SINKING OF SCOUR PROTECTIONS AT HORNS REV 1 OFFSHORE WIND FARM

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The present study is an attempt to explain the reason for the sinking of the scour protection observed at Horns Rev 1 Offshore Wind Farm. A new method for analyzing the survey data has been developed based on detailed descriptions in the literature of the processes causing sinking. The results of the analysis of the survey data have shown that the largest relative damage was observed at shallow water and for the largest scour protections. This is found – based on descriptions found in the literature – to be characteristic for sinking in wave dominated climate and as the current at Horns Rev is found to be too weak to mobilize the sediment underneath the scour protections, it is found likely that the waves had a major influence on the sinking of the scour protections at Horns Rev 1 Offshore Wind Farm.

Keywords: scour protection; offshore wind farms; sinking of scour protections

INTRODUCTION

During the last two decades more and more wind farms have been installed offshore and the trend will continue according to public plans, see e.g. Ministry of Climate, Energy and Building (2012) and The Crown Estate (2014). The rapidly increasing number of offshore wind turbines has unveiled issues not covered by existing theories. This was also the case for one of the first large offshore wind farms: "Horns Rev I Offshore Wind Farm" in Denmark. The Horns Rev I is located in shallow waters (6.5 to 13 m water (MSL)) about 20 km off the Danish west coast in the North Sea. This area is exposed to tidal currents (around 0.5 m/s, up to 0.8 m/s during storm situations) and large waves – up to 3.5 m – from the North Sea. The wind turbines are founded on monopiles with a scour protection made of a two-layer cover (quarry run from around 350 mm to 550 mm) and a 0.5 m thick filter layer (marine stones from around 30 mm to 200 mm) between the armor layer and the seabed. The wind farm was installed in the summer of 2002. A control survey in 2005 showed that the scour protections adjacent to the monopiles sank by up to 1.5 m, Hansen et al. (2007). This was unexpected and shortly after the survey in 2005 the holes were repaired by adding additional stones.

Whitehouse (2011) compiled the experience of scour and scour protections from several offshore wind farms and other piled foundations installed in the North Sea area, at the time of writing. The latter authors reported that the scour protection at Arklow Offshore Wind Farm might have sunk in a similar way as Horns Rev 1 Offshore Wind Farm; however, the scour protection was installed in an already developed scour hole and is for that reason not fully comparable to the Horns Rev case. Furthermore, the rocks at Arklow were placed in an irregular manner and at some places with noticeable voids between the placed rocks.

Scour around unprotected structures – especially monopiles – has been studied extensively over the last decades. Most of the available results are compiled in the books of Breusers and Raudkivi (1991), Hoffmans and Verheij (1997), Whitehouse (1998), Melville and Coleman (2000), and Sumer and Fredsøe (2002). The previously mentioned work made it possible to develop numerical models for long-term prediction of the development of scour holes around monopiles, Nielsen and Hansen (2007), Raaijmakers and Rudolph (2008), Harris et al. (2010), and Dixen et al. (2012a, b). The latter knowledge has been complemented by Nielsen et al's (2012) study on scour in breaking waves and Hartvig et al's (2010) and Sumer et al's (2013) studies on backfilling of scour holes. Also numerical studies of unprotected piles have been performed successfully over the last decades, see e.g. Roulund et al. (2005), Liu and Garcia (2008), and Baykal et al.

On the other hand, scour protection of piles has not been studied nearly as much and some of the mechanisms of failure of scour protections around a monopile have only been described briefly. The stability of scour protections with regard to direct removal of the rocks by waves and current has been studied by Chiew (1995), Chiew and Lim (2000), Lauchlan and Melville (2001), Chiew (2002), and De Vos et al. (2011, 2012) among others. Most recently new studies on edge scour at scour protection around monopiles have been added (Petersen (2014) and Petersen et al. (2014)). As the previously mentioned studies focused on the stability of the of the rocks with regard to the outer flow they could

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not readily be used to explain the sinking of the scour protections at Horns Rev 1 Offshore Wind Farm. In an attempt to explain the sinking a major test program including physical and numerical modelling of the sinking in case of current, waves, and combined waves and current was initiated. The results of the test program are reported in Nielsen et al. (2011, 2013), Sumer and Nielsen (2013), Nielsen et al. (2014), and Sumer (2014). The findings presented in these papers have made it possible both to improve the analysis of the survey data from Horns Rev 1 Offshore Wind Farm and to give better explanations for the damage; this work is presented in the present paper.

Nielsen et al. (2011, 2013) showed that current was able to generate scour holes of the size observed at Horns Rev 1 Offshore Wind Farm. However, the frequency of currents strong enough to mobilize the sediment beneath the scour protections was too low to fully explain the observed sinking of the scour protections. Nielsen et al. (2014) showed that waves can cause the same magnitude of sinking and that the sinking is controlled both by the removal of sediment adjacent to the pile and by the in-filling of sediment from the surrounding seabed; in fact, the sinking of the scour protection could increase for a thicker scour protection as it took longer time to fill the pores between the stones with sediment from the surrounding seabed – leaving longer time for the removal process to work.

One of the major problems of the understanding of the Horns Rev 1 sinking has been that the layout of the scour protections is rather irregular, which has made it difficult to compare the different scour protections. However, the findings in Nielsen et al. (2014) made a strong indication that sinking due to waves was to a large extent controlled by the total volume of the scour protections rather than the actual height adjacent to the pile. This has been used to quantify the damage to the scour protections based on the change in volume of the entire scour protections. This method has shown that the largest damage was observed at foundations at shallow water and with the largest initial volume, while scour protections at deep water and smaller initial volumes observed the smallest damage: all together indicating that a major part of the sinking of the scour protections at Horns Rev 1 Offshore Wind Farm was caused by wave-dominated sea conditions.

THE HORNS REV 1 OFFSHORE WIND FARM

The wind farm was installed in 2002 as the first large offshore wind farm in the world at the time. The wind farm is located off the Danish west coast in the North Sea, see Fig. 1, and consists of 80 2 MW VESTAS turbines founded on monopiles with a diameter of 4.0 m (transition piece 4.2 m).

The location was another major difference to previous offshore wind farms, which were located in relatively calm conditions, e.g. inner Danish waters. The Horns Rev area is known for its harsh environment; it is a relatively shallow (approximately 6 to 13 m within the wind farm) sedimentary reef off the Danish west coast and fully exposed to waves from the North Sea. Large waves are common and the wave height is often limited by the water depth, so severe wave breaking takes place during storms. Furthermore, the area is located at the northern boundary of the Wadden Sea and therefore relatively strong currents are also common – up to around 0.8 m/s (Hansen et al. (2007)).

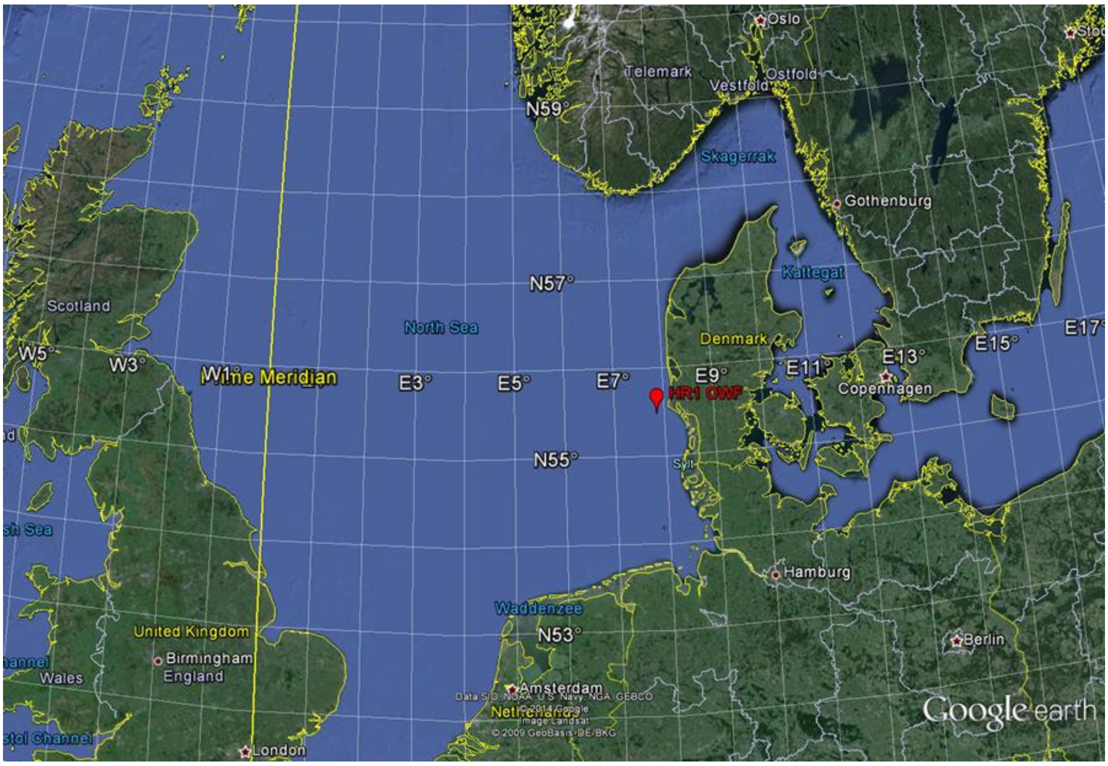

Figure 1. The location of Horns Rev 1 Offshore Wind Farm.

The Scour Protection

Scour protections were applied around the monopiles to prevent scouring of the seabed. The following description of the scour protections is based on Hansen et al. (2007) and Nielsen (2011). The scour protections were traditionally designed with a 0.5 m thick filter layer and a two stone layers thick cover layer, see Fig 2; the diameter of the scour protections was designed to be around 6 times the pile diameter (outer limits). The sizes of the stones used for the scour protections are listed in Table 1; the filter stones were round sea material, while the cover stones were quarry run. The sediment size in the area varies between 0.1 and 1.0 mm.

Table 1. Sizes of the applied stones for the scour protections.

	Minimum size [m]	Median size [m]	Maximum size[m]
Filter layer	0.03	0.10	0.20
Cover layer	0.35	0.40	0.55

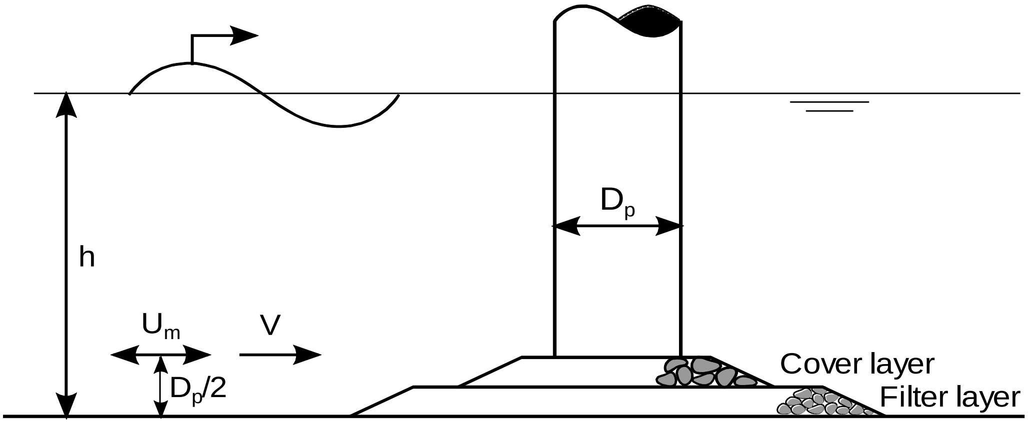

Figure 2 Sketch of the scour protections at Horns Rev 1 Offshore Wind Farm. Not to scale.

Installation of the Foundations

The installation of the monopiles took place during 2002 and the procedure was the following, Nielsen (2011):

1. Installation of the filter layer.
2. Installation of the monopile, driven through the filter.
3. Installation of the transition piece, including J-tubes and ducts for cables.
4. Installation of the cover layer.
5. Installation of the turbine, cables, etc.

Surveys

As part of the planning and installation of the wind farm, an extensive survey program has been carried out. The first survey of the area was conducted in August 1998, followed up by surveys in June 1999, April 2000 and 2001. These four surveys were conducted to obtain the bathymetry of the area and to provide data for an estimate of the morphological stability of the entire area. The surveys showed only very small changes in the bathymetry over the four-year period and in the following the bathymetry obtained in the 2001 survey will be used. More details of the surveys can be found in Nielsen (2011).

During the installation in 2002 a series of surveys was conducted around each foundation:

1. Before installation of the filter layer.
2. After installation of the filter layer.
3. After installation of the cover layer.
4. After extra filter stones were placed.
5. After extra cover stones were placed.

The last survey in the series is used as reference for the development. This survey was conducted during November 2002, around 6 to 9 months after the installation of the filter layers and around 4 to 8 months after the installation of the monopiles.

The 2002 surveys were followed up by detailed surveys of each foundation in April 2005 and autumn 2006; however, in between these two surveys additional stones were added to the scour protection to repair sinking of the scour protections adjacent to the piles observed in the 2005 survey.

Metocean Data

DHI has hindcast models for waves, current and tide covering parts of the North Sea, including the Horns Rev area. Data are available for a long period, including the actual period of interest (2002 to 2005), with a time resolution of 1 hour. The wave climate was modelled using a spectral wave model (MIKE by DHI – MIKE 21 SW) where the Horns Rev area has a spatial resolution of around 400 m – or similar to the minimum distance between the foundations; this is sufficient to include most of the variations in the bathymetry and the model provides reasonable results for each foundation.

The current and tide is modelled using MIKE by DHI – MIKE 21 HD. In this case the spatial resolution is lower – around 1000 m – which cannot resolve all the details in the bathymetry and it cannot provide reliable results for each individual foundation. However, comparison between the model results and current measurements in a point nearby shows good agreement.

Figure 3 shows the wave rose (coming from) for the significant wave height in the period 1 March 2002 to 30 April 2005 at Turbine 44. The period covers from the beginning of the pile installation to the end of the survey in 2005. Most of the waves and all the larger waves came from a westerly direction, with the largest waves coming from southwest to west. The position represents – to a large extend – the wave conditions in the entire farm; nevertheless, there are differences in the wave conditions for each foundation, especially in the northeastern part of the farm where the waves tend to be slightly larger.

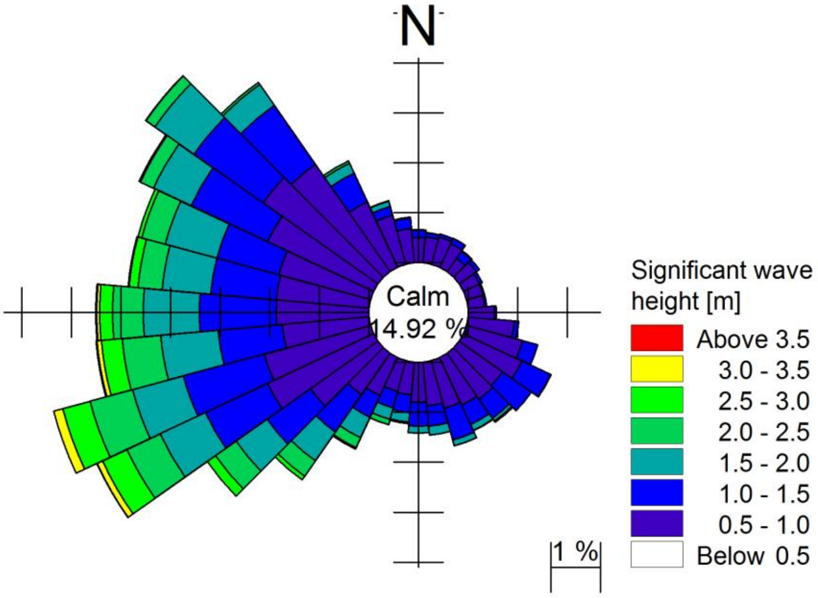

Figure 3. Wave rose for the significant wave height in the period 1 March 2002 to 30 April 2005 at Turbine 44.

Figure 4 shows the distribution of the maximum orbital velocities at five different positions in the period 1 March 2002 to 30 April 2005. The velocities are calculated using linear theory, significant wave height and peak period; the effect of the tide is included. The five turbines represent different parts of the wind farm: Turbine 12 represents the deep north-western part of the park, Turbine 17 represents the shallow south-western part, Turbine 44 represents the central part, with intermediate to deep water, Turbine 82 represents the shallow north-eastern part of the farm, and finally Turbine 87 represents the south-eastern part of the park with primarily intermediate water depth (the location of the turbines can be found in Fig. 7). While the wave heights were almost constant over the wind farm, the maximum orbital velocities – based on the significant wave height and peak period – vary significantly due to the varying water depth. The positions at deep and intermediate water depths (Turbines 12, 44 and 87) have a significantly larger fraction of the waves inducing near bed motions of less than 0.2 m/s, while it is only the shallow and intermediate positions where velocities above 1.2 m/s occurred more than a few hours during the period of interest.

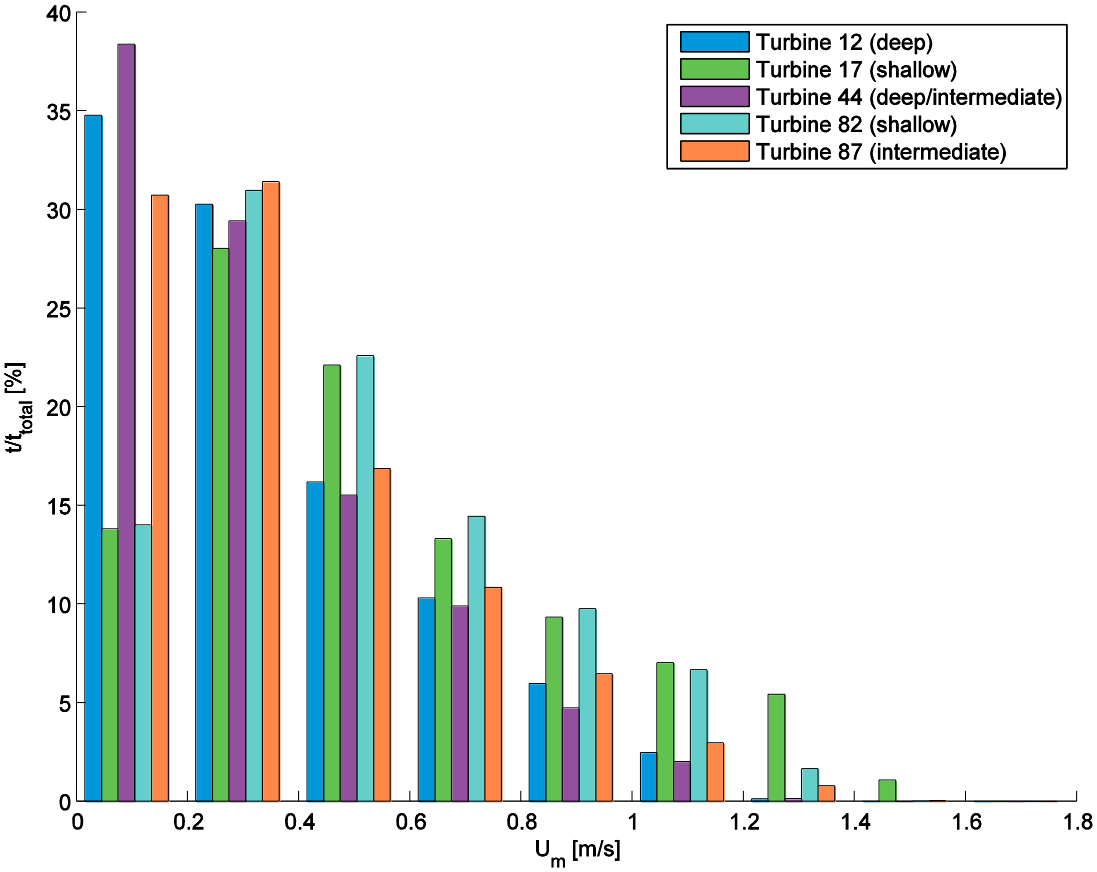

Figure 4. Distribution of the maximum orbital velocities 2 m above the bed at different positions in the period 1 March 2002 to 30 April 2005. The velocities are based on the significant wave height and the peak period and calculated using linear theory.

Figure 5 shows the current rose (going to) for the current in the period 1 March 2002 to 30 April 2005 at Turbine 44. The current is dominated by an approximately north-south tidal current and the current has almost never exceeded 0.6 to 0.7 m/s during the period.

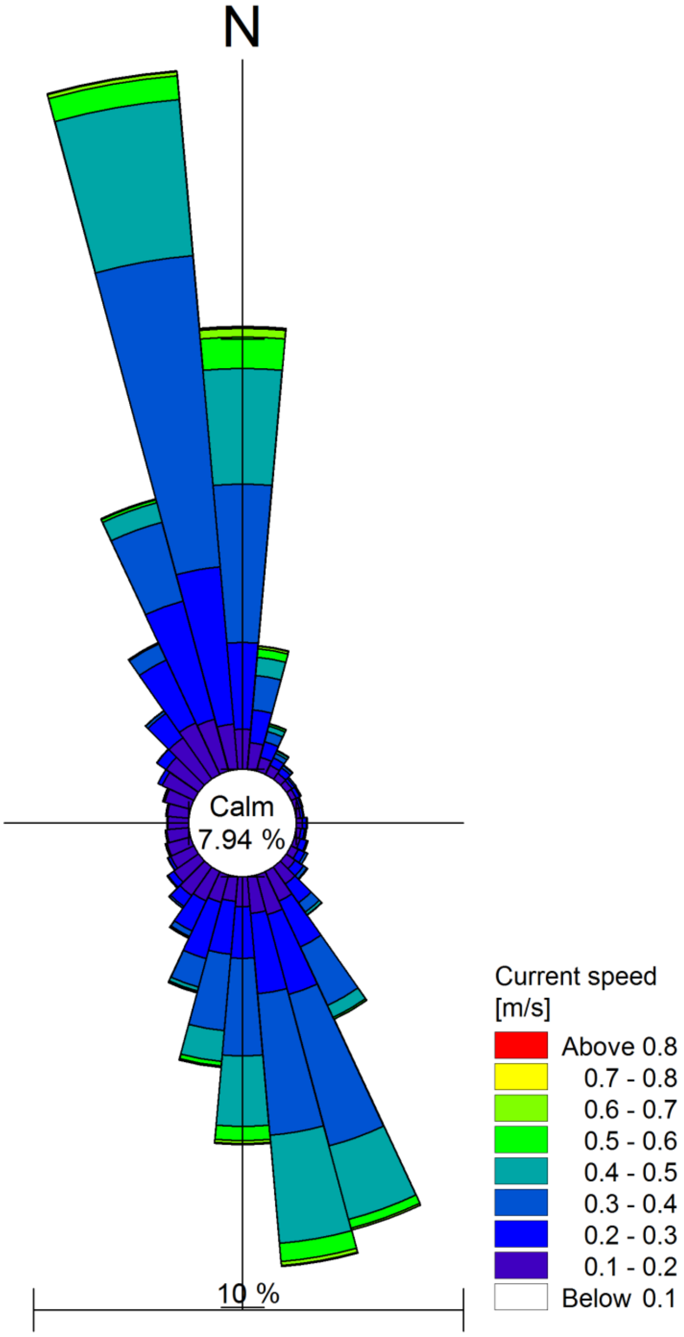

Figure 5. Current rose in the period 1 March 2002 to 30 April 2005 at Turbine 44.

THE SINKING OF THE SCOUR PROTECTIONS

The survey in 2005 showed a significant sinking of the scour protections adjacent to the piles relative to the latest 2002 survey, see Fig. 6. The sinking of the scour protections adjacent to the piles was as much as 1.5 m (Hansen et al., 2007), but there was no clear direct correlation between the damage on each individual scour protection. The main reason for this is that the installation of the scour protections caused a rather irregular, but still dense, placement, with varying height and shape, see example in Fig. 6. This made a direct comparison of the individual scour protections impossible and, in addition, the irregular surface of the scour protection made it impossible to determine a well-defined sinking of the scour protections. Furthermore, the reason for the sinking was not clear, but the attention quickly concentrated on the three options: 1) removal of cover stones, 2) winnowing of filter stones through the cover stones, and 3) removal of the base sediment through the entire scour protection. Hansen et al. (2007) showed that the two first options were unlikely, while the third option was possible, as simplified calculations showed that the base sediment underneath the scour protections might be mobile during storm conditions; however, the calculations were so simplified that they could only be taken as an indication. Furthermore, the method could not be used to determine whether waves, breaking waves, current, or combined waves and current were the main factor causing the sinking.

In order to determine the reason for the sinking and to give a more detailed description of the process an extensive test program of physical and numerical simulations was initiated (Nielsen et al, 2011, 2013 and 2014). During the program the effect of current, waves, and combined waves and current have been studied and the results are described in the following.

Effect of Current

The effect of current on the sinking of the scour protection was described in detail in Nielsen et al. (2011), Nielsen et al. (2013), and Sumer and Nielsen (2013). Nielsen et al. (2011) describes how the sediment is removed under the scour protection when it is exposed to a current; the horseshoe vortex penetrates into the scour protection, mobilizes the sediment underneath, and transports it out through the scour protection where it is carried away by the main flow; a process very similar to the development of scour around an unprotected pile in current. It should, however, be noted that for thick scour protections – more than approximately 0.8 times the pile diameter – the horseshoe vortex breaks down into two or more vortices. Nevertheless, scour protections of this kind of thickness have – for most cases – no practical application. In addition to the description of the mechanisms Nielsen et al. (2011) also presented equilibrium sinking of the scour protection and an estimate of the time scale needed for the sinking process. However, the sinking experiments were carried out using relatively large stones and high current speeds. The reason for this was that the sediment – hence the critical Shields number $\theta = U_f^2 / g(s-1)d)$ – was large (sediment size, *d*, 0.18 mm – similar to typical full-scale sand) in order to avoid problems with cohesion. This means that the experiments can be used to find the equilibrium sinking and to estimate the time scale, but the tests cannot be used to prove actual removal of sediment under typical full-scale conditions. In order to determine the critical conditions for mobilization of sediment underneath the scour protection Nielsen et al. (2013) conducted a large number of physical and numerical experiments. These experiments showed that the mobility of the sediment underneath the scour protection can be described in a similar way as the traditional Shields curve, but with the Shields number replaced by a mobility number:

$$\Omega = \frac{U^2}{g(s-1)d} \frac{1}{D_p} D_f \frac{n_f}{1-n_f} \qquad (1)$$

and the Reynolds number is defined as $Re = Ud/v$, where U is the undisturbed depth-averaged current velocity, g is the acceleration due to gravity, s is the relative density of the sediment, d is the mean size of the sediment, D_p is the pile diameter, D_f is the mean size of the filter stones, n_f is the porosity of the filter layer, and v is the kinematic viscosity of water.

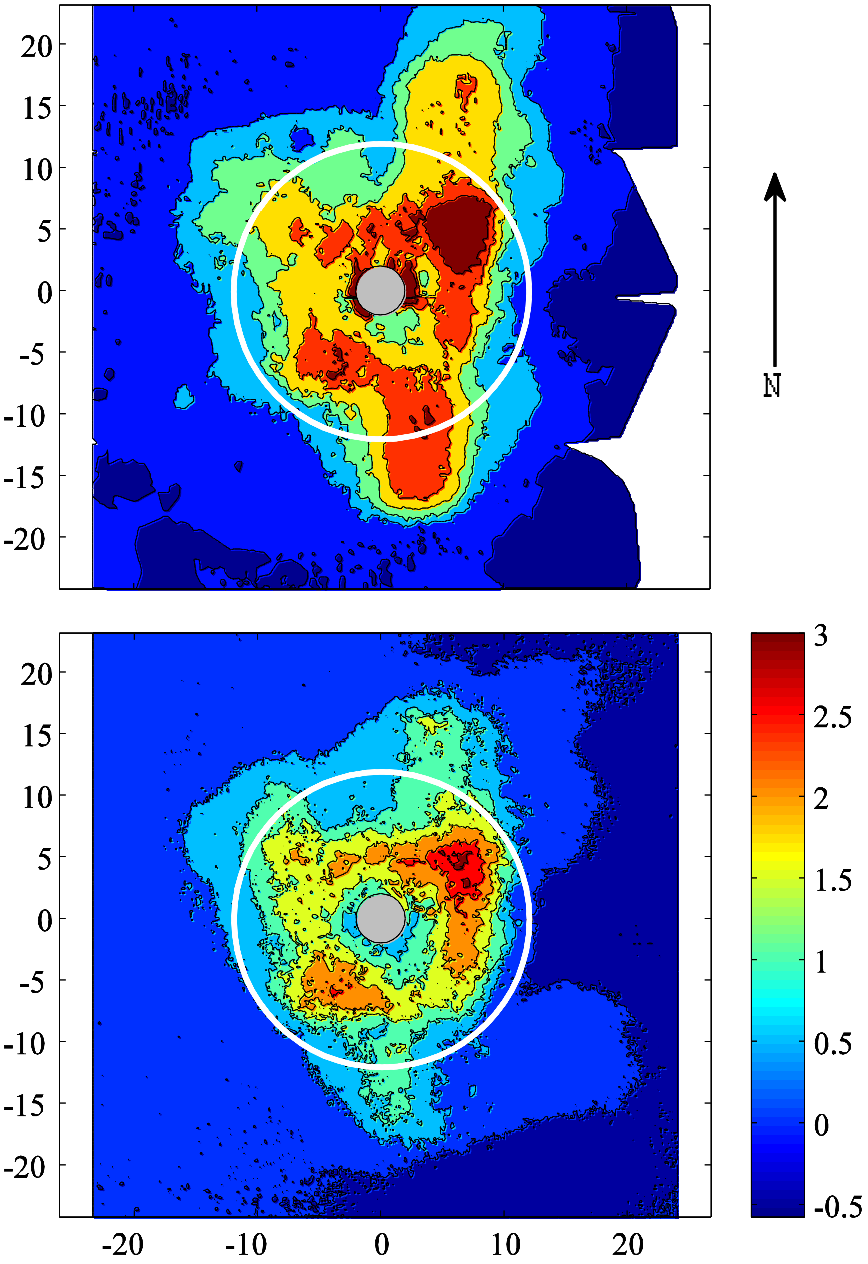

Figure 6. Results of the latest 2002 survey and the 2005 survey of Turbine 44. The upper panel is the 2002 survey and the lower panel is the 2005 survey. The white circles indicate the design limits of the scour protections (Nielsen 2011).

Effect of Waves and Combined Waves and Current

The effects of waves and combined waves and current on the sinking of scour protections were described in Nielsen et al. (2014). The study describes a combination of two processes causing the sinking in the case of waves: a destabilizing process causing suction of sediment through the scour protection adjacent to the pile, and a stabilizing process due to in-filling of sediment from the surrounding seabed into the scour protection. The study showed that the stabilizing process is the strongest for the relevant *KC*-number, but there was a significant time delay from the initial waves until the in-filled sediment reached the pile, and during this period of time sinking took place. The reason for this delay was that the amplitude of the wave motion was too short to carry sediment from the surrounding seabed to the pile during a single wave period. In order to carry sediment to the pile, in these cases, the pores of the scour protection must be filled by sediment, so that the top layer of sediment in the scour protection could be mobilized by the next wave and carried closer to the pile.

During this process removal of sediment, and consequently sinking of the scour protection, takes place adjacent to the pile. As the time-averaged flux of sediment from the surrounding seabed into the scour protection is constant (for a given wave climate and sediment) the time for the in-filled sediment to reach the pile will increase for a larger scour protection as the pore volume to be filled increases with the increased volume of the scour protection. This is also in correspondence with the observations reported in Nielsen et al. (2014) where a thicker scour protection tends to cause larger sinking than a thinner scour protection. This effect might be stronger if the increased scour protection volume is due to a larger width of the scour protection, rather than an increased height; the reason for this is that a wider scour protection will require a longer amplitude of the wave motion to carry sediment from the edge of the scour protection to the edge of the pile during a single wave period. As such long amplitude of the wave motion is usually not present a wider scour protection will leave longer time for the sinking to develop.

Opposite the current case there is no information available on the mobilization of sediment beneath the scour protection in the case of waves and combined waves and current. However, while relatively high velocities are required for the sinking tests in case of current, this is not the case for waves. Nielsen et al. (2014) showed that the removal of sediment adjacent to the pile took place when the wave crest was passing the pile and the removal of sediment was associated with the upward directed pressure gradient caused by the velocity difference between the fast moving water outside the scour protection and the slowly moving water inside the scour protection. This pressure gradient at Horns Rev 1 Offshore Wind Farm will be approximately the same as in the model scale (Froude model law), but the sediment is approximately of the same size in the model (0.18 mm) and at Horns Rev (0.1 to 1.0 mm). The stones in the model and full-scale scour protections are also directly comparable: around 1 to 4 cm in the model and approximately the same for the smallest fraction of stones in the filter layer applied at Horns Rev 1 Offshore Wind Farm, Hansen et al. (2007). This means that the mobility of the sediment will be approximately the same in the model and the wind farm and sinking can take place.

Effect of Breaking Waves

The effect of breaking waves on the sinking of scour protections has not been studied directly, but a study on scour induced by breaking waves (Nielsen et al., 2012) unveils processes, which can be used to estimate the effects of the breaking waves on a scour protection. The study showed that breaking waves could have an influence on the scour when wave breaking generated turbulence is diverted down to the bottom by the pile. However, the small pores in the scour protection generally provide a good protection of the seabed (as long as the scour protection itself remains intact) for externally generated turbulence, as most of the external turbulent kinetic energy is carried by turbulent vortices larger than the typical pore in the scour protection. Although it is measured in steady current, the effect can be seen in Nielsen et al. (2011), where the largest levels of turbulent kinetic energy are just at the top of the scour protections and decrease down in the scour protection. Given these facts, it is very unlikely that breaking waves have caused any significant extra movements of the sand underneath the scour protection compared to non-breaking waves. Nevertheless, turbulence induced by breaking waves may mobilize sediment in-filled in the pores of the scour protection; but, as the occurrence of breaking waves – even during storms – is at least an order of magnitude smaller than non-breaking waves, it is concluded that the effect of breaking waves can be ignored. Clearly, the in-filling of sediment by non-breaking waves will be more pronounced than the possible removal of sediment by breaking waves.

The Reason for the Sinking

The physical and numerical simulations described above give an indication of what causes the sinking of the scour protections at Horns Rev 1 Offshore Wind Farm, and in particular what was not the reason. The first effect to be investigated closely was steady current; physical model tests (Nielsen et al., 2011) showed that current is capable of removing sediment adjacent to a pile in a pattern similar to what was observed at Horns Rev and with similar sinking depths. However, although the current induced sinking gave the similar sinking pattern and depth as observed at Horns Rev, this could not explain the sinking; Nielsen et al. (2013) showed, using both physical and numerical models, that the flow in the scour protection was too weak to mobilize the sediment almost all the time during the period from the installation to the survey in 2005. Nielsen et al. (2013) reported that the required flow velocity to mobilize the sediment underneath the scour protection was around 0.7 to 0.8 m/s, but as seen in Fig. 4, this has practically not occurred during the period and secondly these velocities are the absolute lower limit for mobilization.

The other option is wave and combined waves and current. Fig. 7 shows the level of damage to the scour protections between 2002 and 2005 defined as 1-V_{2005}/V_{2002}, where V_{2005} and V_{2002} are the volume of the scour protection at the 2005 and 2002 surveys, respectively. The volume is defined as the volume above the level of the surrounding seabed; to reduce noise in the calculations parts of the scour protections with a height above the surrounding seabed of less than 0.5 m are excluded from the volume, see Fig. 8. The threshold of 0.5 m is found to be robust and similar volumes are found for thresholds of 0.25 m and 0.75 m.

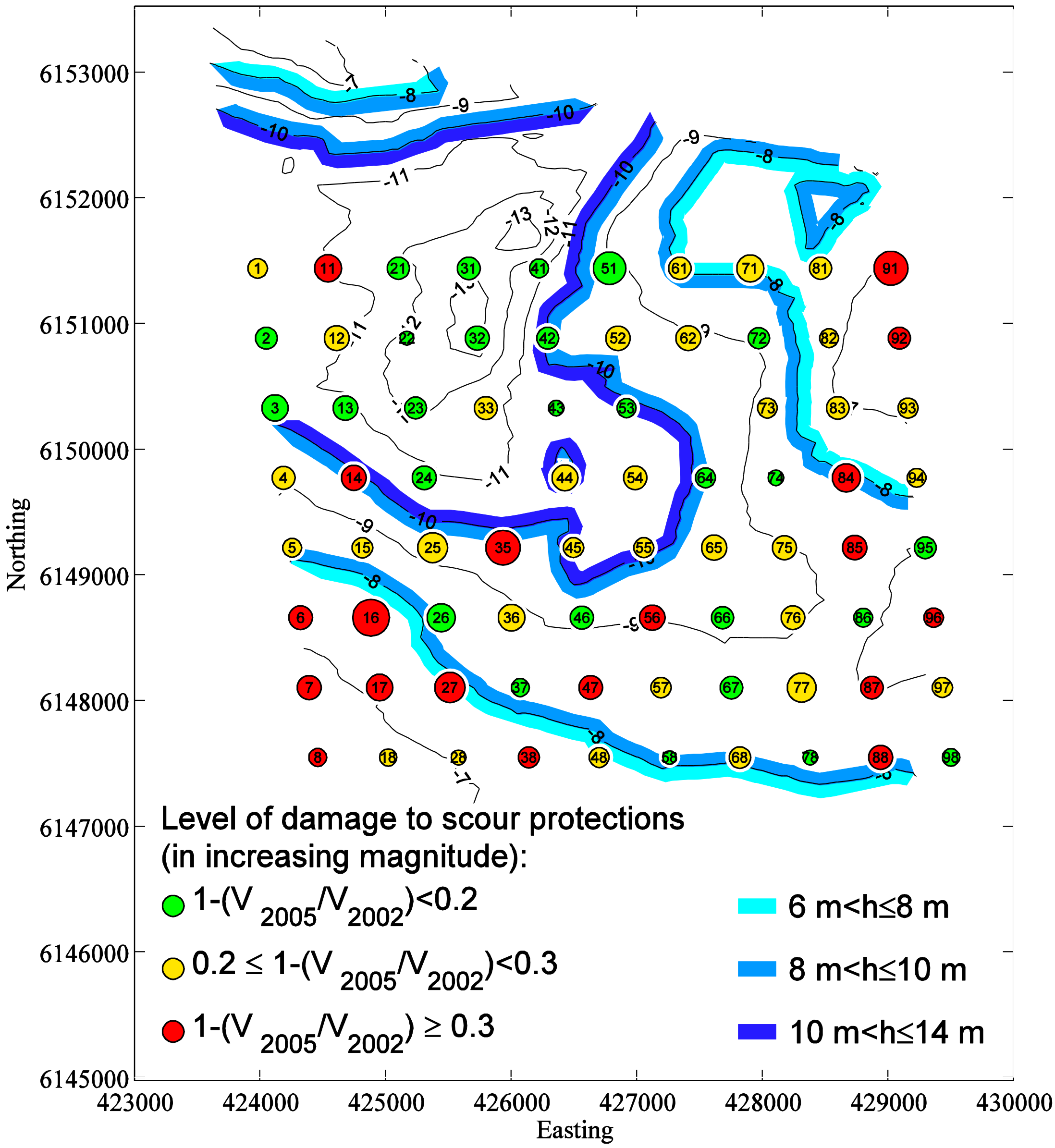

Figure 7. Level of damage to the scour protections. The size of the circles scales with the initial volume of the scour protection.

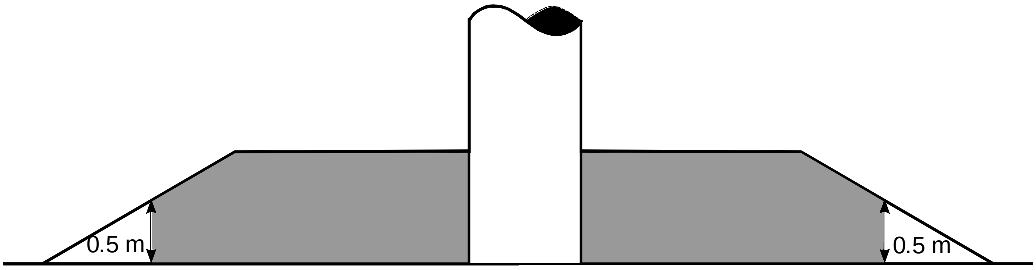

Figure 8 Definition sketch showing the part of the scour protection included in the calculation of the volume (the gray shaded area).

Figure 7 provides an indication that waves have played an important role; the map is divided into three regions: (1) shallow water (6 to 8 m water depth), (2) intermediate water depth (8 to 10 m water depth), and (3) deep water (10 to 14 m water depth). The damage to the scour protections in the deep north-western part of the farm is in general much smaller than the damages observed in the shallow south-western and north-eastern parts of the farm. The picture is less clear in the remaining part of the farm with intermediate water depths, where damages in the entire range are observed.

As seen in Fig. 4 the near-bed maximum orbital velocities were in general largest at the most shallow locations and were decreasing with increasing water depth. In other words, there is a clear trend that the scour protections exposed to the highest near-bed velocities also got the largest damages. The number of scour protections within the three damage levels and water depth regions is listed in Table 2 and it shows the same picture as Fig. 7. In the shallow water part of the farm 50% of the 20 scour protections had damage levels between 0.2 to 0.3 and another 50% had above 0.3. The damage decreased at intermediate water depth and around 40% of the scour protections observed little damage (less than 0.2), a similar number observed moderate damage (between 0.2 and 0.3), while around 20% observed larger damage. In the case of deep water the damage was even smaller: around 65% observed little damage (less than 0.2), around 30% observed moderate damage (between 0.2 and 0.3), and only a single scour protection observed larger damage.

Secondly, Fig. 7 shows a trend regarding the initial volume of scour protections: the larger the initial volume, the larger the damage, which corresponds to the observations in Nielsen et al. (2014) for sinking of scour protections around a monopile exposed to waves.

Based on this, it can be concluded that there is a correlation between the damage to the scour protections and the wave hydrodynamic around the scour protections, while strong current alone is too infrequent to explain the damage observed.

Nielsen et al. (2011, 2014) also presented design curves for the expected sinking in current, waves, and combined waves and current. Some of these experiments were conducted with a thickness similar to that applied on Horns Rev 1, but with a smaller horizontal extension (four pile diameters versus six pile diameters at Horns Rev 1 Offshore Wind Farm). However, the design curves can still be used as an indication of the expected equilibrium sinking and whether or not it was reached. Nielsen et al. (2014) shows that the sinking in waves alone will be around 1.3 to 2.4 times the size of the cover stones – corresponding to around 0.5 to 1.0 m sinking. This number will increase up to 1.3 m in the – unlikely – case of current alone. The sinking at Horns Rev 1 Offshore Wind Farm was between approximately 0.5 and 1.5 m, and in the few cases more, which is above the sinking reported by Nielsen et al. (2014) in case of wave-dominated conditions. However, as mentioned above the scour protections at Horns Rev 1 Offshore Wind Farm are relatively larger than those used by Nielsen et al. (2014) and this is likely to cause larger sinking, and possible up to 1.5 and 2.0 m, as described previously.

Table 2. Number of scour protections for different water depths and damage levels.

	6 m<h≤8 m	8 m<h≤10 m	10 m<h≤14 m
$1-(V_{2005}/V_{2002})<0.2$	0	15	12
$0.2\leq 1-(V_{2005}/V_{2002})<0.3$	10	16	6
$1-(V_{2005}/V_{2002})\geq 0.3$	10	8	1

CONCLUSION

The reason for the sinking of the scour protection adjacent to the monopiles at Horns Rev 1 Offshore Wind Farm has been examined based on previously published data. Previous investigations have concluded that the sinking was caused by removal of sediment from beneath the scour protection through the scour protection; there has been no reason to change this conclusion in the present study. On the other hand the previous studies have not been able to determine the exact cause for the sinking. Both current, waves, and combined waves and current are found to be able to cause sinking in the size experienced at Horns Rev 1 Offshore Wind Farm, but the current alone was found to be too weak leaving waves and combined waves and current to be the main factors.

Based on detailed descriptions of the sinking process found in the literature it has been possible to: 1) quantify the damage to the irregular scour protections in a systematic manner, and thereby show 2) that the relative damage was largest in shallow water regions and 3) that the largest scour protections experienced the largest relative damage – in an overall perspective. These three observations are also found to be characteristic for sinking caused by waves and it is therefore found likely that waves in combination with co-existing currents had a major influence on the sinking of the scour protections adjacent to the monopiles at Horns Rev 1 Offshore Wind Farm.

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