Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)

Ottawa, Canada, May 10-13, 2016

EXPERIMENTAL STUDY ON THE PROGRESSION OF SCOUR AROUND A MONOPILE IN UNIDIRECTIONAL AND TIDAL CURRENTS

ALEXANDER SCHENDEL[1], ARNDT HILDEBRANDT[1], TORSTEN SCHLURMANN[1]

1 Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Hannover, Germany.

Corresponding author: schendel@fi.uni-hannover.de

ABSTRACT

Hydraulic model tests were carried out in a closed-circuit flume in order to investigate the progression of scour at a monopile under tidal currents in clear-water conditions. The tidal currents were based on field measurements and were simulated by a quasi-continuous approach. In addition, as a result of scour measurements at multiple positions around the pile and a high temporal resolution novel insights on the intrinsic progression of sediment displacement and time scale of the scour process around a monopile under tidal currents are presented. Based on infilling and sediment displacement, the time development of the maximum scour depth under tidal flow is unsteady and characterized by periods of stagnating and decreasing scour depth. This leads to a significant slower progression of the scour depth compared to unidirectional currents with a flow velocity based on the maximum peak velocity of the tidal signal. Furthermore, large variations of scour depth at the upstream and downstream side of the pile result in altering positions of maximum scour depth over time.

KEWORDS: scour, tidal currents, laboratory tests.

1 INTRODUCTION

In view of the progressing expansion of offshore wind energy as one viable method of renewable energy resources, the accurate scour prediction for marine environments becomes more and more important for an economically optimized and durable design of foundation structures and scour protection (Schendel et al. 2014). Numerous studies have been carried out on the scour development at piles under unidirectional and steady currents, although most of them regarding the scour development at bridge piers. Raudkivi and Ettema (1983), who investigated the scour development at bridge piers under clear-water conditions, described the influence of water depth, pile diameter and sediment gradation on the scour depth. Detailed measurements and analysis of the flow field around a pile, in particular of the development of the horseshoe vortex during the scour process, can be found in Dey and Raikar (2007). The distribution and amplification of shear stresses around a pile were investigated by Hjorth (1975). Approaches for the prediction of time development of scour around piers for different current conditions and sediment properties were defined by Sumer et al. (1992) and Melville and Chiew (1999). While Sumer et al. (1992) specified the time scale for scour under live-bed conditions, Melville and Chiew (1999) depicted the scour progression as a function of the flow intensity U/U_c. Both approaches refer to the equilibrium scour depth. A comprehensive compilation on the determination of the equilibrium scour depth under unidirectional current is given in Breusers et al. (1977) and Melville and Coleman (2000).

Due to the complex and unsteady flow conditions under tidal currents around piles, a comparison to the scour development under unidirectional current remains challenging, and which is hardly regarded in scour prediction approaches or formulae so far. In order to account for varying flow conditions Harris et al. (2010) proposed the scour time evolution predictor (Step) model based on Whitehouse (1998). The Step-model involves the calculation of an increment scour depth for (pre)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 aforementioned approach from Breusers et al. (1977) and for wave and wave-current conditions the approaches of Sumer and Fredsøe (2002) are implemented. While the Step-model was validated against laboratory and field data, it is still based on approaches for unidirectional current and therefore neglects the characteristics of complex tidal flow conditions.

Investigations on the scour development due to unsteady tidal currents are to this date limited, although tidal currents decisively depict a determining factor in marine conditions. Recent studies have provided first interesting results for either live-bed conditions or clear-water conditions. Escarameria and May (1999) carried out a laboratory study on the scour development around different foundation structures under tidal conditions. In this study 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 were investigated. The tidal flow was simulated with tidal half cycles of different duration and reversing flow direction. The flow velocities during each tidal cycle were either assumed constant or varying sinusoidally. For a square-shaped structure they observed that the equilibrium scour depth in the tidal tests was lower than the equilibrium depth for equivalent unidirectional conditions. The equilibrium scour depth in the tidal test was reached after 4 to 5 tidal half cycles. Furthermore, the equilibrium scour depth increased with increasing duration of the tidal cycle. In addition, the results indicated that the equilibrium scour depth under tidal current increases under live-bed conditions, in contrast to the scour depth under unidirectional flow. Based on the results a design method was developed that predicts the scour development under tidal flow by adjusting the scour development for equivalent unidirectional currents. Unfortunately, only one tidal test series with a circular cylinder in reversing currents and with constant flow velocity was carried out.

McGovern et al. (2014) investigated the scour development under tidal currents by resolving the tidal signal into three time steps with constant flow velocity in clear-water, transitional and live-bed conditions. The scour depth was measured at 3 positions in each streamwise and lateral flow direction around the pile. They reported a shallower and slower developing scour hole under tidal currents compared to unidirectional tests for live-bed conditions. Furthermore, the final scour depth at the end of the tidal test was found to be lower than that in the unidirectional test. However, the comparison with the scour development under unidirectional current might be subject to uncertainties because of the short test duration of only four tidal half cycles. In addition, the unidirectional control test was performed under live-bed condition involving a flow velocity comparable to the maximum velocity during the tidal test.

Porter et al. (2014) performed laboratory tests on the scour development through a complete spring-neap tidal cycle. The tests were run under clear-water conditions and the simulated tidal signal was based on field measurements. The tidal signal was discretized in 8 minute 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, covered by the fact that even after the full spring-neap tidal cycle no equilibrium scour depth was reached. Furthermore, Porter et al. (2014) highlighted the latent effect of the asymmetry between flood and ebb tidal cycles on the scour process. However, scour measurements were only taken on the upstream side of the pile, which limits the insight on temporal progression of scouring around the whole pile and may lead to a misleading deduction of the maximum scour depth as will be shown later in the present paper.

The literature review reveals that there are still unresolved questions regarding the progression of scour under tidal currents. Apart from assessing the influence of the reversing current or the differences in the scour susceptibility and lateral extent between clear-water and live-bed conditions, the fundamental physical processes of sediment displacement and dependency on varying flow velocities during each tidal cycle still have to be examined systematically. For that reason, hydraulic model tests were conducted in a unique laboratory facility in the Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz Universität Hannover, Germany.

The objectives of this study were to investigate the influence of tidal currents on the progression of scour and advance insight on scour prediction in marine conditions by means of assessing the influence of sediment displacement and time-varying flow velocities on the maximum scour depth and time development in contrast to unidirectional currents. Thus, the test program incorporated unidirectional and tidal currents in clear-water as well as live-bed conditions. This paper focuses on the results under clear-water conditions and the comparison to corresponding unidirectional flows. In order to consider the asymmetry of a tidal current, the tidal signals were based on field measurements and simulated under laboratory conditions with a quasi-continuous approach. In addition, the scour depth was measured at eight positions around the pile allowing a quantitative assessment of sediment displacements and infilling processes on the circumference of the pile while being exposed to a tidal current.

2 EXPERIMENTAL SETUP

The hydraulic model tests were carried out in a closed-circuit flume. Detailed information and technical drawings of this unique flume can be found in Goseberg et al. (2013) who developed a novel laboratory method to generate tsunami-like long waves while Schendel et al. (2015) conducted experiments to gain insight on the stability of a wide-graded quarry-stone mixture in this facility. The flume is driven by four pipe pumps with a maximum flow capacity of 0.5 m³/s. The pump design enables a continuous adjustment of flow velocity in both flow directions. However, a calibration of the electrical pump controller was conducted as the performance per flow direction is slightly different.

The flume provides a sediment pit with a length of 2.7 m, a depth of 0.6 m and a width of 1 m, which also represents the flume width. The total dimensions of the flume are 60 m in length and 1 m in height. For the purpose of this study, the length of the sediment pit was increased to overall 7.5 m. The extended sediment bed had a thickness of 11 cm and was enclosed by a sediment trap and a ramp on either side. The sediment traps, designed as artificial pit traps, featured a length of 30 cm and were covered with a perforated steel plate to minimize the influence on the flow while still be capable of collecting bed load (particularly for live-bed conditions). Furthermore, the ramps consisted of 2 m long aluminum plates mounted on a stable framework. Groin-like structures and flow straightener were installed on both sides of the sediment bed to mitigate the inevitable influence of the flume curve on the flow, particularly on the lateral velocity distribution during maximum flow conditions. Inspection windows on both sidewalls allowed the undisturbed observation of the scour process from outside of the flume.

As sediment a crystal quartz sand with a median diameter d_{50} = 0.2 mm, a geometric standard deviation σ_g = 1.44 and a density of ρ_s = 2.65 g/cm³ was used. To guarantee a good compaction and to reduce entrapped air, the sand was installed in wet condition with a water level at the height of the sediment bed. Settlement of the sediment bed could not be observed even after a waiting period of over 12 hours with a water level equivalent to that in the tests. The surface of the sand bed was then smoothed by making use of guiding bars at both sidewalls. A monopile structure was simulated by a transparent pile with a diameter of D = 150 mm. The pile was positioned in the center of the sediment bed and screwed into the flume bottom. In order to minimize blockage effects Whitehouse (1998) suggested a maximum blockage ratio of pile width to flume width of 1:6. Since this criterion is fulfilled, the influence of the blockage on the flow is assumed to be negligible. Scour measurements were carried out by attaching a transparent foil around the pile, which was provided with a 2.5 mm grid to deliver a spatial reference scale of scour progress. The scour development was monitored by a camera (Logitech®, HD Pro C920) placed inside the transparent pile. The camera was installed in the center of the pile and could be continuously adjusted in height and viewing direction, enabling a high temporal resolution of the scour development at the pile.

Depending on the flow direction the flow velocities were measured 2 m upstream from the pile by applying an Acoustic Doppler Velocimeter (ADV, Nortek AS, Vectrino II Profiler) with a maximum sample rate of 100 Hz. The temporally variable flow velocities during the tidal tests prevented the measurement of otherwise useful vertical velocity profiles. Instead, flow velocities were measured stationary at half the water depth since the field data, which were used as basis for the investigated tidal currents, were available for the equivalent position. However, velocity profiles for multiple flow velocities were measured in preliminary tests (not shown here) to ascertain comparable velocity distribution in both flow directions. The water depth h was kept constant at 50 cm (h/D = 3.3) above the sediment bed in order to concentrate on the influence of flow direction and variable flow velocity. Information on the experimental setup is shown in Fig. 1.

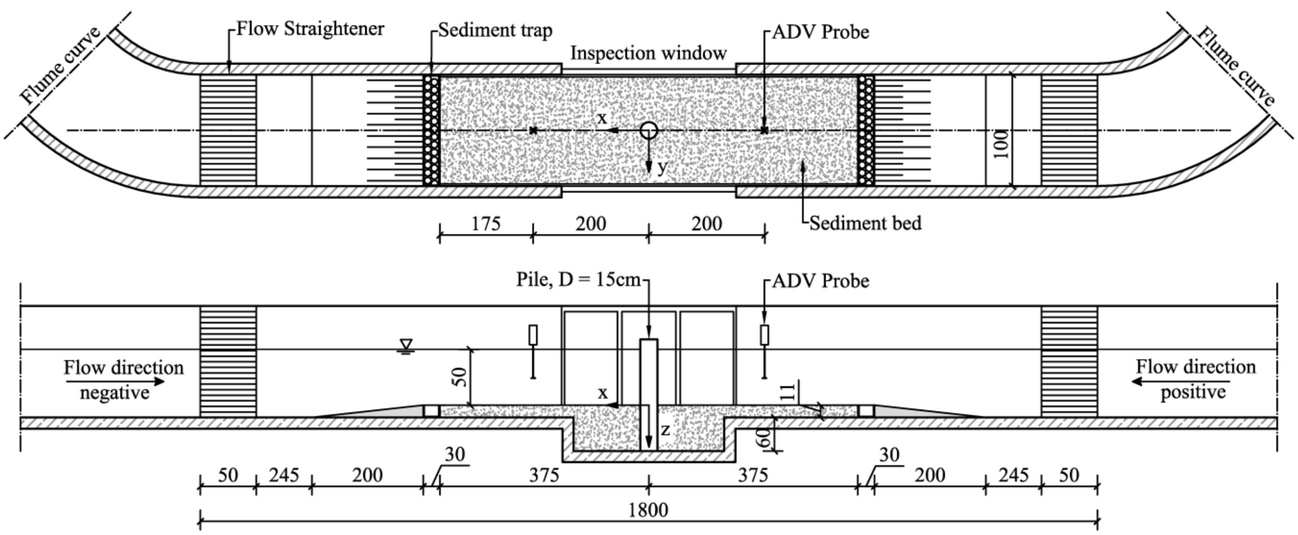

Figure 1: Schematics of experimental setup in top and side view with numbers in centimeter (not to scale).

3 METHOLOGY

In order to consider the asymmetry of a tidal current and thereby allow the investigation of time varying flow velocities, the tidal signals in this study were based on field measurements, acquired at the FINO I platform located in the North Sea, by the Federal Maritime and Hydrographic Agency of Germany (BSH). At FINO I tidal data, including velocity profiles and flow direction, have been monitored since 2004 allowing long-term studies in future investigations. It has to be noted that the field measurements showed an elliptical change of flow direction, which was adapted by a bidirectionally reversing current in the tests. For this study a series of eight consecutive tidal half cycles was selected from the available field data, representing flow velocities at the peak of a tidal spring phase (see Fig. 2). The time scale of the original tidal signal has been downscaled according to the model scale of 1:40 following Froude's Law, resulting in a duration of approx. 1 h for each half cycle. Due to the known difficulties regarding sediment scaling, the flow velocities were scaled by matching the maximum peak velocity within the chosen tidal signal to flow intensities U/U_c required for clear-water and live-bed conditions (live-bed not part of this paper) for the given sediment properties (d_{50} = 0.2 mm). As a result, peak flow velocities were achieved that are relatively but not unrealistically larger than in prototype scale. Fig. 3 compares the original tidal signal with the two scaled signals for clear-water conditions used in this study. The critical flow velocity of U_c = 29.6 cm/s for the given sediment properties was determined in accordance to Melville (1997) by applying the logarithmic form of the velocity profile as an approximation. In the presence of a pile the bed shear stress is amplified, resulting in smaller approach velocity needed for sediment movement. As indicated by Breusers and Raudkivi (1991) as well as Hoffmans and Verheij (1997) the amplified shear stress at a pile reaches 4 times the undisturbed bed shear stress. Consequently, only an approach velocity of half the critical velocity (in this case 14.8 cm/s) should be needed to initiate sediment motion at the pile.

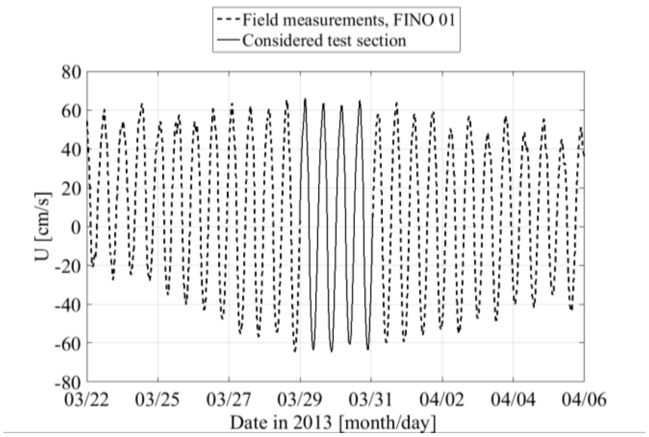

Figure 2: Velocities measured at half water level.

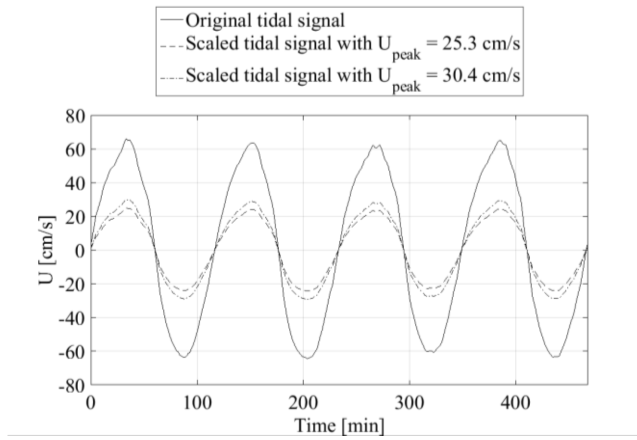

Figure 3: Comparison of original tidal signal with scaled tidal signals used in this study.

The scaled tidal signals were discretized in 95 s long velocity steps, one step for every given data point of the field measurements. Each velocity step was centered around the corresponding data point while maintaining a constant velocity. A similar approach was used by Porter et al. (2014), but with fewer discretization steps. An evident disadvantage of the approach is the limited resolution of phases in the tidal signal that reveal a strong flow velocity gradient, in particular during slack water conditions which resembles the zero-crossing of tidal current. However, with 38-39 incremental velocity steps for each tidal half cycle, depending on the length of the half cycle, a quasi-continuous flow representation could be obtained in order to ensure an adequate reproduction of the original tidal signal in the tests. Fig. 4 shows the flow velocities measured during the first tidal test Tide_01 with a peak velocity of 25.3 cm/s in comparison to the original scaled field data. The highest differences between measured and original velocities came from technical restrictions of the pumps at lower speed. Since the deviations occurred only at velocities slower than the critical flow velocity (14.8 cm/s at the pile) the scour process should not be affected significantly.

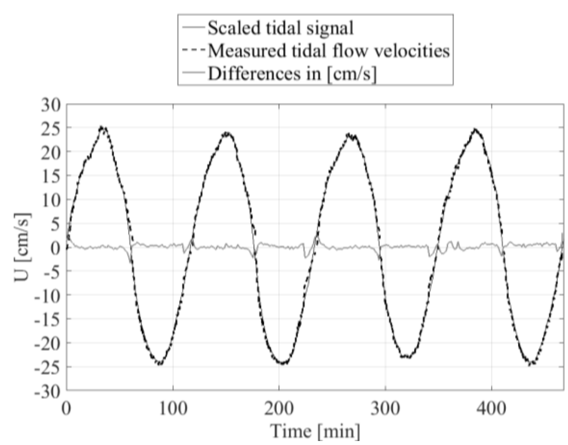

Figure 4: Comparison of measured velocities for tidal test Tide_01 with a peak velocity of U_{peak} = 25.3 cm/s and the corresponding original scaled field data.

The scour development under tidal current was compared to the progress under unidirectional current. Due to the existing lack of knowledge, there are still uncertainties in choosing adequate unidirectional currents for comparison. Therefore, two unidirectional currents for each tidal test were selected. The constant flow velocities for the unidirectional tests were based on either the mean velocity (RMS) or the maximum peak velocity within the tidal signal. While it can be expected that the unidirectional flow based on the peak velocity will lead to a larger scour depth, the approach based on the mean velocity might not be practical for all cases because it could produce velocities smaller than the critical flow velocity of the sediment. Overall two tidal and four unidirectional currents with a duration of eight half cycles were investigated under clear-water conditions in the present paper. Table 1 summarizes the test conditions.

Table 1: Test conditions. D is the pile diameter, h is the water depth above the sediment bed, T is the test duration, U_{mean} is the temporal average flow velocity for unidirectional tests and U_{peak} the maximum peak velocity within a tidal test. S/D are the final scour depths at the end of the tests.

Test	h [cm]	D [cm]	U_{mean} [cm/s]	U_{peak} [cm/s]	U/U_c [-]	T [min]	S/D [-]
Uni_01	50	15	16.6	-	0.56	479	0.18
Uni_02	50	15	19.8	-	0.67	481	0.30
Uni_03	50	15	25.3	-	0.86	482	0.81
Uni_04	50	15	30.4	-	1.03	478	1.03
Tide_01	50	15	-	25.3	0.86	466	0.38
Tide_02	50	15	-	30.4	1.03	467	0.62

The scour development was continuously measured by the camera placed inside the pile, with a set of pictures taken every 3 min in the tidal tests. For the unidirectional tests the amount of pictures taken was reduced to one set every 3 min in the first hour and thereafter every 10 min, since the scour development after passing the initialization phase was not as variable as in the tidal tests. A set of pictures consisted of eight pictures successively taken in radial intervals of 45° around the pile (see Fig. 5), starting at the right side of the pile for positive flow direction. This allowed the accurate determination of the maximum scour depth around the pile and the description of sediment displacements and infilling processes during the tidal current. A delay of 7 s between the pictures had to be accepted resulting from the rotation of the camera, which has been accounted for in the analysis. Furthermore, in order to follow the increasing scour depth the height of the camera was adjusted multiple times during the tests. The maximal scour depth at a time was defined as the maximal scour depth within the eight depths in a set of pictures. It has to be noted that the comparison of the eight scour depths might imply some inaccuracies, due to the stated delay of the time stamp of recordings. The first set of pictures was taken as soon as the intended flow velocity of the test was reached.

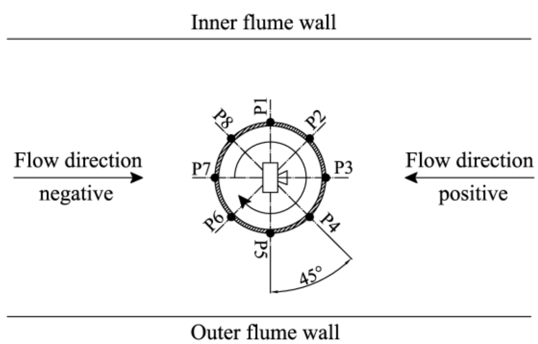

Figure 5: Positions for scour measurement around the pile in top view.

3.1 Test procedure

At the beginning of the tests water was carefully filled in from both sides of the sediment bed to avoid unwanted washout until a water level of 50 cm above the sediment bed was achieved. No additional sediment was added to the flume upstream of the test bed during the experiments. Subsequent to each test the water was cautiously drained. Before the test started a preliminary measurement of the sediment bed was performed as reference. In the unidirectional tests the flow velocity was slowly increased to prevent the formation of flow-induced ripples of the water surface. As soon as the desired flow velocity was achieved the scour measurement was initialized. In contrast to the unidirectional tests the tidal tests had to be stopped after each half cycle in order to adjust the position of the ADV probe for the reverse flow direction. Because the flow velocity was almost zero at this time, the influence on the scour development is assumed to be negligible. After repositioning the ADV probe and without draining the water the next tidal half cycle was generated with reversed flow direction. Under clear-water conditions only small amounts of transported sediment were collected by the sediment trap.

4 RESULTS

4.1 Variation of maximum scour depth around the pile

As a result of the reversing current loads a combination of sediment infilling from the scour edge and of sediment displacement within the scour hole could be observed, leading to large variations of scour depth at the upstream and downstream side of the pile. Fig. 6 exemplarily shows the scour development at four positions around the pile for the tidal test Tide_02 with a flow intensity of $U/U_c = 1.03$.

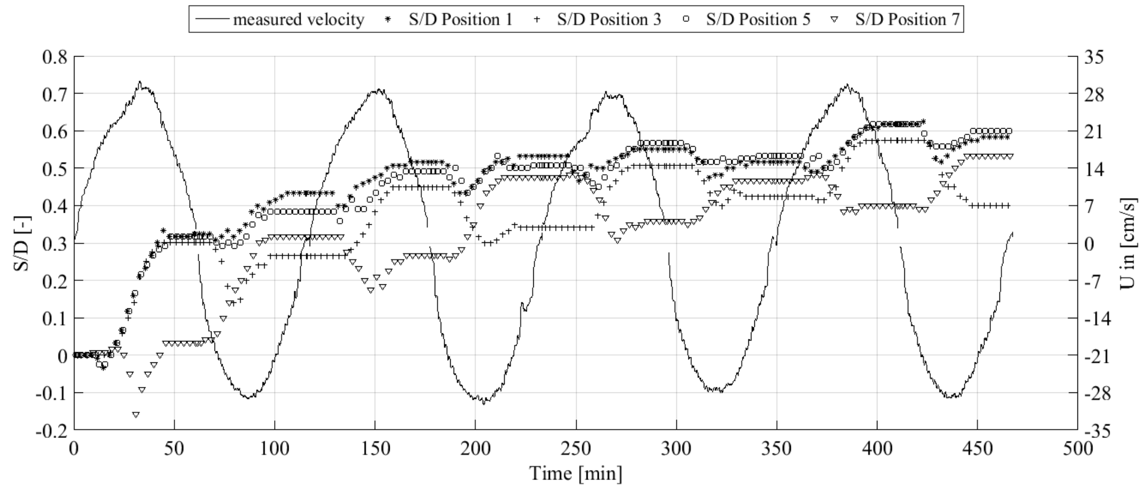

Figure 6: Scour development at the streamwise (position 3 and 7) and lateral (position 1 and 5) positions around the pile for Tide_02 with a maximum $U/U_c = 1.03$ in comparison to ADV velocity measurements at half water depth for Tide_02.

Within a tidal half cycle, the development of scour depth is determined by the variable flow velocity. As soon as the amplified critical shear stress of the sediment is exceeded, the scour process is initiated and prolonged until the velocity falls below this critical threshold, resulting in phases of stagnating bed development. Depending on the location on the circumference of the pile in reference to the flow direction the scour depth increases or declines within a tidal half cycle. While the largest increase of scour depth is taking place on the corresponding upstream side of the pile (position 3 for positive flow direction), the scour depth significantly decreases on the downstream side of the pile (position 7 for positive flow direction). This strong variation in scour depth occurs in every tidal half cycle without losing in intensity over the test duration. At the same time the scour depth at the lateral sides of the pile is much less influenced by the change in flow direction.

Fig. 7 compares the scour depth for the streamwise and lateral measurement positions. The differences in scour depth between the upstream and downstream side of the pile range from S/D = 0.07 during the sixth half cycle to S/D = 0.3 during the first half cycle for tidal test Tide_02. For the last tidal half cycle, a difference in scour depth of still S/D = 0.13 could be determined. Since the test started in positive flow direction, with position 3 being at the upstream side of the pile, larger scour depths are achieved at position 3 than at position 7. However, the existing scour hole and the downstream sediment deposition (at the upstream side of the pile when reversing the flow) might also have an influence on flow and sediment transport and therefore on the scour development during the following tidal half cycles. As expected from the symmetry of the experimental setup the scour depths on both lateral sides are quite similar throughout the test which also indicates the persistency of constant flow conditions across the flume.

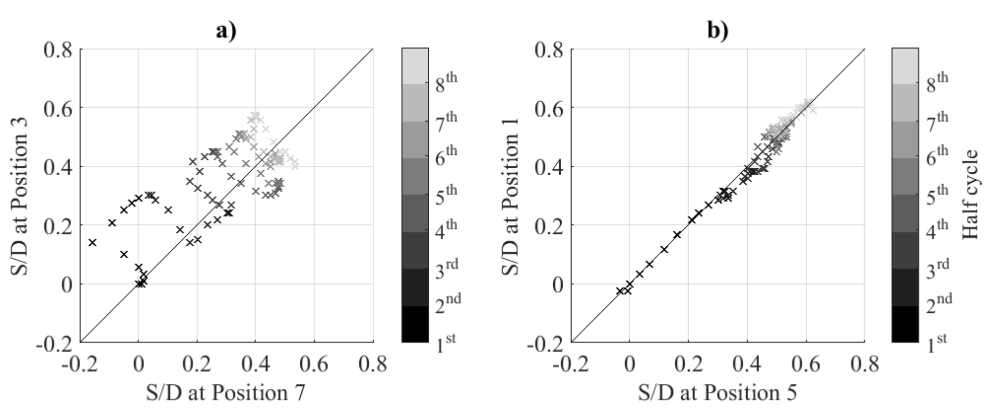

Figure 7: Comparison of scour depth for a) measurement positions in streamwise direction and b) lateral direction for test case Tide_02. The colorbar shows the development of scour depth over the individual tidal half cycles.

Although the variations in scour depth are the largest between the upstream and downstream side of the pile, the maximum scour depth does not appear at these positions as it would be expected for the scour development under unidirectional flow. Fig. 8 illustrates the variation of position of maximum scour depth at any given time for the second tidal test Tide_02. During the first three tidal half cycles, and despite the change in flow directions, the maximum scour depth can be found at position 2, which is located at 45° to the direction of approaching flow. For the positive flow direction in this study, the position of initial scour development is therefore in agreement with the shear stress measurements conducted by Hjorth (1975) and the scour observations carried out by Ettema (1980). However, with the beginning of the fourth tidal half cycle the maximum scour depth relocates to position 8 on the other side of the pile. Subsequently, the position of maximum scour depth changes with every further tidal half cycle from the upstream to the downstream side of the pile and vice versa. This observation demonstrates clearly the influence of the reversal of flow direction on the scour process. While the position of the maximum scour depth changes mostly within one lateral side of the pile, i.e. from position 4 to 6, a very similar scour was also measured at the other lateral side as indicated by Fig. 7.

The maximum scour depth is not located at the direct upstream or downstream side of the pile (position 3 and 7) at any time and therefore differs from the scour process under unidirectional flow, in which the maximum scour depth propagates to the upstream side of the pile over time (Chiew, 1984; Meville and Coleman, 2000). McGovern et al. (2014) also carried out scour measurements at multiple positions around the pile by means of an ultrasonic ranging system. Although the measurements are limited to four directions (streamwise and lateral), they show a similar change in the position of maximum scour depth from the initial upstream to the downstream side of the pile by the start of the fourth half cycle. However, it has to be noted that the scour depths in McGovern et al. (2014) could not be measured directly at the pile and that live-bed conditions were investigated.

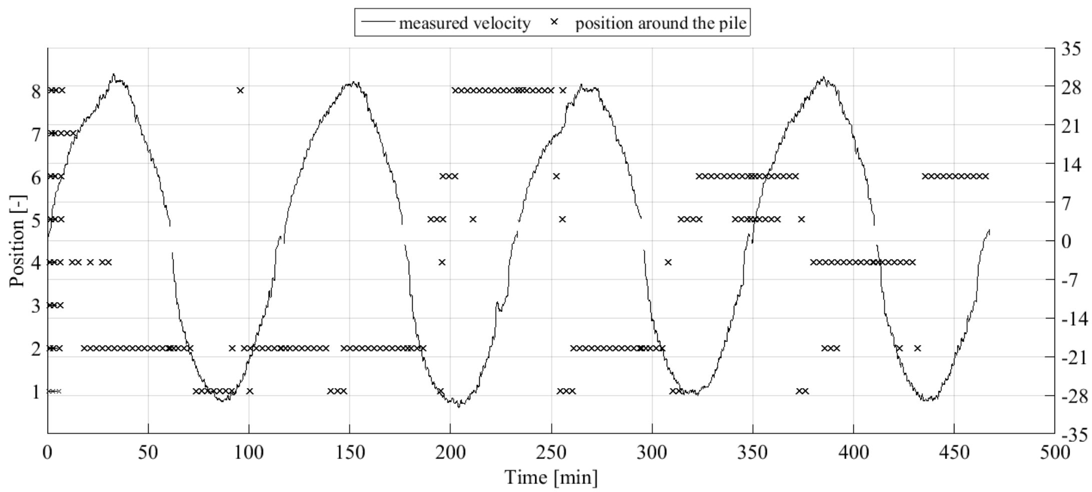

Figure 8: Variation of position of maximum scour depth at the pile over time for the Tide_02 test case in comparison to ADV velocity measurements for Tide_02.

4.2 Time development

The temporal development of the maximum scour depth for all test cases is presented in Fig. 9. Although the variations in scour depth are obviously not as pronounced as between individual positions (cp. Fig. 8), the time development of the maximum depth under tidal flow is nonetheless unsteady and characterized by phases of stagnating and decreasing scour depth. At the beginning of a new tidal half cycle the scour depth is declining, but increasing again over the duration of the half cycle. Furthermore, the variations of scour depth are larger for the second tidal test with a peak velocity of 30.4 cm/s compared to the first one with a peak velocity of 25.3 cm/s. The scour progression is clearly a result of the described sediment displacement and infilling initiated by the reversal of the flow direction and the influence on the flow by the scour development of the preceding tidal half cycle.

These observed processes lead in combination with the temporal shorter erosive exposure due to smaller velocity to a significant slower progression of the scour depth in contrast to unidirectional currents with flow velocity based on the maximum peak velocity (Uni_03 and Uni_04) of the corresponding tidal current. In relation with results conducted for unidirectional currents, which are based on the mean flow velocity of the tidal signal (Uni_01 and Uni_02), an obvious underestimation of the scour development is given. Final scour depths for the unidirectional and tidal tests are given in Table 1. The equilibrium scour depth for tidal conditions has yet not been reached and scour depth are still increasing in both test series. Therefore, the difference in the final scour depth between unidirectional und tidal tests might not remain the same with ongoing test duration. However, this finding demonstrates the existing challenges in adequately mimic and predict the scour development under tidal currents by means of a constant unidirectional flow velocity and thereby illustrates the need for approaches that consider the time varying flow velocities and reversal of flow direction.

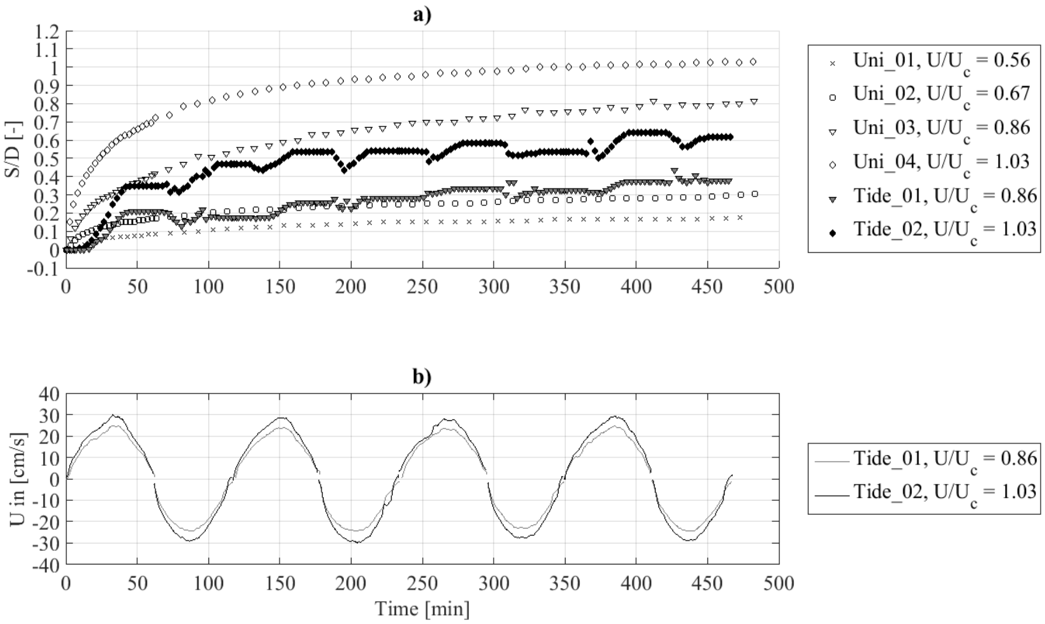

Figure 9: Development of maximum scour depth over time for unidirectional and tidal test cases. b) ADV velocity measurements for both tidal test cases.

In addition, Fig. 10 compares the scour development for the individual half cycles of both tidal test cases. It stands out that the scour development during the first half cycle accounts for 57% for Tide_02 and 56% for Tide_01 of the total final scour depth after eight half cycles. Interestingly, the scour progression during both first half cycles is quite similar and stops for both configurations at around 45 min. The reason for this might be the related shape of the two tidal signals, which only differ in the peak velocity but expose the sediment bed for the same time span. The point in time at which the critical flow velocity (14.8 cm/s) is reached is consequently very close between both tidal signals. As a comparison, in the unidirectional test cases the time needed to reach 57% of the final scour depth is much more dependent on the flow velocity and ranges between 93 min for Uni_01 and 35 min for Uni_04. Because of the steep increase in scour depth during the first half cycle, a separation into two parts for the prediction of the temporal scour development under tidal current might be considered. The first part could govern the scour development during the first tidal half cycle and the second part the one afterwards.

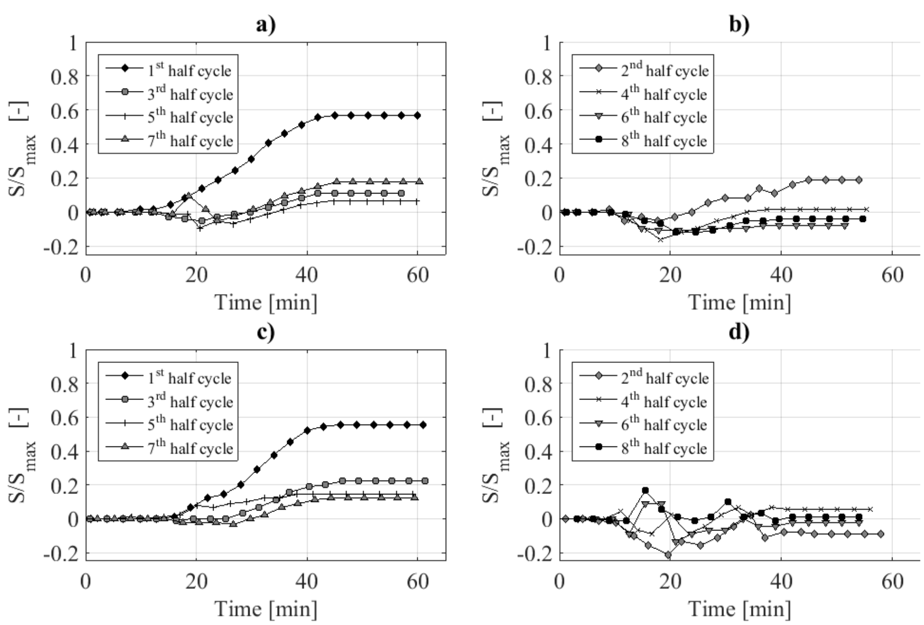

Figure 10: Comparison of scour development for each tidal half cycle with S/S_{max} as the ratio of the maximum scour depth in a half cycle to the final scour depth at the end of the test case. a) Scour development in Tide_02 for positive flow direction and b) for negative flow direction. c) Scour development in Tide_01 for positive flow direction and d) for negative flow direction.

The scour development is dominated by the scour process under positive flow direction. The increase in scour depth during each tidal half cycle with positive flow direction is higher than in almost every tidal half cycle with negative flow direction. This might be explained by the fact that the tidal tests started with the flow in positive direction and is assumed to be “mirrored” if the first half cycle would have been started with negative flow direction. Furthermore, while the increase in scour depth slows down with every successive half cycle for the first tidal test Tide_01 with positive flow direction (Fig. 10 c)) it does not follow the same expected order during the other half cycles. Therefore, the scour development depends strongly on the initial load, i.e. tidal phase, and the flow direction as already pointed out by Porter et al. (2014).

5 DISCUSSION

In this study the simulated tidal currents are based on field measurements. Since the flow velocity could be measured only at one fixed position during the tidal tests, measurements were carried out at half water depth and compared to the corresponding ones from the field measurements. As a result, the tidal signal in this study showed a good agreement with the field data (see Fig.4). Furthermore, the flow velocity at half water depth differed only slightly from the mean flow velocity of the field measurements, averaged over the whole water depth, and therefore should depict a first good approximation. However, the field measurements showed a complex tidal flow field with significant differences in the vertical velocity profile depending on the flow direction. The flow velocities near the bed were much larger during flood periods than during ebb periods. The asymmetry in the vertical velocity profile between flood and ebb has not been accounted for in this study, but might represent a significant influence on the scour process in the field.

Although the studies were performed under clear-water conditions, ripples as well as sediment deposition formed at the respective downstream side of the pile. Since the ripples and the deposition were not removed or smoothed after a tidal half cycle they could have influenced the flow field and thereby the scour development during the successive reversing tidal flow. The effects of the present scour hole and associated dunes on the local velocities is also discussed in Escarameia und May (1999). Because the ripples and the shape of the scour hole are continuously changing over time, it is also challenging to quantify the direct impact of the bed changes on the scour depth. However, since the ripples and the deposition will also form in the field, even though implying a different scale, no re-smoothing of the sediment bed has been performed during the tests.

6 CONCLUSIONS

Hydraulic model tests were carried out in a closed-circuit flume in order to investigate the progression of scour at a pile under tidal currents. While this paper focuses on the scour development under clear-water conditions, experiments under live-bed conditions have already been performed and will be presented and contrasted to each other in future publications. The tidal currents were based on field measurements and were simulated by a quasi-continuous approach. In addition, as a result of scour measurements at multiple positions around the pile and a high temporal resolution novel insights on the intrinsic progression of sediment displacement and time scale of the scour process around a monopile under tidal currents could be presented. Thereby, the following findings might help improving the quantitative assessment of scour development under marine conditions as integrated part of the design of offshore structures:

- The reversing currents stemming from mimicking tidal conditions under laboratory conditions induce constantly varying sediment infilling and displacement processes in the scour hole. As a result, large variations of scour depth occur at the upstream and downstream side of the pile leading to an altering position of maximum scour depth over time. It is thus essential to capture the scour depth at multiple positions around the pile for the accurate prediction of scour progression under tidal currents.
- Within a tidal half cycle, the scour development is determined by the variable flow velocity, i.e. scouring commences or terminates by exceeding the critical amplified shear stress at the pile. Since the required shear stress is only reached for a short period of time within a half cycle, at least in case of the investigated clear-water conditions, common approaches for scour prediction based on unidirectional currents should consider for that particular timeframe.
- Based on the described sediment infilling and displacement processes the time development of the maximum depth under tidal flow is unsteady and characterized by periods of stagnating and decreasing scour depth. This leads, in reference to phases of smaller velocity, to a significant slower progression of the scour depth compared to unidirectional currents with flow velocity based on the maximum peak velocity, which is in agreement with previous results from McGovern et al. (2014) and Porter et al. (2014). On the contrary, in contrast to unidirectional currents, which are based on the mean flow velocity of the tidal signal, scour development is evidently underestimated.
- Irrespective of the maximum peak velocity of the tidal signals, the scour development during the first half cycle accounted for almost 60% of the final scour depth after eight half cycles. Due to the steep increase in scour depth during the first half cycle, a two-parted prediction approach for scour development under tidal currents is suggested.

In order to achieve equilibrium scour depths as a requirement for a meaningful assessment of the temporal scour development under tidal currents, more temporal extensive tests will be conducted in the future. Furthermore, comparisons with field measurements from offshore sites will be carried out as they often seem to differ from laboratory results (Harris and Whitehouse, 2014).

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the German Federal Ministry for Economic Affairs and Energy within the funded project "Giga-Wind Life" (BMWI: 0325575A).

REFERENCES

Breusers, H. N. C., Nicollet, G. and Shen, H. W. (1977). Local Scour at Bridge Piers, *Journal of Hydraulic Research*, Vol 15(3), pp. 211-252.

Breusers, H. N. C. and Raudkivi, A. J. (1991). *Scouring*, Balkema, Rotterdam, The Netherlands.

Chiew, Y. M. (1984). *Local Scour at Bridge Piers*, Doctor Thesis, School of Engineering, University of Auckland, New Zealand.

Dey, S. and Raikar, R. V. (2007). Characteristics of Horseshoe Vortex in Developing Scour Holes at Piers, *Journal of Hydraulic Engineering*, Vol. 133(4), pp. 399-413.

Escarameia, M. and May, R. W. P. (1999). *Scour around structures in tidal flows*, Report SR 521, HR Wallingford, UK.

Ettema, R. (1980). *Scour at bridge piers*, Rep. No. 216, Univ. of Auckland, Auckland, New Zealand

Goseberg, N., Wurpts, A., and Schlurmann, T. (2013). Laboratory-scale generation of tsunami and long waves, *Coastal Engineering*, Vol. 79, pp. 75-74.

Harris, J. M., and Whitehouse, R. J. S. (2014). Marine scour: Lessons from nature's laboratory. *Proc. 7th Int. Conf. on Scour and Erosion*, Univ. of Western Australia, Perth, Australia.

Harris, J. M., Whitehouse, R. J. S. and Benson, T. (2010). The time evolution of scour around offshore structures, *Proc. ICE Maritime Engineering*, Institution of Civil Engineers, London.

Hjorth, P. (1975). *Studies on the nature of local scour*, Bull. Series A, No. 46, viii + 191 p., Department of Water Resources Engineering, Lund Institute of Technology, Schweden.

Hoffmans, G. J., and Verheij, H. G. (1997). *Scour manual*, Balkema, Rotterdam, The Netherlands.

McGovern, D. J., Ilic, S., Folkard, A. M., McLelland, S.J. and Murphy, B. (2014). Time development of scour around a cylinder in simulated tidal current, *Journal of Hydraulic Engineering*, Vol. 140 (6).

Melville, B. W. (1997). Pier and abutment scour: An intergrated approach, *Journal of Hydraulic Engineering*, 123:2(125), 125–136.

Melville, B.W. & Chiew, Y-M. (1999). Time scale for local scour at bridge piers, *Journal of Hydraulic Engineering*, Vol. 125(1), pp. 59–65.

Melville, B.W., and Coleman, S. E. (2000). *Bridge scour*, Water Resources Publications, CO.

Porter, K. E., Simons, R. P. and Harris, J. M. (2014). Laboratory investigation of scour development through a spring-neap tidal cycle, *Scour and Erosion, Proc. of the 7th International Conference on Scour and Erosion*, Perth, CRC Press, pp. 667-677.

Raudkivi, A. J. and Ettema, R. (1983). Clear-water scour at cylindrical piers, *Journal of Hydraulic Engineering*, Vol. 109(3), pp. 338-350.

Schendel, A., Goseberg, N. and Schlurmann, T. (2014). Experimental study on the performance of coarse grain materials as scour protection, *Coastal Engineering Proceedings, 1*(34), http://dx.doi.org/10.9753/icce.v34.structures.58

Schendel, A., Goseberg, N., and Schlurmann, T. (2015). Erosion Stability of Wide-Graded Quarry-Stone Material under Unidirectional Current, *J. Waterway, Port, Coastal, Ocean Eng.*, http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000321 (in press)

Sumer, B. M., Christiansen, N., and Fredsøe, J. (1992). Time scale of scour around vertical pile, *2nd Int. Offshore and Polar Engineering Conf.*, The International Society of Offshore and Polar Engineers, Colorado.

Sumer, B. M., and Fredsøe, J. (2002). *The Mechanics of Scour in the Marine Environment*, World Scientific, New Jersey, Singapore, London, Hong Kong.

Whitehouse, R.J.S. (1998). *Scour at marine structures*. London: Thomas Telford Ltd.