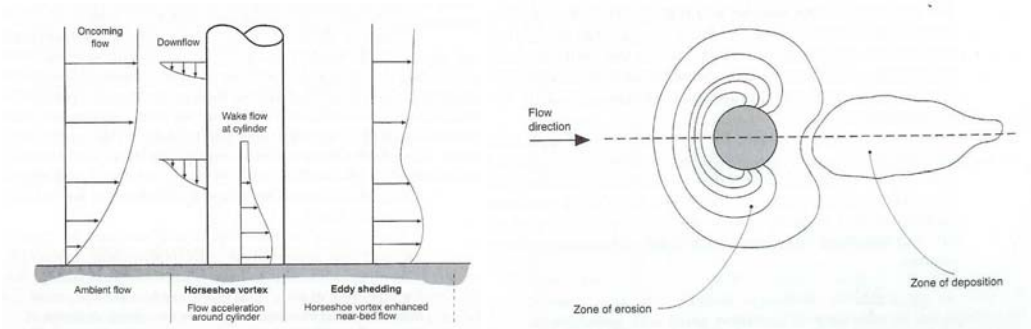

Figure 3. Flow-structure interaction for a vertical cylinder and characteristic scour hole and deposition pattern [2]

For scour due to waves only or combined waves and current, the same mechanism creates a scour hole: moving water particles are accelerated in the vicinity of the structure, carrying small particles along, away from the structure. When waves are present, the scour hole is usually a more uniform dent around the structure. No deposition zone can be distinguished as in the case of current-only scour.

Types of scour

Basic scour can readily be found on any sandy beach at low tide as shown in the left-hand side of figure 4. The alternating currents of waves washing ashore have caused a steep scour pit of more or less conical shape. This type of scour is called *local scour*.

Figure 4 (left) Local scour: steep-sided scour pits around single piles
(right) Local and global scour around a jacket structure [2]

Around more complex structures, with several legs, not only local scour around each separate leg can be distinguished, also the lowering of a large area around the entire structure is observed as shown in the right-hand side of figure 2. This type of scour is called *global scour* or *dishpan scour*. This type of scour does not occur around monopiles and will therefore not be treated further in this paper.

A final seabed phenomenon that affects the design of offshore wind turbine support structures is an overall movement of the seabed: *sand waves*. The movement of the seabed is not affected by the presence of the structures, but is a result of large-scale morphological effects. The movement of these sand waves is a slow process covering several years. This may mean that the general seabed level may have changed several meters a few years after installation.

Effects of scour on offshore wind turbines

When scour is likely to occur around an offshore wind turbine, it has to be incorporated in the design of the structure. Scour will have an effect in three main areas:

1. foundation length
2. natural frequency
3. J-tube

The main transfer of loads from the structure to the seabed is through lateral loading. When the top part of the soil is removed because of scour, the foundation pile needs to be extended deeper into the ground to ensure sufficient lateral bearing. In the design, the most probable combination of maximum scour depth and maximum extreme loads must be used to find the appropriate foundation length.

As offshore wind turbines are dynamically sensitive structures, the natural frequency must be designed in such a way that it does not coincide with excitation frequencies of waves, wind and turbine rotation. When scour occurs, the pile will effectively lengthen, making it more flexible: the natural frequency changes. Because the effect of the dynamic sensitivity of the structure is most pronounced in fatigue, which spans the lifetime of the structure, the mean scour depth is dominant for this part of the design process. Should sand waves occur in the area, different mean seabed and scour levels could be taken into account for periods of the lifetime.

It is common practice to support the power cable from the turbine to the seabed with a plastic J-tube. When scour occurs, this J-tube could be free spanning over the scour hole. Because the power cable is of vital importance for the power production of the offshore wind turbine, damage to the cable should be prevented. Detailed design of the J-tube for different scour scenarios is therefore crucial, but will not be treated in this paper.

Preventing scour

The effects of scour on the design of the offshore wind turbine can also be mitigated by protecting the soil around the pile against scour. Several types of scour protection exist, ranging from asphalt to concrete mattresses, but most options require expensive offshore installation. The most cost effective method is therefore the dumping of crushed rock. The scour process, as described in earlier sections and detailed later, is driven by increased current velocity around the structure, picking up soil particles and washing them away from the structure. The basic idea behind the placing of a layer of rock is that the rock particles are selected in such a way that the increased current around the structure will not be able to wash them away. In some cases, several layers of rock need to be placed on top of each other to prevent smaller particles from being washed out between the larger rocks. Figure 5 shows a typical design of such a scour protection [3]. In this case 6500 tons of rock was used. It effectively fixes the seabed, making the design of the foundation depth, the natural frequency and the fixation of the J-tube much easier. It must be noted though, that local scour protection will not have any effect on passing sand waves. At a first guess rate of 50 euro/ton, the total cost of the scour protection would be 12Meuro for 36 turbines.

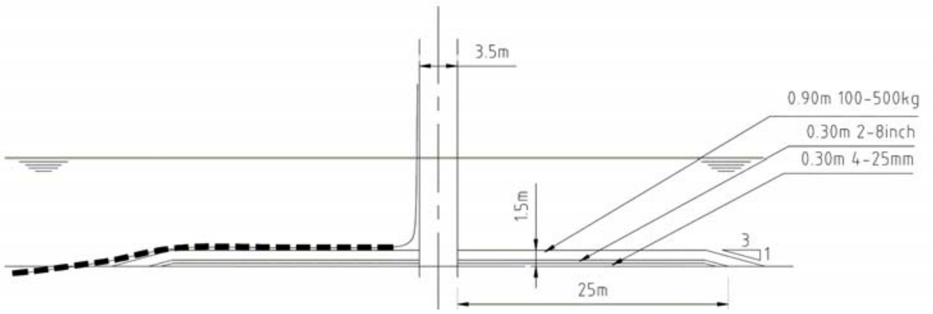

Figure 5 Design solution: three rock layers on top of seabed [3].

CALCULATING SCOUR

Although the detailed calculation of scour around structures may require extensive computer models, detailed site investigations or even scale model testing, a number of empirical formulae exist to approach the occurrence of scour in a pragmatic way. This section gives and overview of these calculation methods in order to give the reader insight in the critical parameters influencing scour.

Will scour occur?

The first thing that should be determined is whether the seabed will be susceptible to scour after the installation of a structure. To do this, Whitehouse [2] gives a very clear flowchart of the critical parameters as shown in figure 6.

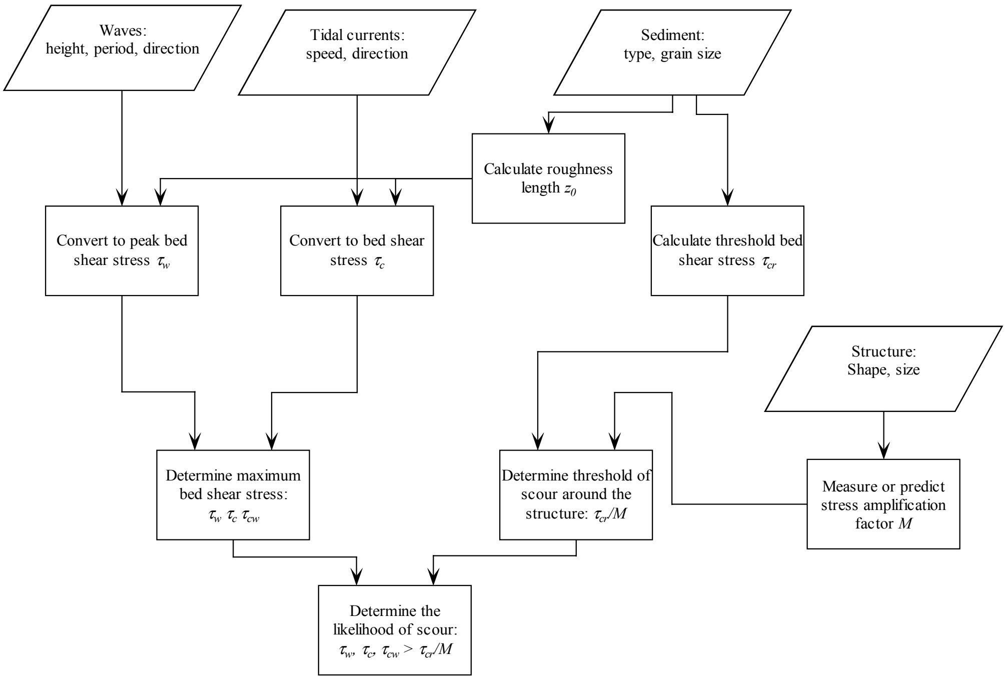

Figure 6. Flowchart for determining whether scour will occur around a structure [2]

On the left-hand side, the wave and current particle velocity is calculated and converted to maximum shear stress on the seabed. On the right-hand side the allowable shear stress for the seabed under consideration is determined. By adding the effect of the structure on the amplification of the seabed shear stress as a factor *M*, the threshold for scour around the structure is determined. Scour will occur if any wave and/or current induced shear stress lie above this threshold.

Scour depth determination

If scour is likely to occur, the next thing is to determine the depth of the scour hole. Sumer and Fredsøe [4] have done extensive experiments for different structures under wave and current conditions. Figure 7 shows the results of these measurements including the fitted curves to approach the variation of scour depth for different wave and current magnitudes, the curve description is given in equation 1.

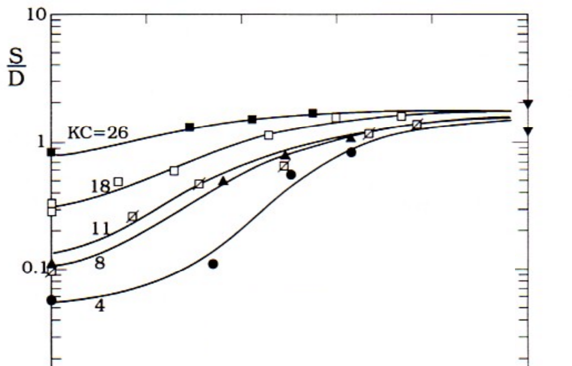

Figure 7. Measured scour depths for different *KC* numbers under waves and current [4]

$$\frac{S}{D} = \frac{S_c}{D}\left[1-\exp\{-A(KC-B)\}\right] \tag{1}$$

Where: $A = 0.03 + \frac{3}{4}U_{cm}^{2.6}$ and $B = 6\exp(-4.7U_{cw})$

with: S_c, the scour depth in case of a steady current alone

KC the Keulegan-Carpenter number

U_{cw} the velocity ratio between wave and current induced water particle velocity

The value for S_c is determined by the mean scour depth found in numerous laboratory tests combined with one or two times the standard deviation of this scour depth to cover all variation. The goal is to define a maximum possible scour depth for design purposes, S_c as shown in equation 2.

$$\frac{S_c}{D} = \left[\overline{\frac{S}{D}}\right] + \sigma_{\frac{S}{D}} \text{ or } \frac{S_c}{D} = \left[\overline{\frac{S}{D}}\right] + 2\sigma_{\frac{S}{D}} \tag{2}$$

with: $\left[\overline{\frac{S}{D}}\right]$ mean value of measured scour depth over pile diameter = 1.3m

$\sigma_{\frac{S}{D}}$ standard deviation of measured scour depth over pile diameter = 0.7m

This means the design maximum scour depth due to current only can be chosen $S_c = 2.0D$ or $S_c = 2.7\ D$. Note that these values are laboratory maximum values applied for use in design formulae, not the final answer to the question how deep the actual scour hole will be!

The Keulegan-Carpenter number gives an indication of the turbulence of the flow around the structure under wave motion. It is calculated from the particle velocity at the seabed, based on appropriate wave theory for the wave and the site under consideration, the wave period and the diameter of the structure, equation 3.

$$KC = \frac{U_m T_w}{D} \tag{3}$$

with: U_m the maximum horizontal orbital water particle velocity at the seabed

T_w the wave period

Finally, the velocity ratio is determined to incorporate the effect of current in equation 4.

$$U_{cw} = \frac{U_c}{U_c + U_m} \tag{4}$$

with: U_c current velocity at $D/2$ above the unscoured seabed.

For all waves in the scatter diagram in figure 2 $KC < 6$, resulting in a negligible scour from waves only. For scour due to current, the predicted value is purely dependent on the assumed mean and standard deviation used in equation 2, ranging up to $2.7D$.

Time scale of scour

Finally, the time scale of the scour process can be calculated. This can be used to plan installation works of further structural elements, for instance J-tubes and cables or for the installation of scour protection. First, the undisturbed bed friction velocity is calculated; equation 5.

$$U_f = \frac{V}{2.5\left[\ln\left(\frac{30h}{k_s}\right) - 1\right]} \tag{5}$$

With: V mean current velocity [m/s]

h water depth [m]

k_s surface roughness $k_s = 2.5d_{50}$

d_{50} grain size

Then the undisturbed Shields parameter can be found with equation 6.

$$\theta = \frac{U_f^2}{g(s-1)d_{50}} \tag{6}$$

With: g acceleration due to gravity [m/s^2]

s specific gravity of sediment grains [m]

The normalized time scale is then found via equation 7.

$$T^* = \frac{1}{2000}\frac{\delta}{D}\theta^{-2,2} \tag{7}$$

With: δ flow depth (usually $\delta = h$)

From the normalized time, the total time can be derived, equation 8.

$$T = \frac{D^2}{(g(s-1)d_{50}^3)^{\frac{1}{2}}} T^* \tag{8}$$

The time scale for wave induced scour can be determined similarly but then the Shields parameter is found from the maximum orbital water particle velocity and the normalized time scale is based on the *KC*-number, equation 9.

$$T^* = 10^{-6}\left(\frac{KC}{\theta}\right)^3 \tag{9}$$

For the reference location the time scale for scour under the maximum current only (1.1 m/s) would be in the order of 10 hours. For a mean current of 0.4 m/s, the scour process would reach its equilibrium in 300 hours

Application of scour calculations in a random marine climate

The calculation methods mentioned in the previous section all focus on specific design parameters: a current velocity, certain wave heights and periods. At a real location, all these parameters change constantly. In areas where an offshore wind turbine will suffer from scour, the total seabed itself is usually already subjected to a constant sediment transport. This is called a *live seabed*. In that case, the scour hole will constantly vary in depth. During a storm high currents and waves may create a large scour hole due to the very high total flow velocity near the pile. After the storm, the velocities will be reduced to normal whereby the local speed at the bottom of the scour hole will be zero, causing live seabed sediment to settle and backfill the hole.

Standards and measurements

For the design of offshore structures, most design standards refer to specific scour literature to determine the actual scour depth. The new guidelines for the design of offshore wind turbines by DNV [5] include an appendix giving more background. The designer is advised to use a scour depth of S = 1.0 D to S = 1.5 D.
For 2 monopile structures in the Dutch part of the North Sea scour data is available. The Europlatform outside the port of Rotterdam is installed in 32m of water on a 3.5m diameter pile [6]. The scour depth measured was about 3m, less than 1D. For the N7 platform, north of Schiermonnikoog, a 6m-diameter structure in 7m water depth has had an increasing scour hole ranging from 2m after installation in 1997 to 4.8m in 2002. It is expected that the scour process will continue [7].

EFFECTS OF SCOUR ON THE DESIGN OF OFFSHORE WIND TURBINES

The previous sections have shown that the basic principle of scour is easily understood, but the prediction of the actual design scour depth incorporates uncertainties. For the design of offshore wind turbines, the question is: does this matter? To answer this question, a series of the designs have been made for different scour depths: 0, 0.5, 1, 1.5, 2 and 2.5D, where D is the pile diameter. These designs were then subjected to a varying scour depth ranging from 0D to the design scour depths in steps of 0.5D. For these situations, the natural frequency was calculated and the lifetime fatigue.

Pile designs

The soil provides lateral and axial resistance to displacements of the foundation pile and thus avoids overturning of the structure under loading. The foundation must be designed in such a way that sufficient resistance can be built up, before failure of the soil, including some safety margin. The limit of the resistance that can be mobilized by the soil depends, among others, on the downward pressure on top of the soil. This pressure is called the overburden pressure and in general a larger overburden pressure results in a higher limit of the resistance. For pile foundations, the overburden pressure is created by the soil itself and as a consequence, the overburden pressure and limit of resistance increases with depth below the mudline. In the case of scour, two effects reduce the resistance of the soil. First, the upper layers of soil are removed and therefore their resistance is lost. Second, the contribution of the upper layers to the overburden pressure is removed, thus reducing the limit of resistance of lower layers. As a consequence, the pile has to become stronger (to resist the higher moments in the pile) and has to be driven deeper into the seabed (to generate sufficient soil resistance).

The effect of scour is commonly modeled as illustrated in Figure 8 [8]. The effect of local scour is a reduction of the overburden pressure that reduces linearly until the overburden reduction depth. Below the overburden reduction depth the effect of local scour vanishes. A typical value for the overburden reduction depth is 6 times the pile diameter.

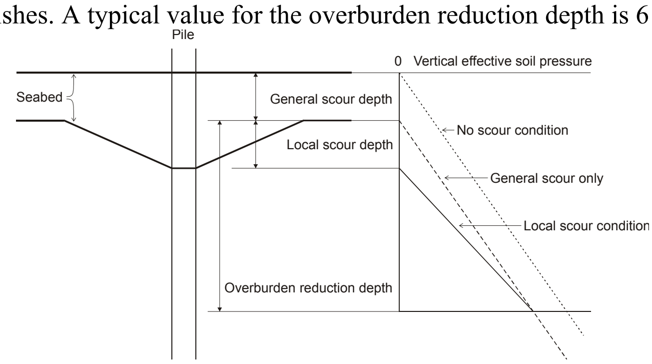

Figure 8. Overburden reduction depth determination for global and local scour

Taking these considerations into account, 6 pile designs were made. The reference structure was designed with a scour depth of 8.5m or 1.8 *D*. The pile optimisation program gave results comparable to this reference design.

Natural frequency

Because offshore wind turbines are subjected to constant dynamic loading by wind, waves and rotation of the blades, the design of the support structure should be such that the natural frequency of the structure does not coincide with any of the loading frequencies [9]. To test the impact of (incidental) scour on any of the previously designed structures, the scour depth is varied. For all structures the scour depth is stepped down from 0*D* to the maximum depth the pile was designed for: deeper scour holes would mean that the structure would fail on bearing capacity.

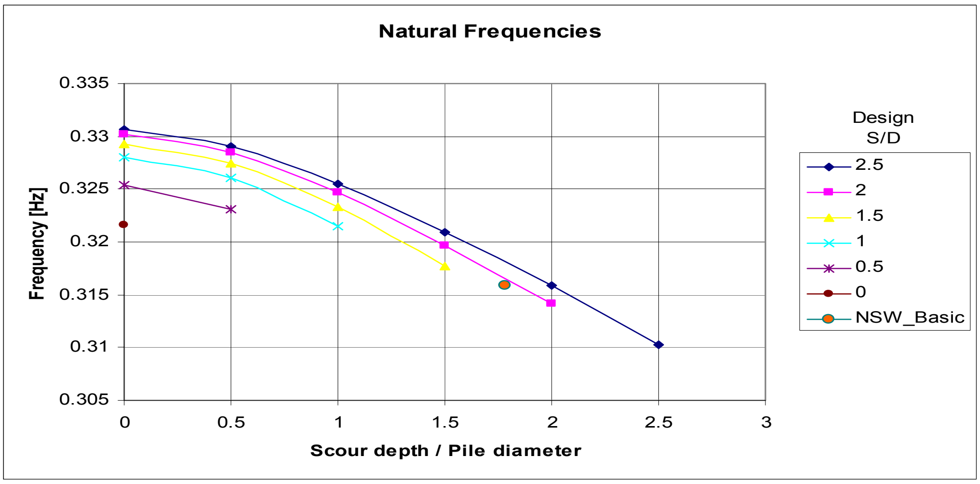

Figure 9. Natural frequency variations for different designs under varying scour depth

It can be seen that the natural frequency decreases with increasing scour depth. Further, the different designs tend to be somewhat less stiff (lower natural frequency) due to the increased soil support of the upper (unscoured) soil layer. The frequency variations are shown in figure 10 together with the frequency band of the rotor speed (1P) and the blade passing frequency (3P). The band of wave frequencies is also indicated.

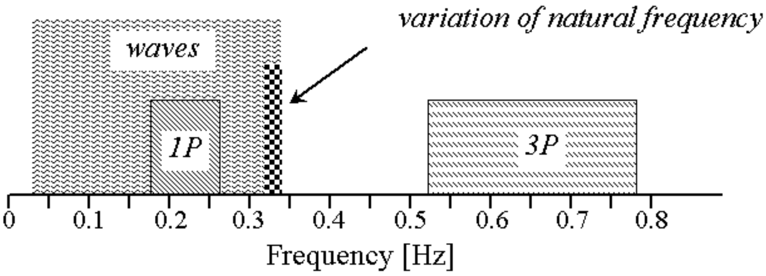

Figure 10. Frequency ranges for waves, rotation of the rotor (1P), blade passing (3P) and the structure

Fatigue

Although the natural frequency of the support structure is designed in such a way that direct overlap with the excitation frequencies is prevented, dynamic amplification around the natural frequency will still occur. Therefore, offshore wind turbines need to be checked whether the structure has a fatigue life longer than the required economic life of 20 years. Normally a large number of time domain simulations of the operating offshore wind turbine need to be carried out to incorporate all non-linear load combinations of wind and wave loads. Because this is a time consuming exercise, a simplified fatigue check is carried out. The structure is modelled in the offshore design package Sesam, where wave load only, frequency domain calculations can be performed to check the lifetime fatigue. The effects of the operating turbine are only incorporated through additional structural damping to simulate the actual aerodynamic damping. Further, all waves are assumed to come from only one direction.

Although these assumptions result in a very crude first guess of the real fatigue, for the objective of this paper, they give results that can be obtained quickly and be compared properly as shown in figure 11. A fatigue damage $D_{life} = 1$ means the fatigue life is 20 years, $D_{life} = 0.1$, 200 years. For structural parts that cannot be inspected (in the ground) the goal is to have a fatigue life 3 times the economic lifespan: $D_{life} < 0.33$. Although the fatigue damage increases dramatically with increasing scour depth, the final fatigue checks still comply with the design requirement.

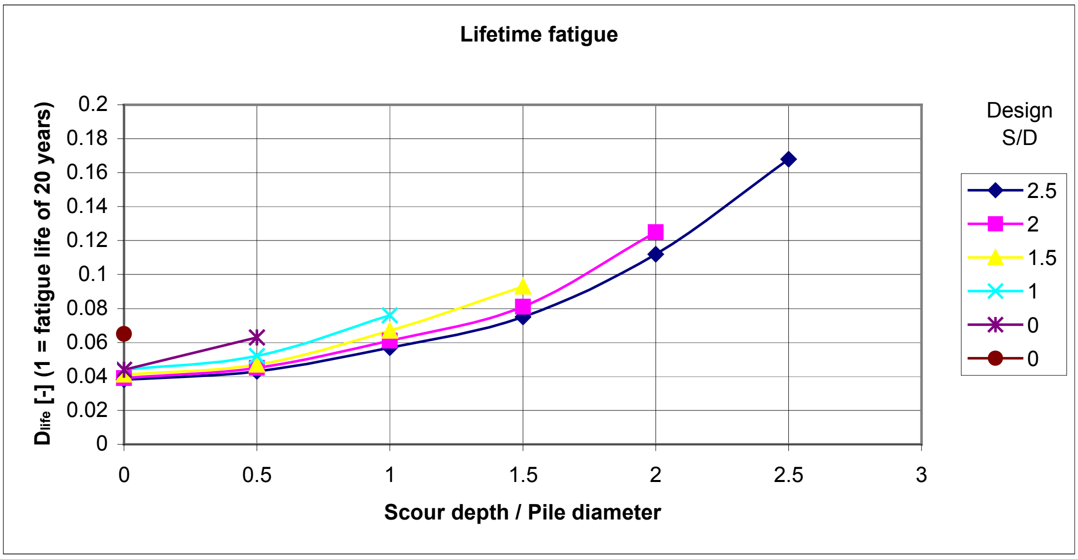

Figure 11. Lifetime fatigue for different pile designs with varying scour depth

CONCLUSIONS AND DISCUSSION

Scour is a common phenomenon around the North Sea. It will have an impact on the design of many of the planned offshore wind farms. Understanding of the basic principles behind scour is easy; predicting the extent of it for a specific structure on a specific location is rather dramatic. But looking at the few available measurements on monopile structure in the North Sea, most calculated scour depths seem to overestimate reality.

When looking at the design of offshore wind turbines, the small variation of the scour depth has a minor impact on the natural frequency of the structure. The fatigue of such a structure on the other hand is very sensitive to the lowering of this frequency, and will increase substantially. This relation between small decrease of natural frequency and large increase in fatigue is typical for the dynamically sensitive monopile supported offshore wind turbines, but can be addressed adequately in design.

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