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Sinking of armour layer around a vertical cylinder exposed to waves and current

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ABSTRACT

The mechanisms of the sinking of a scour protection adjacent to a monopile are described in this paper, together with the determination of the equilibrium sinking depth in various wave and combined wave and current conditions based on physical model tests.

Sinking of the rocks may ultimately lead to failure of the scour protection. It may cause exposure and free-span of cables, and possibly change the natural frequency of the wind turbine in an unfavourable manner. For these reasons it is important to consider the possible effects of sinking in the scour protection design, and to understand the mechanisms that could lead to unacceptable sinking of the scour protection.

The study showed that the sinking is controlled by two mechanisms: removal of sediment adjacent to the pile (destabilizing) and infilling of sediment into the scour protection from the surrounding seabed (stabilizing). The latter mechanism is found to be the strongest, but it might take some time to fill the pores of the scour protection with sediment and during the time delay considerable sinking might take place. This means that the larger the scour protection, the larger the sinking will be (for a given KC-number smaller than approximately 15). The magnitude of the sinking of the scour protection adjacent to a monopile exposed to waves, and combined waves and current, was found to be similar to the current case.

1. Introduction

During the last two decades more and more wind farms have been erected 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 farms and the subsequent design considerations have 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 1 is located in shallow water (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 more than 0.8 m/s during storm situations) and large waves – significant wave heights of up to around 3.5 m – from the North Sea. The wind turbines are founded on monopiles with a scour protection designed to consist of two layers of armour rocks and a 0.5 m thick filter layer between the armour layer and the seabed (Hansen et al., 2007); the actually installed quantities were somewhat larger, see e.g. Fig. 1.3 in Nielsen (2011). The armour rocks were designed to weigh from 50 kg to 350 kg, corresponding to approximately 0.30 m to 0.55 m, while the filter material was designed to consist of marine stones from around 30 mm to 150 mm (Tech-wise, 2001). Note, Hansen et al. (2007) gave slightly different dimensions for the cover rocks and filter stones; these dimensions were based on an older and – to the knowledge of the authors – not applied design. The wind farm, including scour protection, was installed in the summer of 2002; a control survey in 2005 showed that the scour protection 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 depressions caused by the sinking were repaired by adding additional stones.

Whitehouse et al. (2011) compiled the experience of scour and scour protections from several offshore wind farms and other piled foundations installed in the North Sea area. Whitehouse et al. (2011) 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 Offshore Wind Farm 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 few decades. Most of the available

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laboratory results are summarised in Breusers and Raudkivi (1991), Hoffmanns 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 knowledge obtained via these studies 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 few decades; see e.g. Roulund et al. (2005), Liu and García (2008), and Baykal et al. (2015).

On the other hand, scour protection of piles has not been studied nearly as much, and some of the failure mechanisms of scour protection with regard to a monopile have only been briefly described. The stability of scour protection 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), Petersen et al. (under review) and Petersen et al. (2014)). As the previously mentioned studies focused on the stability of the rocks with regard to the outer flow, they could not readily be used to explain the sinking of the scour protection at Horns Rev 1 Offshore Wind Farm. In an attempt to explain the sinking, a major test programme has been conducted and the results are reported in Nielsen (2011), Nielsen et al. (2011, 2013), Sumer and Nielsen (2013), and Sumer (2014). The findings of the tests showed that the current could cause sinking of the magnitude experienced on Horns Rev 1 Offshore Wind Farm. However, the frequency of such strong currents was too low to fully explain the observed sinking of the scour protection. Nielsen (2011) also presented results of sinking of the scour protection adjacent to monopiles in the case of waves; these results were in all, but one, cases based on just a single layer of stones (two layers in a single case) and in all cases without filter layer. These results were, in other words, based on a thin scour protection (relative to the pile diameter) and with a relatively small volume. The results showed very little sinking and consequently the actual reason for the sinking of the scour protection at Horns Rev remained unclear.

Although the physical model tests with waves, reported in Nielsen (2011), showed little sinking a more extensive test programme with waves was launched — providing most of the results in the present paper. The major change, compared to Nielsen (2011), is that the thickness of the scour protection was increased to two to four layers of stones. Although the increased thickness, and consequently increased volumes of rock, could be expected to provide a better protection for the sediment underneath the rock armour, the results showed the opposite: a thicker armour layer led to a larger sinking of the scour protection adjacent to the monopiles. The reason for this observed effect was found to be opposite acting mechanisms that control the sinking of the armour in waves: removal of sediment adjacent to the pile and infilling of sediment from the surrounding seabed into the pores of the scour protection, as will be detailed later.

In addition to the wave tests, a series of tests with combined waves and current has been conducted in the present study. These tests showed a complex relation between the equilibrium sinking depth, scour protection thickness and the ratio between waves and current. However, it should be mentioned that the sinking never exceeds the maximum sinking in waves or current alone for any of the tests, as will be detailed later.

2. Experimental set-up

Two experimental campaigns were undertaken in the study: the first campaign was conducted as part of Anders Wedel Nielsen's PhD work (Nielsen, 2011) which was followed by the second campaign where an extensive series of tests were conducted. The experiments conducted by Nielsen (2011) were made using similar test conditions, but some were made in a narrower flume (0.6 m wide) and the thickness of the sand section was different; details on the set-ups used in the first campaign can be found in Nielsen (2011, pp. 121–130) and will not be repeated in the present paper. The following description of the experimental set-up applies for the second measuring campaign.

The experiments were conducted in DTU's hydraulic laboratory in a 4 m wide, 34 m long and 1.0 m deep flume, see Fig. 1. The flume was equipped with a piston type wavemaker and recirculation pumps for generating current. The wavemaker was controlled by a DHI Wave Synthesizer with AWACS version 2.15 (Active Wave Absorption Control System). The recirculation pumps provided a mean current speed of up to 75 cm/s for the actual set-up, co-directional with the waves.

An approximately 13 m long sand section was installed over the entire width of the flume. The sand section was 15 cm deep and slopes were installed at both the offshore and onshore ends of the sand section (off- and onshore are used for the relative direction of a structure to the waves; analogous to up- and downstream in the case of current). The slopes had an inclination of 1:15 and were made of crushed stones with a mean size of approximately 2.1 cm. The offshore end of the sand section was located approximately 10 m from the wavemaker.

Two piles were tested at the same time. This was done in order to save time, and to be able to compare different set-ups under the same wave and current conditions. The centre-lines of the piles were located at the same distance (approximately 16 m) from the inlet, 2 m apart, and 1 m from the side walls as shown in Fig. 1. These distances were large enough to ensure no interference between the individual piles as well as eliminating any side wall effects, considering the selected pile

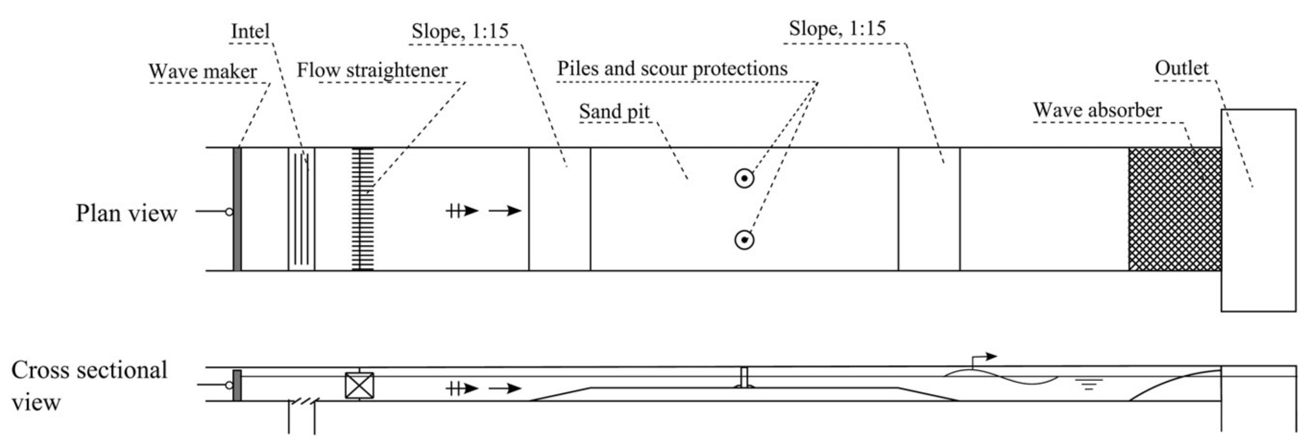

Fig. 1. Experimental set-up of the flume. Not to scale.