LARGE-SCALE MODEL TESTS ON SCOUR AROUND SLENDER MONOPILE UNDER LIVE-BED CONDITIONS

ULRIKE PREPERNAU (1), JOACHIM GRUENE (2), REINOLD SCHMIDT-KOPPENHAGEN (3), ZEYA WANG (4) and HOCINE OUMERACI (5)

(1) Dipl-Geogr., Coastal Research Centre (FZK), Merkurstr. 11, Hannover, 30419, Germany. prepernau@fzk.uni-hannover.de
(2) Dipl-Ing., Coastal Research Centre (FZK), Merkurstr. 11, Hannover, 30419, Germany. gruene@fzk.uni-hannover.de
(3) Dipl-Ing., Coastal Research Centre (FZK), Merkurstr. 11, Hannover, 30419, Germany. sk@fzk-uni-hannover.de
(4) M-Ing., Coastal Research Centre (FZK), Merkurstr. 11, Hannover, 30419, Germany. wang@fzk.uni-hannover.de
(5) Prof. Dr.-Ing., Coastal Research Centre (FZK), Merkurstr. 11, Hannover, 30419, Germany. h.oumeraci@tu-bs.de

This paper presents the results of an experimental investigation on scour around monopiles exposed to irregular waves. The large-scale laboratory tests in the Large Wave Channel (GWK) of the Coastal Research Centre (a joint institution of both universities Hannover and Braunschweig) were focussed on the development of scour under live-bed conditions with varying intensities of spectra (Jonswap) without grading the mobile bed surface, as it occurs similar to a strong wind field passing a monopile location. The scour process was monitored continuously by an installed observation window and a digital camera. The results of the physical large-scale tests are used in order to validate available formulas for predicting scour depth and to consider new findings concerning to the physics of scour. As expected for these conditions the scour depths grow with increasing wave height and wave period. However shifting to another wave energy whatever increasing or decreasing causes occurrence of additional sand transport which fill up the scour before the scour processes prevail and deepen the hole around the pile. Furthermore the test results present certain variations compared to small-scale test results of Sumer and Fredsøe (2001) probably due to scale effects.

Keywords: Large-scale tests; Scour; Live-bed conditions; Slender pile; Coastal structure.

1. Introduction

This study analyses local scour development around a vertical slender monopile induced by irregular waves under live bed conditions, such scour may occur during a storm surge at an offshore wind turbine monopile structure in the North Sea in shallow water (water depths 20 – 30m). The large-scale model tests were carried out within the framework of the EU-funded project Hydralab III (CoMIBBS). The project is aimed at testing different types of sediment transport (scour development around a slender monopile in this case) and at developing a composite modelling procedure.

Scour around a pile occurs due to the fact that the sediment transport rate close to the structure becomes much larger than the rate in absence of a structure. The interaction of structure and wave induced flow results in the following processes contributing to scour development:

- Formation of a horseshoe vortex in front of the pile
- Lee-wake vortices with or without vortex shedding behind the structure
- Contraction of streamlines
- Turbulences near sea bottom
- Wave breaking
- Liquefaction due to wave induced pore pressure in the sandy bed.

In the marine environment the structure is exposed to waves, steady currents and combined waves and currents. Scour around slender piles in marine environment has been studied by several scientists, e.g. Sumer et al., 1992; Carreiras et al., 2000; Sumer and Fredsøe, 2001; Rudolph and Bos, 2006.

Scour around a slender monopile in regular waves was investigated by Sumer et al. (1992), where the Keulegan-Carpenter number *KC*:

$$KC = \frac{v * T}{D} \qquad (1)$$

(with v = maximum value of the undisturbed oscillatory flow velocity [m/s], T = wave period [s] and D = pile diameter [m]) has been recognized as the major parameter to account for the scour processes around vertical monopiles exposed to waves. Small-scale experiments of Sumer et al. (1992) on local scour produced by regular waves around a single pile have shown that under live bed conditions the equilibrium scour depth S varies with the KC number as follows:

$$\frac{S}{D} = 1.3\{1 - \exp(-0.03(KC - 6))\} \qquad (2)$$

where S = scour depth. Sumer and Fredsøe (2001) reviewed the developed formula for scour around piles in regular waves and discussed the applicability for monopiles exposed to irregular waves. The small-scale laboratory tests and the scour depth formula in eq. (2) provide a good agreement with the measured scour depths for the KC number:

$$KC = \frac{v_{rms} * T_p}{D} \tag{3}$$

where the velocity v_{rms} is defined as the particle velocity at the sea bed:

$$v_{rms} = \sqrt{2}\sigma_U \tag{4}$$

in which σ_U = root mean square (RMS) value of the orbital velocity v at the bottom, defined by

$$\sigma_U = \int_0^\infty S_U(f)df \tag{5}$$

with $S_U(f)$ = power spectrum of v corresponding to the wave component of the flow, and f = wave frequency.

The first aim of the performed research work is a comparison of the large-scale tests on scour around a vertical slender monopile with the results of the small-scale tests of Sumer and Fredsøe (2001) in order to identify possible scale effects. Furthermore, the most appropriate characteristic orbital velocity as well as the characteristic wave period to estimate the Keulegan Carpenter number *KC* are discussed. Besides, the time durations and the measured final scour depths of the preliminary test and the tests of the simulated storm surge are compared among each other according to the variations of the measured scour depth development. A further aim was to estimate the influence of the general sand transport in the vicinity of the monopile on the scour evolution process. Moreover, the scour evolution process for different wave intensities and different initial condition (existing scour hole or even bottom) is investigated.

2. Experimental set-up and test conditions

The experiments were carried out in the Large Wave Channel GWK of the Coastal Research Centre FZK in Hannover. The flume has a width of 5 m, a height of 7 m, and an operational length of 307 m. During the tests a sand bed of roughly 1 m thickness ($d_{50} \approx 0.3$ mm) was installed. The monopile with the diameter D = 0.55 m was built in at a distance of 111 m from the wave paddle and the water depth above flume bottom was 4.20 m (3.20 m above sand bed).

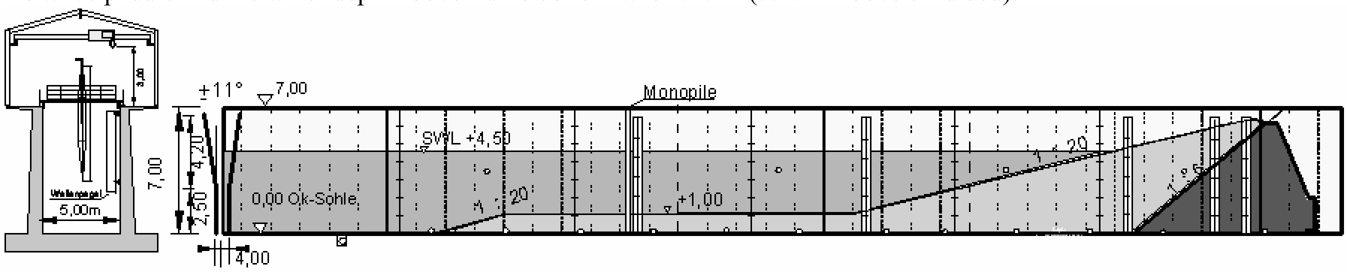

Figure 1: Large Wave Channel (GWK) with installed monopile and sand bed.

The test series described in this paper is a continuation of a large-scale test program on scour and scour protection. In the previous test series the sea bottom has been reshaped to even conditions before starting each test. In spite of that in this test series the sea bottom was left with the scour from the preceding test when starting a new test.

The test series were carried out with varying wave intensities thus simulating the development of an entire storm surge event schematically. Four differing wave spectra were generated as shown in Table 1 in a successive row as shown in Fig. 2, firstly with increasing wave energy and afterwards with decreasing wave energy.

The preliminary tests were performed with the wave spectra no. 2 (H_s = 1.00 m; T_p = 8.00 s; h = 3.20 m). Only after these tests the sand bed was set back to the original state with an even sand bed around the pile.

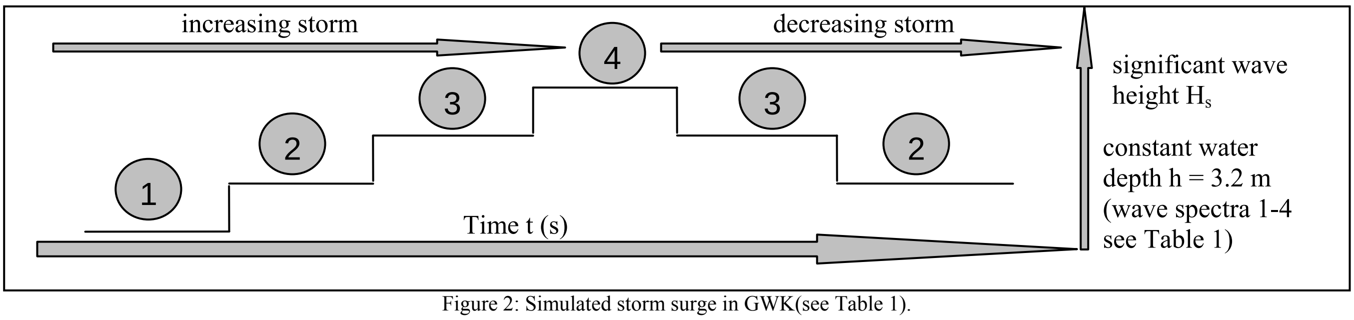

Figure 2: Simulated storm surge in GWK(see Table 1).

Table 1. Wave spectra and parameter variations.

Wave spectra	Sig. Wave Height $H_{1/3}$ (m)	Spect. Peak Period T_p (s)	water depth h (m)	pile diameter D (m)
1	0.9	7.6	3.20	0.55
2	1.0	8.0	3.20	0.55
3	1.1	8.4	3.20	0.55
4	1.2	8.8	3.20	0.55

Figure 3 shows the installed sand bed and the monopile with the measurement technique (velocity meter at one side of the pile at different elevations and an observation window with an installed digital camera inside the pile). Additionally, transducers and wave gauges were used during the tests to measure the orbital velocity at different elevations and wave parameters in a cross-section, which is not affected by the pile.

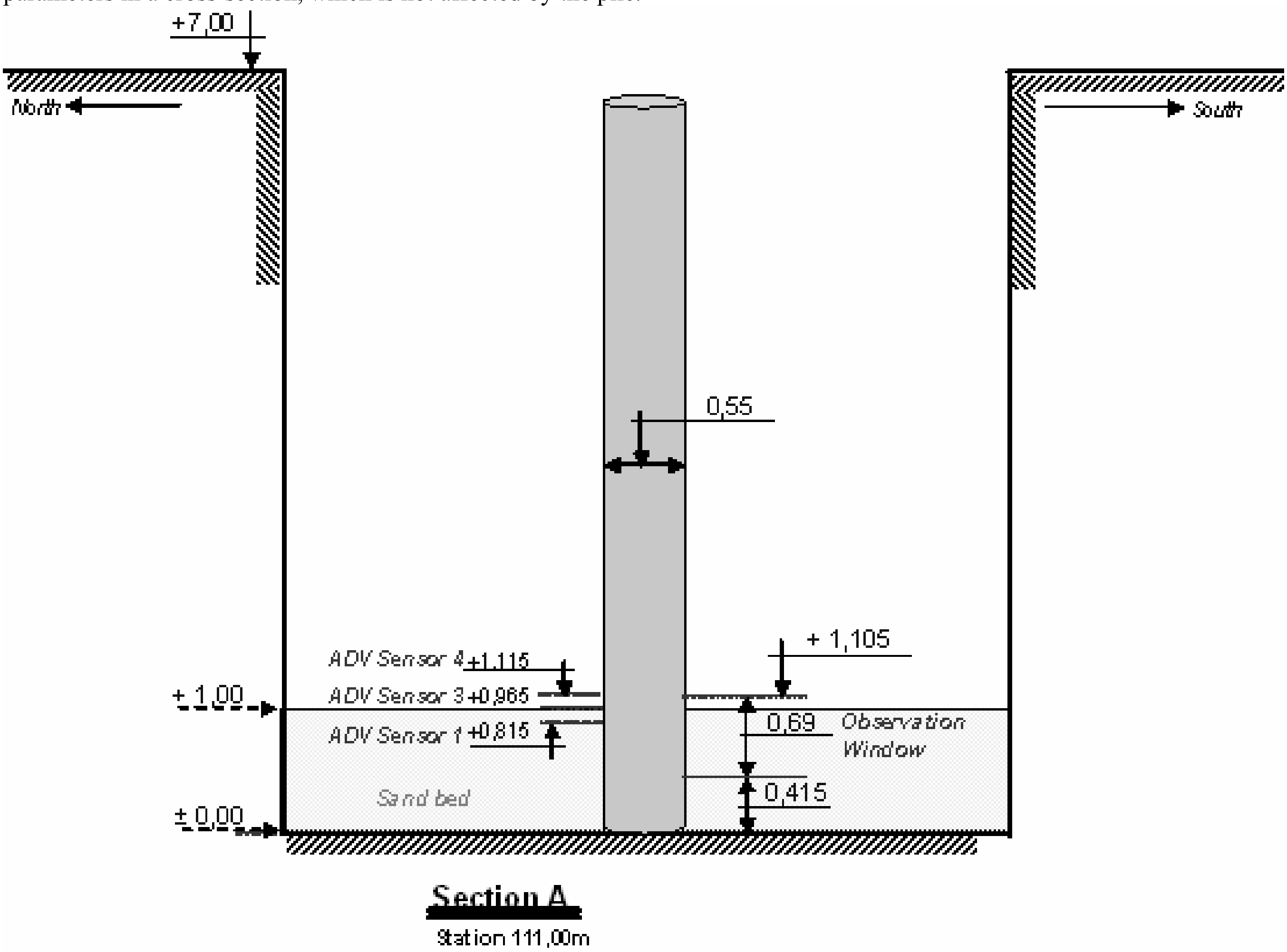

Figure 3: Experimental set-up before tests.

The observation window at one side of the monopile provides the monitoring of the scour around the monopile continuously. A digital camera (see Figure 5a) was fixed on a vertical lift system inside the monopile. The sand level at the bottom of the actual scour was monitored through the observation window. The digital images taken by the camera in time steps of some minutes during the tests were transferred online by a telemetric system to a computer. Figure 5(b) shows the vertical lift system with the fixed camera before installing the pile and 5(c) the installed pile with the observation window at the height of the sand bed.

The results of the preliminary test show that the equilibrium scour depth for the selected wave conditions is achieved after approximately 3,000 waves (see Figure 6) for an initial even bottom around the pile (test spectra 2, see Table 1). The depths vary with a standard deviation σ of 0.56 for the equilibrium depth of 0.15 m.

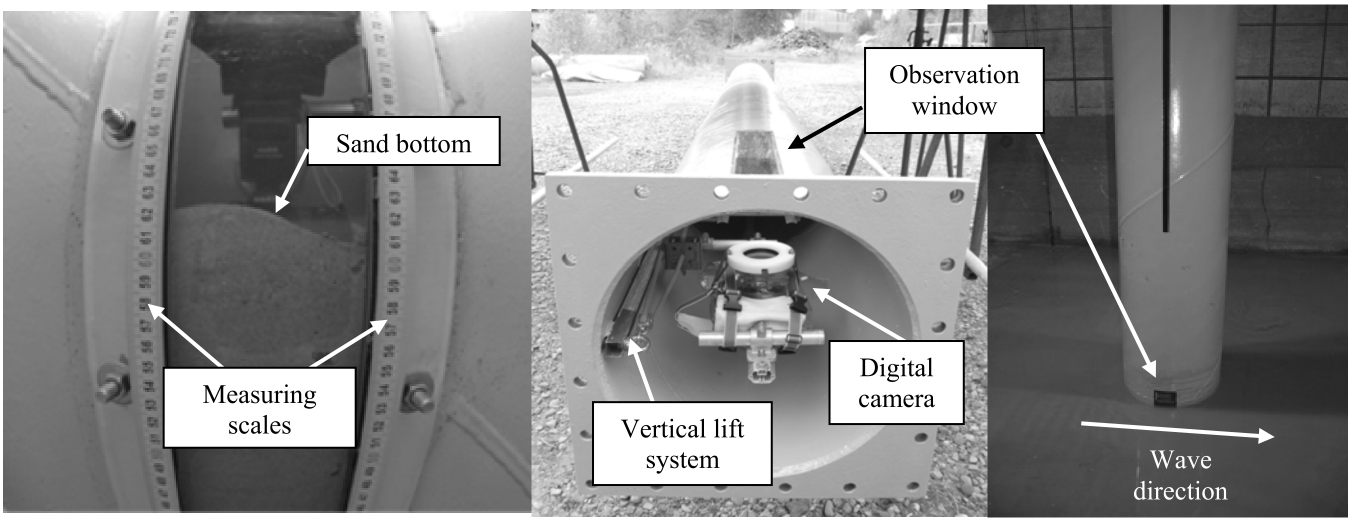

Figure 5: (a) Sand bottom of the scour around the pile; (b) Digital camera and vertical lift system in the pile; (c) Monopile with the observation window.

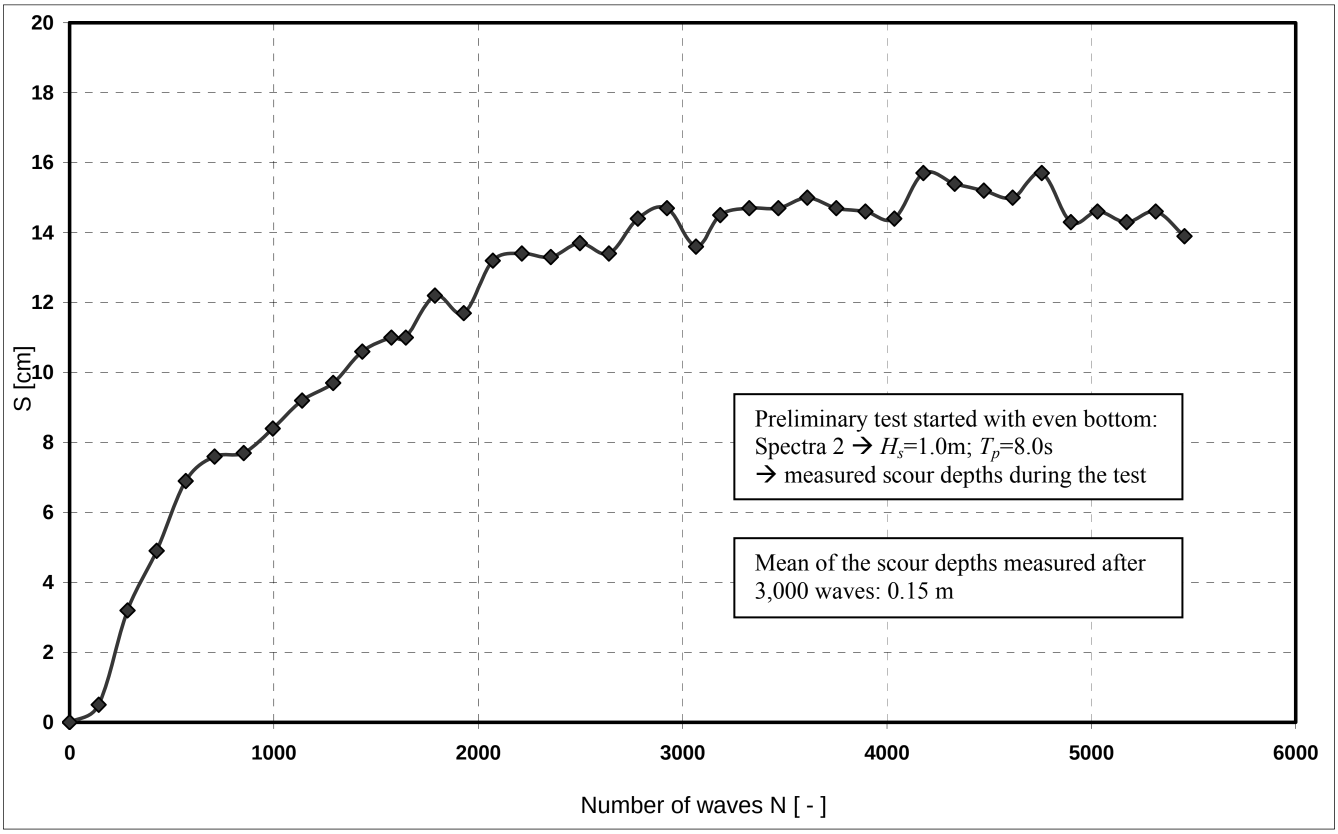

Figure 6: Measured scour depths during the preliminary test (spectrum 2, see Table 1).

3. Test results and discussion

Some measured wave parameters of the test series are presented in Table 2. The mean value of the one third highest velocities in wave direction $v_{+1/3}$ (m/s) was measured at an elevation of 0.31 m above sand bed unaffected by the pile or the sidewalls of the channel. The mean value of the significant wave height $H_{1/3}$ (m) and the spectral peak wave period T_p (s) were recorded at the wave gauge fixed at the wall of the channel at the position of the pile. The parameters $v_{+1/3}$ and $H_{1/3}$ are evaluated in time domain.

The photos taken by the installed digital camera record the sand bed of the scour around the pile (example see Fig. 5a). From these photos the mean elevations of the sand bed in the scour were evaluated by using the fixed measuring scales in the pile which were referred to the initial sea bottom level before starting the test. The measured depths are plotted against the number of waves in Figure 7. For all wave conditions a scour occurs.

As expected, the scour depths increase with increased wave energy and decrease with decreased wave energy in general. However, discrepancies were observed for tests with an existing scour hole at starting, which obviously are affected by the modification of the sand transport processes in the vicinity of the pile due to the changed wave conditions. Thus, the scour hole of the previous test is firstly filled up. But after a while the scouring process again prevails and deepens the scour hole.

The scour evolution process behaves in a different way for tests with increased and decreased wave energy. For tests with increased wave energy the filling up of the scour hole dominates for a shorter time period *(s2(up)*: 3,075 waves; *s3(up)*: 2,835 waves; *s4(up)*: 1,742 waves) compared to tests with decreased wave energy. For tests with decreased wave energy the filling up of the existing scour hole dominates for a longer time period due to the general sand transport process *(s3(down)*: 5,535 waves; *s2(down)*: 6,222 waves).

For *spectrum 3 (decreasing storm)* the trend of the filling up of the scour hole and the later prevailing scouring process can not clearly be observed. This may be due to the short total duration of the test. For this test a development of the scour hole with further sand erosion and a deeper final scour depth might have occurred for longer duration.

Table 2. Measured wave parameters during the tests (see also Table 1 and Figure 2).

Test series no.		No. of waves N (-)	sig. wave height $H_{+1/3}$ (m)	orb. velocity $v_{1/3}$ (m/s)	wave period T_p (s)
Spectrum 2 (preliminary test)	s2(pre)	5,456	1.05	0.95	7.89
Spectrum 1 (increasing storm)	s1(up)	5,472	0.95	0.82	7.47
Spectrum 2 (increasing storm)	s2(up)	7,137	1.02	0.83	7.91
Spectrum 3 (increasing storm)	s3(up)	7,290	1.20	1.10	8.84
Spectrum 4 (increasing storm)	s4(up)	6,432	1.41	1.23	8.78
Spectrum 3 (decreasing storm)	s3(down)	5,940	1.18	1.08	8.70
Spectrum 2 (decreasing storm)	s2(down)	13,908	1.09	0.83	7.84

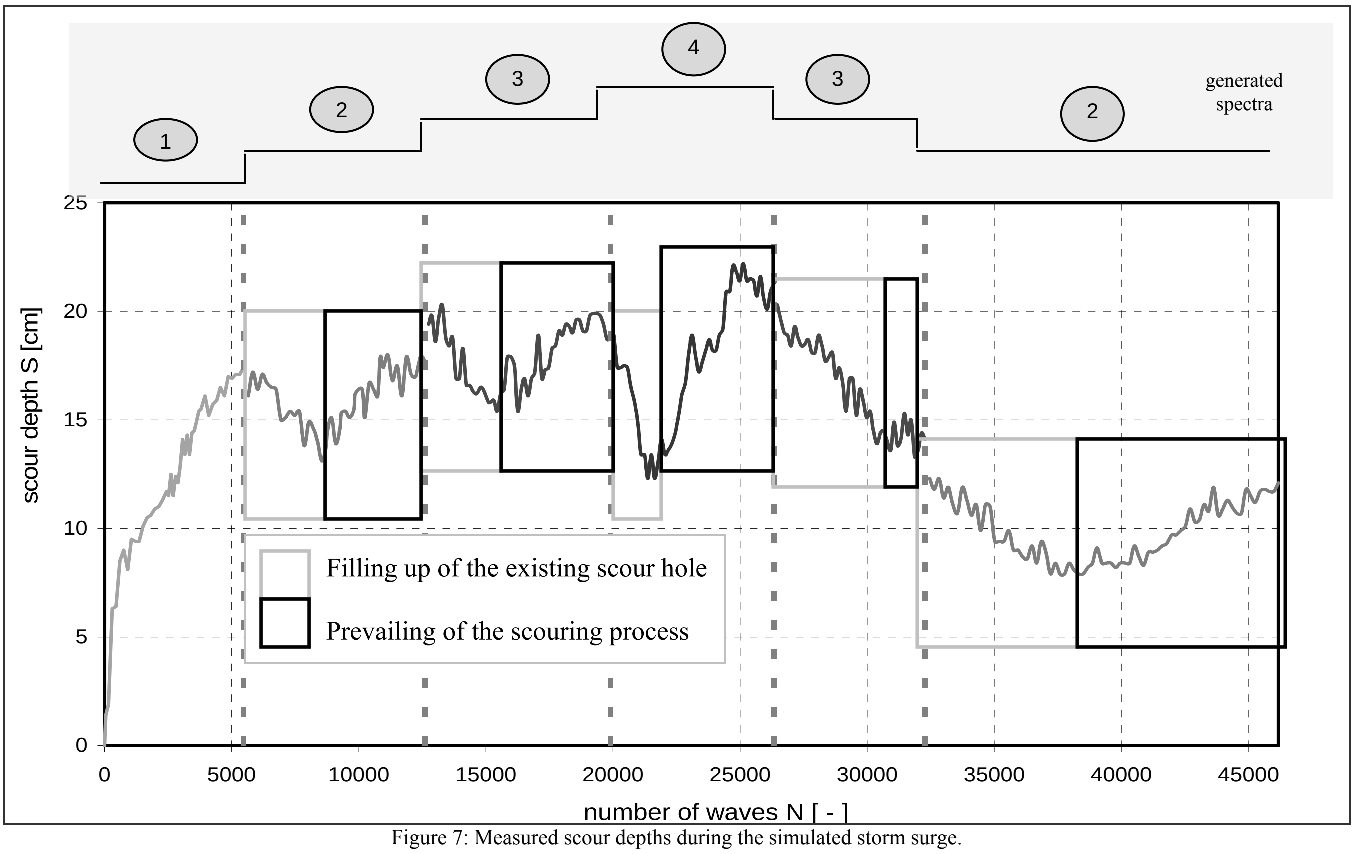

Figure 7: Measured scour depths during the simulated storm surge.

In Figure 8 the final scour depths of the several test series and the preliminary test are plotted versus the mean of the measured one third highest velocities in wave direction $v_{+1/3}$ (m/s) (time domain). The observed final scour depths show differences between tests with increased or decreased wave energy. For tests with an existing scour hole the scours are deeper when the storm conditions changed to higher wave parameter values (increased wave energy) compared to a change to lower values (decreased wave energy). The differences between scour depth of: *S2(up)* and *S2(down)* = 0.10 m; *S3(up)* and *S3(down)* = 0.09 m). The scour development of the preliminary test *S2(pre)* started with an even bottom around the pile and the final scour depth is between the depths of *S2(up)* and *S2(down)*. The results show a different scour development for the initial conditions “existing scour hole” or “even bottom” around the pile.

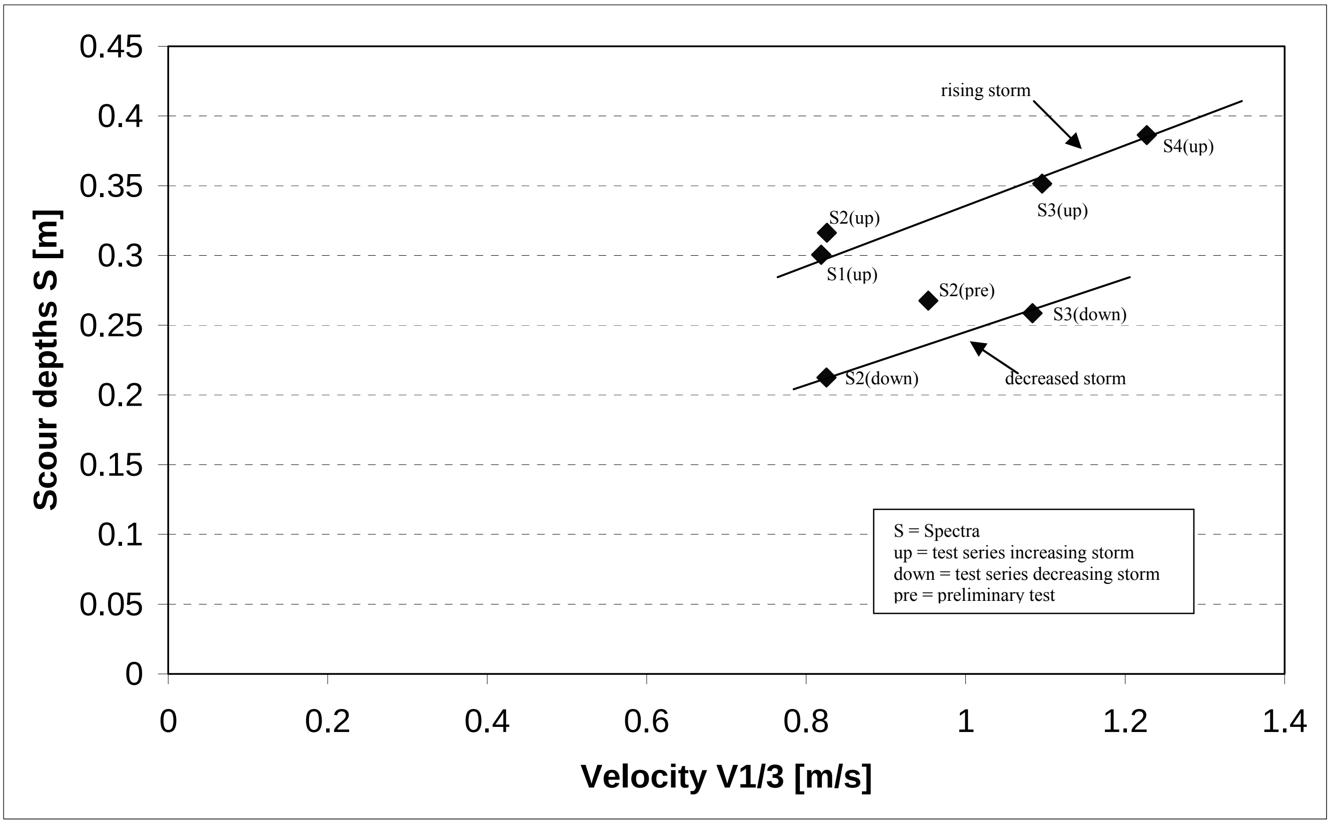

Figure 8: Final scour depths of the several test series of the simulated storm surge.

To compare the test results with previous reported small-scale test results, the Keulegan-Carpenter number *KC* (Eq. 3) was calculated with different characteristic velocities and wave periods. Selected results of the calculated *KC* numbers are shown in Table 3.

For calculating the *KC* numbers firstly the characteristic values v_{rms} and T_p (Eqs. 4 and 5) as used by Sumer and Fredsøe (2001) are adopted. Furthermore, *KC* was calculated with the velocities v_{+max}, $v_{+1/3}$ or v_{+m} and with the wave periods T_m and T_p. The characteristic velocities, evaluated in the time domain, are defined as follows: v_{+max}= the highest velocity value during the test, $v_{+1/3}$= the mean value of the one third highest velocities and v_{+m}= the mean velocity value. The mean wave period (T_m) was evaluated in time domain, the spectral peak wave period (T_p) in frequency domain.

Table 3. Calculated KC number using different characteristic wave parameters.

Test series no.	$v_{+max}*T_p/D$	$v_{+m}*T_p/D$	$v_{rms}*T_p/D$	$v_{+max}*T_m/D$
Spectrum 2 (preliminary test)	20.06	8.16	7.69	17.76
Spectrum 1 (increasing storm)	18.35	6.29	6.19	16.19
Spectrum 2 (increasing storm)	20.43	7.18	7.08	18.04
Spectrum 3 (increasing storm)	28.83	11.10	9.32	22.63
Spectrum 4 (increasing storm)	31.83	12.49	10.05	26.90
Spectrum 3 (decreasing storm)	25.44	10.81	9.12	20.31
Spectrum 2 (decreasing storm)	19.27	7.29	7.13	14.40

The relative scour depths *S/D* measured in GWK and in the small-scale tests by Sumer and Fredsøe (2001) are plotted in Figure 9 versus the *KC* numbers calculated with different parameters in Figure 9. The values of the *KC* number calculated by different parameters differ significantly.

In Figure 10 the relative scour depth *S/D* measured in the GWK, are compared with the calculated ones with the formula of Sumer et al. (1992) (Eq. 2) using both the parameters v_{rms} and T_p applied by Sumer and Fredsøe (2001) and the parameters v_{+max} and T_m, which lead to the best correlation. The calculated scour depths *S/D* using the parameters v_{+max} and T_m, lead to an underestimation of the scour depth and therefore these parameters are not appropriate for the GWK data.

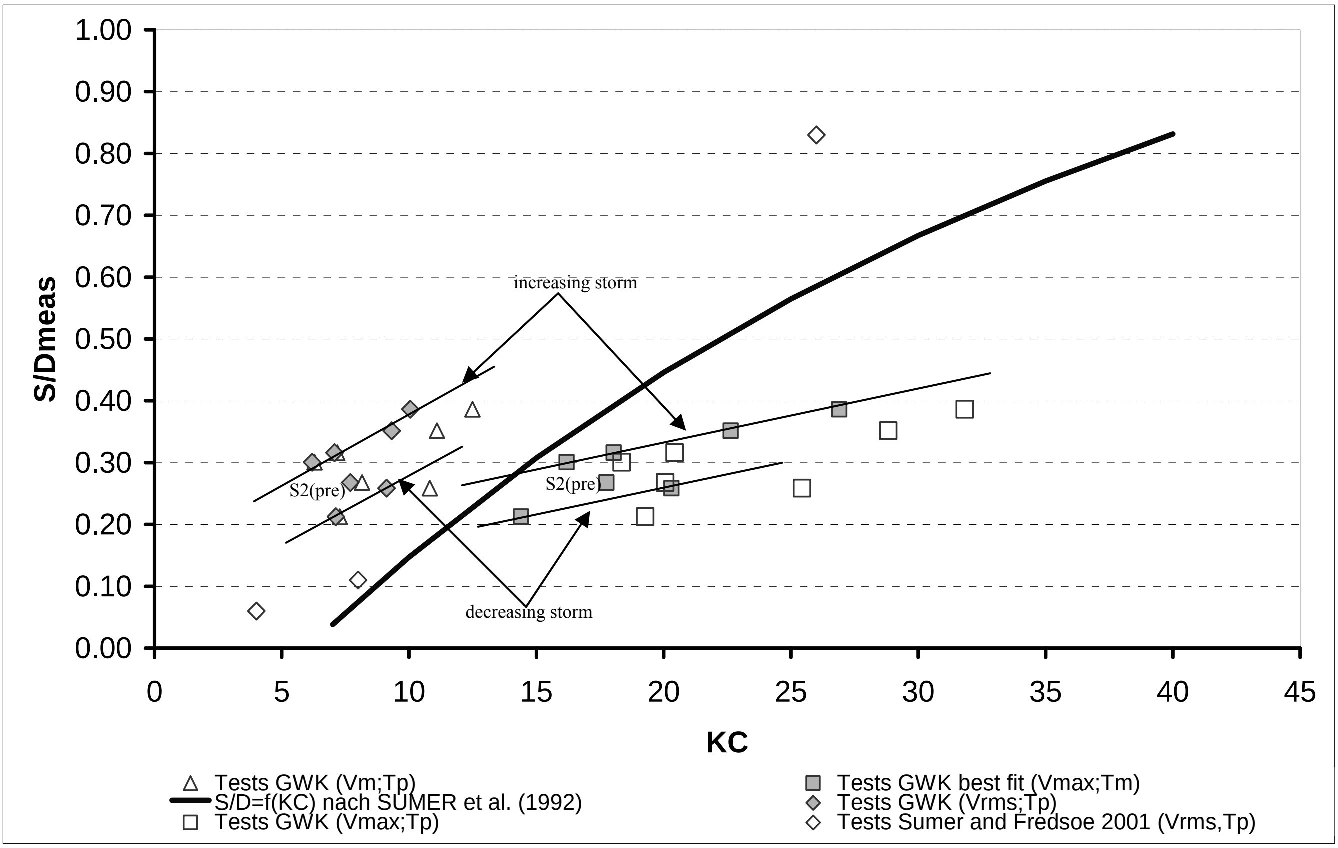

Figure 9: Measured S/D of GWK tests and small scale tests of Sumer and Fredsøe (2001) for different definitions of KC number.

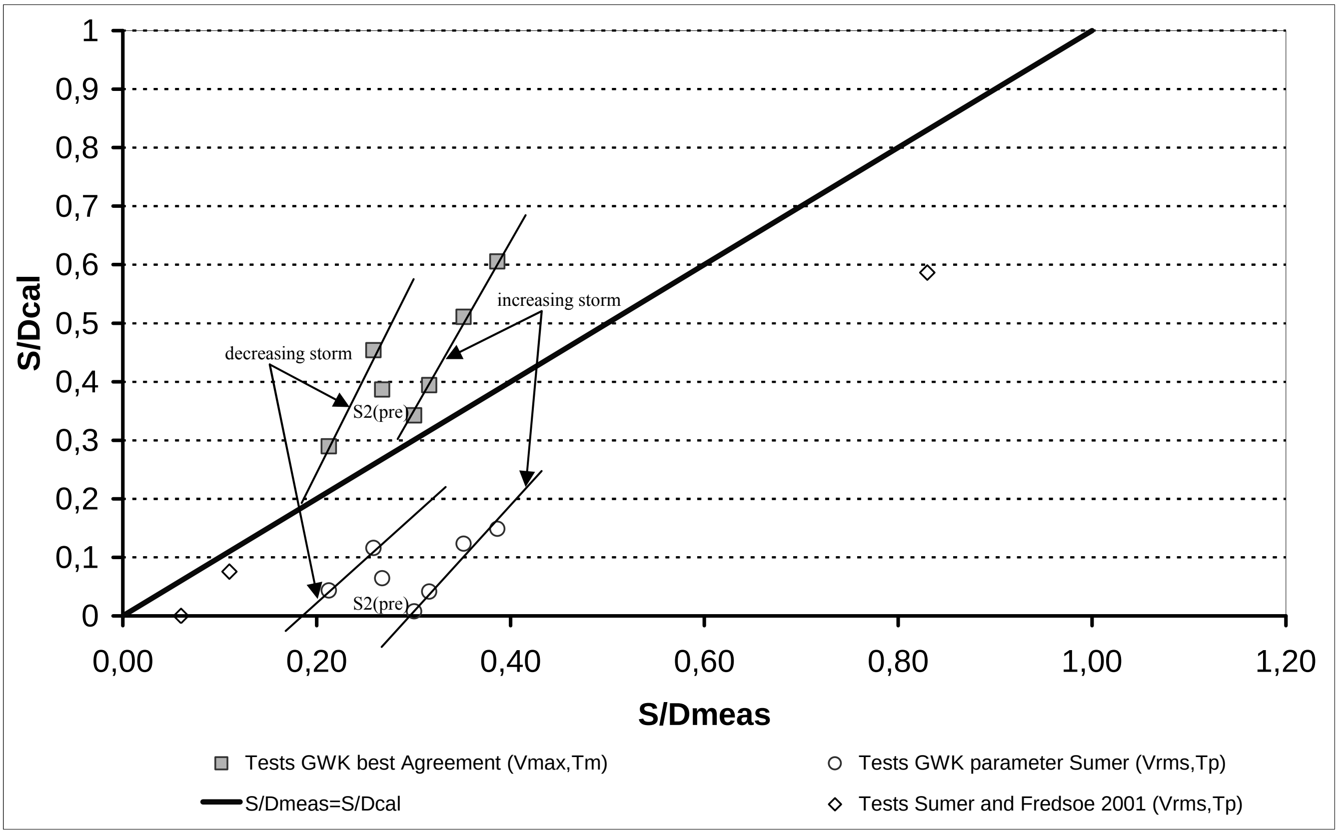

Figure 10: Comparison between calculated and measured scour depths from GWK tests and small-scale tests of Sumer and Fredsøe (2001) using different parameters for KC calculation.

At present possible modifications of the formula and additional parameters are being tested. A goal of the ongoing research is to modify the formula using alternative parameter combinations to achieve a better agreement with the measured scour depths of the large-scale tests. Generally, scale effects might be expected. However, the detailed analysis is still ongoing. Final statements about scale effects cannot be given at the moment.

4. Concluding remarks

From the large-scale tests in the GWK the following results were achieved:

- As expected the scour depths increases with increasing wave energy and decreases with decreasing wave energy.
- The development of the scour hole depends on the initial seabed conditions around the pile.
- For the initial condition "existing scour hole at starting the test" the scour depth is deeper for tests with increased wave energy compared to those with decreased wave energy.
- Besides the scour processes around the pile sand transport effects are observed, so that the scour hole from the previous test is filled up firstly. However after a while the depth of the scour increases again.
- The filling up of the scour hole has a shorter duration for tests with increased wave energy during the storm compared to those with decreased wave energy, where the sand deposition in the scour hole dominates for a longer time.
- The time duration to achieve the equilibrium scour depth seems to be shorter for tests with increased wave energy than for ones with decreased wave energy.
- The best agreement with the Sumer and Fredsøe formula was achieved with the measured data using v_{+max} and T_m for the KC number instead of v_{rms} and T_p as adopted by Sumer and Fredsøe (2001).
- The results of small-scale tests compared to the large-scale tests seem to be affected by scale effects and will be investigated in more detail within the ongoing research work.

Acknowledgments

The work described in this paper was supported by the European Community's Sixth Framework Programme, Integrated Infrastructure Initiative HYDRALAB III, Contract no. 022441 (RII3) within the Joint Research Activity "CoMIBBS".

References

Carreiras, J., P. Larroundé, F. Seabra-Santos, M. Mory. 2000. 'Wave scour around piles'. Proceeding of the International Conference on Coastal Engineering (ICCE), Sydney, pp 1860-1871.

Rudolph, D., K.J. Bos. 2006. 'Scour around a monopile under combined wave-current conditions and low KC-numbers'. Proceedings of the International Conference on Scour and Erosion (ICSE), Amsterdam.

Sumer, B.M., J. Fredsøe. 2001. 'Scour around pile in combined waves and current'. Journal of Hydraulic Engineering, 127, 5, pp 403-411.

Sumer, B.M., R.J.S. Whitehouse, A. Torum. 2001. 'Scour around coastal structures: a summary of recent research'. Journal of Coastal Engineering, 44, pp 153-190.

Sumer, B.M., J. Fredsøe. 1999. 'Hydrodynamics around cylindrical structures'. Technical University of Denmark, Advanced Series on Ocean Engineering, 12, World Scientific, Singapore.

Sumer, B.M., J. Fredsøe, N. Christiansen. 1992. 'Scour around vertical pile in waves'. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, 118, 1, pp 15-31.