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Processes and evolution of scour around a monopile induced by tidal currents

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ABSTRACT

Despite offshore wind farms being mostly situated in tidally dominated waters, only limited research on the effects of tidal flow on the scour process around offshore foundation structures has been carried out so far. To further improve the prediction of scour around those structures, systematic laboratory tests were conducted in a closed-circuit flume on the processes and time development of scour around a monopile in tidal flow. The tidal currents were adapted by bidirectionally reversing currents with continuously changing flow velocity. Therewith, multidirectional flow aspects were simplified into flow components in tidal main direction. Tidal cycles and flow intensities were scaled with regard to field measurements at the FINO 1 platform in the North Sea. The model tests were conducted at a length scale of 1:40 and scour depths were measured at multiple positions around the monopile by a camera system. Novel insights on the intrinsic progression of sediment displacement and time scale of the scour process were gained and in the following presented as a function of flow intensity for clear-water and live-bed conditions. In addition, baseline tests with unidirectional currents were conducted, in which the constant flow velocity was either based on the maximum peak or the root mean square velocity of the tidal currents. Significantly slower scour progression and smaller scour depths in tidal currents were found, compared to unidirectional currents based on the maximum peak velocity. In contrast, scour depths in tidal currents exceed those for unidirectional currents by up to 51%, if the unidirectional currents are based on the root mean square value. The comparison further implies that a flow velocity of around 15–20% larger than the root mean square flow velocity of the tide is needed to accurately estimate tidal current induced scour depth by unidirectional current. Thereby, the results underline the importance of selecting suitable conditions for the design process of offshore structures. For design purposes, the evolution of tidally induced scour could be well predicted with a time discretised stepping approach.

1. Introduction and motivation

In view of the progressing expansion of offshore wind energy, the reliable scour prediction for marine environments becomes more and more important for an economically-optimized and durable design of foundation structures and their scour protection (Schendel et al., 2016a). The significance of scour for the design is reflected by the amount of publications, dealing with the emergence and characteristics of local scour in various hydraulic conditions. Numerous studies have been carried out on the scour development at piles under unidirectional, steady currents (e.g. Breusers et al., 1977; Raudkivi and Ettema, 1983; Sheppard et al., 2004) or under time varying unidirectional velocity (e.g. Chang et al., 2004; Chreties et al., 2013; Hager and Unger, 2010; Link et al., 2017), most of them addressing the scour development at bridge piers. Scour development induced by waves (e.g. Carreiras et al., 2000; Stahlmann, 2013) and in combined wave-current conditions (e.g. Eadie and Herbich, 1986; Sumer and Fredsøe, 2001) for structures in the marine environment has also been investigated. Approaches for the prediction of time development of scour around piers for different current conditions and sediment properties were elaborated by Sumer et al. (1992a) and Melville and Chiew (1999). A comprehensive compilation on the determination of the equilibrium scour depth under unidirectional current is furthermore given in Breusers et al. (1977) and Melville and Coleman (2000).

However, investigations into scour development due to tidal currents with time varying average flow velocities are limited to this date, although tidal currents depict a key factor for scour development in

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marine conditions. Escarameia and May (1999) carried out a laboratory study on the scour development around different foundation structures for tidal conditions. They investigated the effects of water depth, shape of structure and flow direction as well as the duration of a tidal cycle on the equilibrium scour depth. The tidal flow was modelled with tidal half cycles of different duration and reversing flow direction. For a square-shaped structure the depth-averaged flow velocity during each tidal cycle were either assumed constant or varying in sinusoid form. The tests with varying flow velocities were conducted, that either the duration or the peak velocity of a tidal half cycle would match those of tests performed with constant flow velocity, assuring an equivalent volume of tidal discharge. The results indicated that the equilibrium scour depth for tidal currents increases with live-bed conditions, in contrast to the scour depth under unidirectional flow conditions. However, for a cylindrical structure tidal currents were only modelled based on the first method, while live-bed conditions were not tested. The equilibrium scour depth for the tidal tests was typically reached after 4 to 5 tidal half cycles.

In comprehensive laboratory tests, Jensen et al. (2006) compared the scour development at piles under unidirectional and tidal currents. The tests were performed in a recirculation flume and focused on the influence of water depth and pile diameter, while flow intensities were kept to live-bed conditions. Assuming simplified flow conditions, tidal currents were simulated by reversing the constant flow velocity of unidirectional reference tests every 30 min. Most tests lasted two hours, i.e. four tidal half cycles, although some long duration tests were carried out as well. Overall, slightly larger scour depths and eroded sediment volumes were found for reversing as compared to unidirectional currents. A more detailed analysis of selected test cases is given in Margheritini et al., (2006), including a comparison of erosion volumes and scour hole shapes, which tend to be asymmetrical for unidirectional currents and symmetrical in reversing currents.

McGovern et al. (2014) investigated the scour development for tidal currents by resolving a tidal signal, based on field data, into three time steps with constant flow velocity in clear-water, transitional and live-bed conditions. The scour depth was measured at three positions in each stream-wise and lateral flow direction around the pile; they reported a shallower and slower developing scour hole under tidal currents, compared to unidirectional tests with live-bed conditions. Furthermore, the final scour depth at the end of the tidal test was found to be smaller than the final scour depth in the unidirectional test. The unidirectional baseline test was performed under live-bed conditions involving a constant flow velocity comparable to the maximum velocity of the generated tidal current (i.e. the live-bed time step). Scour depths larger than those in tidal currents can thus be expected, as the flow intensity is significantly larger for most of the tidal half cycle. Furthermore, a comparison to the actual underlying field data might reveal additional insights as the flow velocity of the unidirectional current test represents a mean value of the flow velocities of the field data, instead of their peak value. However, the comparison with the scour development under unidirectional current might be subject to temporal uncertainties, due to the short test duration of only four tidal half cycles.

Porter et al. (2014) performed laboratory tests on the scour development through a complete spring-neap tidal cycle. The tests were conducted under clear-water conditions and the simulated tidal signal was based on field measurements. The tidal signal was discretised into 8-minutes-long velocity steps, resulting in 7–8 steps per tidal half cycle. They found the time scale for the scour development under tidal current to be much slower than under unidirectional current. This observation was based on the fact that even after the full spring-neap tidal cycle, no equilibrium scour depth was reached and scouring remained active. Since a tidal signal over a spring-neap cycle with varying peak velocities was investigated, Porter et al. (2014) used the root mean square (RMS) value of all tidal peak velocities as basis for a unidirectional reference test. Furthermore, Porter et al. (2014) highlighted the latent effect of the asymmetry between flood and ebb tidal cycles on the scour process which has previously not been addressed.

Most recently, Yao et al. (2016) conducted an experimental study on the scouring process in tidal currents, by using a sinusoidal tidal current and a reversing current. The reversing current test was performed after an equilibrium scour depth was initially generated by a unidirectional current. The sinusoidal tidal test started from a flat sediment bed using a tidal period of about 35 min. Both tests were run in live-bed conditions while the scour depth was continuously measured at both stream-wise sides of the pile. In contrast to a unidirectional reference test, they observed a periodic fluctuation in scour depth between the stream-wise sides in tidal currents. The scour depth was found to develop slower under sinusoidal tidal flow than in unidirectional current. The flow velocity of the unidirectional test was equal to the peak velocity of the sinusoidal tidal tests.

Although all of these studies mentioned above indicate significant differences in the scour development between unidirectional and reversing currents, the results are comparable only to a limited extent. This is due to the fact that the tests rely on different methods to simplify tidal currents with time varying flow velocities. The influence of tidal currents on scouring, especially on the progression over time as revealed in the studies by McGovern et al. (2014), Porter et al. (2014) and Yao et al. (2016), is rarely addressed in scour prediction approaches or formulae to date. A suitable approximation of the temporal scour progression might be obtained by time-discretised prediction models. To account for time-varying flow conditions, Harris et al. (2010) proposed the scour time evolution predictor (STEP) model based on former studies by Whitehouse (1998). The STEP model involves the calculation of an increment scour depth for defined time steps. During the time steps, quasi-steady current conditions are assumed, which also requires the determination of a varying equilibrium scour depth. The equilibrium scour depth for current conditions is based on the approach from Breusers et al. (1977), for wave and wave-current conditions the approaches of Sumer and Fredsøe (2002) are implemented.

Raaijmakers and Rudolph (2008) developed a scour prediction model, based on existing formulae and laboratory experiments on the scour progression under combined time-varying current and wave conditions. By incorporating the relative sediment mobility (θ/θ_c), new expressions for the characteristic time scale of either current or wave dominated scour were defined. As in Harris et al. (2010), the scour development is described by means of an exponential function, which was found to predict the scouring for waves-only conditions and low Keulegan-Carpenter numbers (KC) suitably.

While these time step models were validated against laboratory or field data, they are still based on approaches for unidirectional current, which means they neglect the characteristics of complex reversing flow conditions. The laboratory studies by McGovern et al. (2014), Porter et al. (2014) and Yao et al. (2016) indicate that the reversing flow conditions will lead to a periodically changing fluid-sediment-structure interaction. Bed forms and sediment depositions at the respectively downstream side of the structure will affect the flow field and the scouring process in the following tidal half cycle. Since the scour hole progresses in a non-linear way, the described influences would increase the non-linear behaviour, thus leading to time scales which significantly differ from those under unidirectional current. Therefore, while the time step models of Harris et al. (2010) and Raaijmakers and Rudolph (2008) performed reasonably well for the given data sets, their applicability for higher order non-linear scour processes has to be tested.

This literature review reveals that quite a number of unresolved questions remain regarding the progression of scour induced by tidal currents, hence leaving planners and designers of marine structures partially unprepared as to how scour around piles might evolve in coastal and offshore waters. As a consequence, scour protection is either planned more conservatively or unnecessary monitoring activities might take place. Apart from assessing the influence of the reversing current on the scour susceptibility and lateral extent in clear-water and live-bed conditions, the fundamental physical processes of sediment displacement and dependency on varying flow velocities during each tidal cycle remain