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# Edge scour at scour protections around piles in the marine environment — Laboratory and field investigation

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When building offshore wind turbines with monopile foundations, scour protection typically is placed to avoid scouring of the soil close to the monopile. An important aspect is that the scour protection itself causes erosion, inflicted by the local increase in current and/or wave velocities and in turn increased bed shear stresses. Scour of the edge material alongside the scour protection may cause deformations and failure of the scour protection of offshore wind turbine foundations. This can reduce the stability of the stone layer and cause exposure of cables running between the monopiles where they go from buried to the transition piece on the foundation. Although much information is available on the design of scour protection systems around monopiles, little is known on the mechanisms causing edge scour and the equilibrium stages of the edge scour process in steady current, waves and combined waves and current.

This paper presents an extensive experimental campaign to explain the edge scour process in current and combined irregular waves and current, as well as tidal current. The three-dimensional flow field around the pile and scour protection is resolved by particle image velocimetry and bed shear stress measurements, showing a local increase in the flow velocities and bed shear stresses leading to increased sediment transport and scour. The governing process in steady current is a pair of symmetrical counter-rotating vortices emerging in the near bed region in the wake of the pile and scour protection, causing a significant downstream scour hole. It is found that the equilibrium scour hole depth and length scales with the pile diameter and the ratio between the thickness- and the width of the scour protection.

In the second part of the present paper, the results from the experimental campaign are compared with the edge scour experienced in practice, outlined by a survey program of the offshore wind park Egmond Aan Zee and a published field investigation of Scroby Sands OWF by Whitehouse et al. (2011).



## 1. Introduction

Over the last two decades the offshore wind industry has grown, with more and more offshore wind farms erected. The first larger offshore wind farm (OWF) in the North Sea off the Dutch coast is the offshore windpark Egmond aan Zee (OWEZ), located in shallow waters (16–21 m water (MSL)) 10–18 km off the coast at the city of Egmond Aan Zee. This location is exposed to strong tidal currents (up to 1.3 m/s) and large waves from the North Sea. The wind turbines are founded on mono-piles with a typical scour protection system with rock dump around the base of the mono-pile. The wind park was installed through May to October 2006, and a survey program running from 2006–2013 showed considerable edge scour developing outside the cover stone area of up to 2.7 m (Louwersheimer et al., 2009; Raaijmakers et al., 2007, 2010). The edge scour development over the survey campaign shall be displayed and discussed in the second part of this paper. The edge scour was in fact taken into account in the design, which included physical model tests, and sufficient filter material was installed at the edges of the scour protection. This filter material acts as a falling apron, meaning that the stones in the filter layer are allowed to slump into the edge scour hole as it develops, thereby protecting the slope and bottom of the edge scour hole, and in turn preventing the edge scour hole from causing damage to the armor layer.

Whitehouse et al. (2011) compiled data in relation to and discussed the development of edge scour (termed secondary scour) around scour protections at offshore wind turbine foundations at several locations, such as Scroby Sands OWF, Arklow Bank OWF and Horns Rev 1 OWF. The latter study reports edge scour predominantly in the range of 0.2–

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$1.2D_p$ (with $D_p$ = pile diameter), noticeably in the same range as for scour around an unprotected mono-pile (see Figs. 12 and 17 in Whitehouse et al., 2011).

Scour around unprotected monopiles have received a vast amount of attention over the last decades, with a detailed account on the topic given in the books of Breusers and Raudkivi (1991), Hoffmanns and Verheij (1997), Whitehouse (1998), Melville and Coleman (2000) and Sumer and Fredsøe (2002); and more recently in numerical studies by Roulund et al. (2005), Liu and Garcia (2008), Zhao et al. (2010) and Khosronejad et al. (2012), Baykal et al. (2015) and experimental studies on scour and backfilling of scour holes around piles by Sumer et al. (2013). The information rendered in the latter works has also made it possible for establishing long-term numerical models to estimate the time development of the scour depth around mono-piles with the changing sea climate (Harris et al., 2010; Nielsen and Hansen, 2007; Raaijmakers and Rudolph, 2008a,b). More recently, such models were applied over larger areas to study at which locations allowing free scour development (i.e. leaving out the scour protection and adjusting the monopile design) would be more cost-efficient compared to installing scour protections (e.g. Raaijmakers et al., 2013).

Investigations have also been presented on flow and scour mechanisms with the scour protection installed at the base of the monopile by Chiew (1995), Chiew and Lim (2000), Lauchlan and Melville (2001), Vos et al. (2011, 2012), Nielsen et al. (2011, 2013) and Sumer and Nielsen (2013). Some results have also been collected with respect to scour alongside riprap berms in steady current by Fredsøe et al. (2001) and Petersen et al. (2012a, 2015), and these studies show that the scour of the adjacent sea is caused by the combined effect of primary and secondary flow. Sediment is stirred up by the turbulence generated by the primary flow and is brought up into the main body of the flow, and the secondary flow carries the sediment away from the junction between the bed and the stones, resulting in the edge scour. In waves Sumer et al. (2005) showed that scour at the edge of submerged berms is caused by steady streaming. However, to the authors' knowledge no study is yet available investigating, in a systematic manner, the edge scour developing around scour protections at monopiles in current and combined waves and current. The development of edge scour is important for the structural stability of the stone cover, as well as to counteract free-span of cable ties where they go from buried to the transition piece (Hansen and Gislason, 2005; Whitehouse et al., 2011).

The present study aims to understand the mechanisms that cause the edge scour at the perimeter of the scour protection and the subsequent failure of the stone layer in accordance with the definition sketch (schematic) in Figs. 1 and 2. To this end, an extensive program of physical model scour tests with steady current, combined irregular waves and current; and simulated tidal current has been carried out, supported by three-component flow measurements via particle image velocimetry (PIV) and measurements of the bed shear stress. This study shows that in steady current edge scour happens in the near-field domain of the scour protection and in the farther downstream area, caused by the following two mechanisms, respectively: (1) the horseshoe-vortex generated in front of the scour protection and the deviation and acceleration of flow at the transverse sides of the scour protection scours the neighboring sea bed; (2) a pair of symmetrical counter-rotating vortices generated downstream of the monopile and scour protection, suspends the sediment and scours the wake area downstream.

To enhance the understanding of the flow and improve the design criteria, this study investigates the flow field, velocity distributions, coherent turbulent flow structures and the bed shear stress around scour protections at circular monopiles in steady current, combined waves and current and simulated tidal current, using physical model tests. To further support the findings in the experimental campaign, a field investigation of edge scour development is made for two offshore wind farms where scour protection is installed. It is found that the observed edge scour development and the measured equilibrium edge scour depth in the physical model tests agrees well with the edge scour experienced in the field at OWF Egmond aan Zee and Scroby Sands OWF.

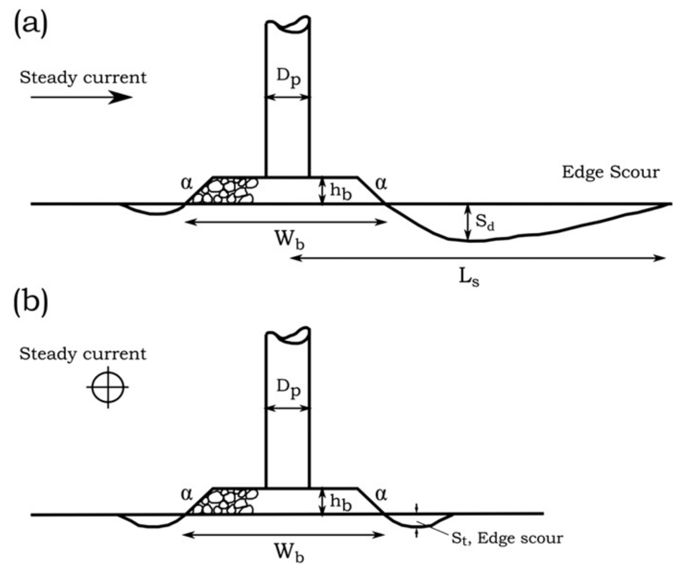


**Fig. 1.** Definition sketch (schematic) for the setups with scour protection installed on the sea bed. (a) scour hole generated by current downstream of scour protection; (b) scour generated by current at the transverse section of the scour protection. Note that the setup for the scour test in combined waves and current are identical, and the current and waves are collinear.

## 2. Experimental setup

Three kinds of experiments were carried out: (1) Scour experiments where the scour process adjacent to the berm was monitored in the live-bed regime in steady current, combined waves and current and tidal current conditions. All the measurements were for the most part conducted with a monopile and a scour protection system with several layers of cover stones; (2) Velocity measurements by Particle Image Velocimetry (PIV) mapping the flow field from the pile section until $7D_p$ in the downstream direction, in steady current conditions; and

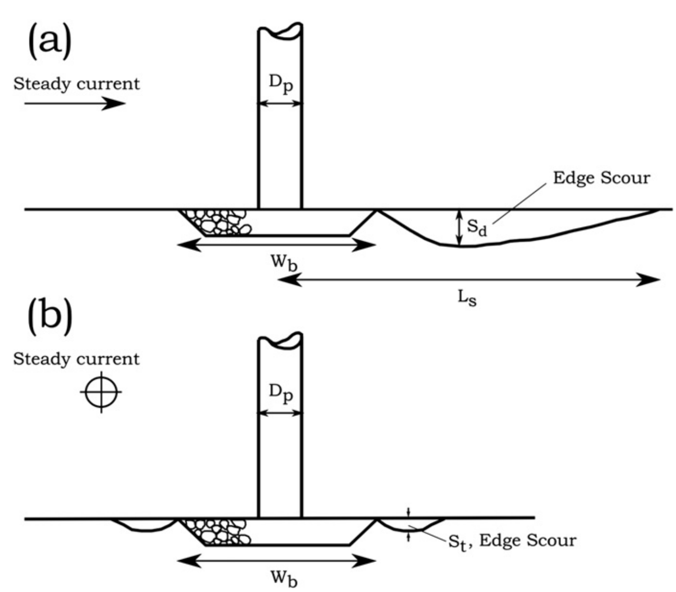


**Fig. 2.** Definition sketch (schematic) for the setups with scour protection installed flush with the sea bed. (a) scour hole generated by current downstream of scour protection; (b) scour generated by current at the transverse section of the scour protection. Note that the setup for the scour test in combined waves and current are identical, and the current and waves are collinear.