LARGE-SCALE MODEL STUDY ON SCOUR AROUND SLENDER MONOPILES INDUCED BY IRREGULAR WAVES

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Physical large-scale tests on Scour around a slender vertical monopile by irregular waves were carried out in the Large Wave Channel (GWK) of the Coastal Research Centre (a joint institution of both universities Hannover and Braunscheig). The objective is to classify the shape and the magnitude of scour as a function of incident wave climate characteristics. The results of the large-scale laboratory tests are used in order to validate available formulas for predicting scour depth. The design water depth (20 m) and wave conditions (H_s = 7.5 m) of a common offshore wind farm in the German Bight of the North Sea were tested. It was found that for these conditions only small scour depths occurred which however grow with increasing wave height and wave period. The test results present certain variations compared to small-scale test results of Sumer and Fredsøe (2001) probably due to scale effects.

INTRODUCTION

This study analyses local scour development around a vertical slender monopile induced by irregular waves under live bed conditions. Such scour may occur for example 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) and a nationally funded (BMU, Germany) project. Both projects are aimed at testing scour development while the latter is also aimed at tested different alternatives for scour protection.

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, whereas wave induced flow in exposed areas represents the primary cause of scour. 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.

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

$$KC = \frac{v * T}{D} \tag{1}$$

(with v = maximum value of the outer 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:

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

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:

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

Calculated using the following input characteristics for 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 large-scale tests in GWK on scour around a vertical slender monopile are compared to the results of the small-scale tests of Sumer and Fredsøe (2001). Furthermore the most appropriate characteristic orbital velocity as well as the characteristic wave period to estimate the Keulegan Carpenter number KC are discussed.

EXPERIMENTAL SETUP 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 a useable length of 307 m. During the tests a sand bed of roughly 2 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 4.10 m (2.10 m above sand bed). The temperature of the water was 4 degree Celsius so that the density ρ was $\approx$1,000 kg/m³.

The waves generated are both regular and irregular (Jonswap spectra). The installed power of the piston type wave generator combined with an upper flap is about 900 kW. The gearwheel driven carrier gives a maximum stroke of ±2.10 m to the wave paddle. The stroke can be superimposed by upper flap movements of ± 10 degree in order to simulate natural water wave kinematics most accurately.

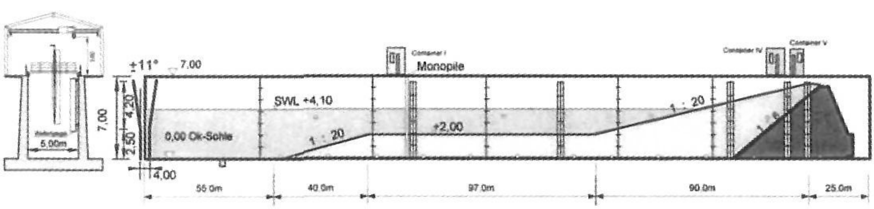

Figure 1: Large Wave Channel (GWK) with installed monopile and sand bed.

The tests were carried out in four test series with varying wave parameters. For the first test series the design sea conditions (scaled 1:10 to: H_s = 0.75 m; T_p = 5.04 s; h = 2.10 m) of a planned wind farm in the North Sea were generated. The further test series were performed with increased wave conditions. Before starting a test series the sand bed was flattened and the scour development started with an even bottom around the pile. The several generated wave parameters are illustrated in Table 1.

Table 1. Test series and parameter varieties

Test Series	1	2	3	4
Significant wave height $H_{1/3}$ [m]	0.75	0.80	0.90	1.00
Spectral peak period T_p [s]	5.04	6.66	7.60	8.60
Water depth h [m]	2.10	2.10	2.10	2.10
Pile diameter D [m]	0.55	0.55	0.55	0.55
Scour profile measurement after N waves	1,000 2,000 3,000 6,000 9,000	3,000 6,000	3,000 6,000	6,500

Figure 2(a) shows the installed monopile and the initial sand bottom before a test series. The transducers to measure the orbital velocity at different elevations and the wave gauges are indicated. Figure 2(b) shows the experimental set-up during a test with breaking wave conditions at the monopile.

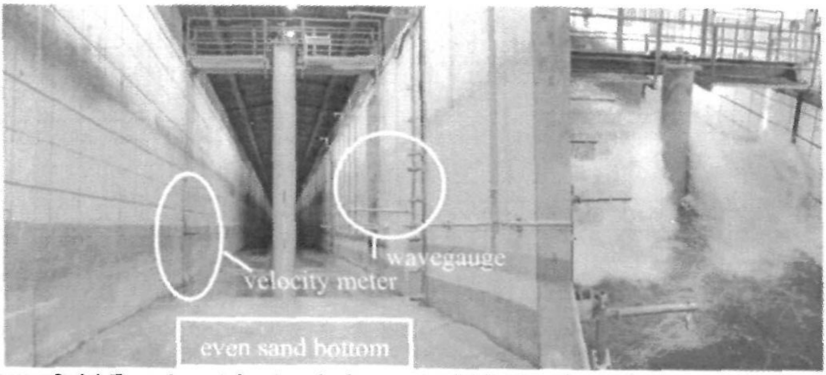

Figure 2: (a) Experimental set-up before tests; (b) During the tests.

During the first test series the development of the scour in time was recorded in different time intervals (5 times, after 1,000 to 9,000 waves as listed in Table 1). The time history of the scour depth is shown in Figure 3.

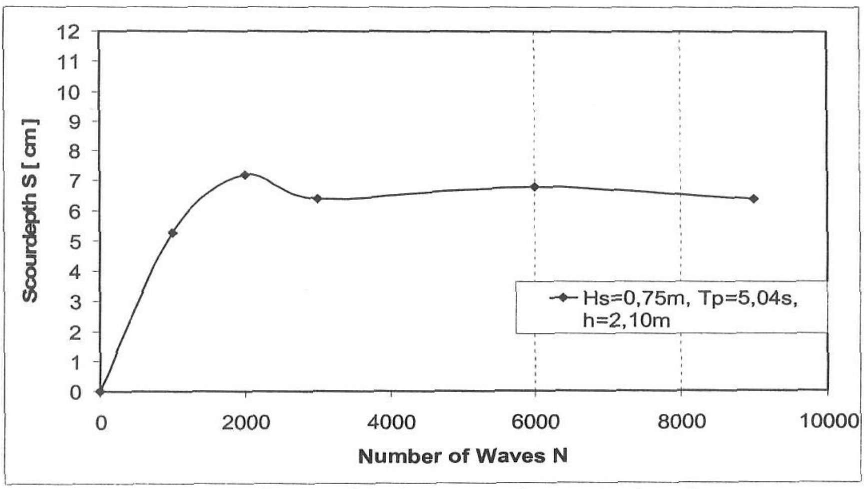

Figure 3: Measured scour depths of the first test series vs. number of waves.

It was found that the equilibrium scour depth is achieved after 3,000 waves for the design wave conditions (test series 1, see Table 1). So the following test series were interrupted to record the scour evolution after 3,000 and 6,000 waves, except the last series with one levelling after 6,500 waves.

To record the scour evolution during and after the test series several surveys were done. For the surveys the test series were interrupted and the water was drained off. The surveys were done as a geodetic measurement of the sand bed level, using a grid, around the monopile and its vicinity. With these level data from the grid a three-dimensional sand bed profile was created using a computer program, as shown in Figure 4. The shape of the scour increases exponentially with increasing wave intensity.

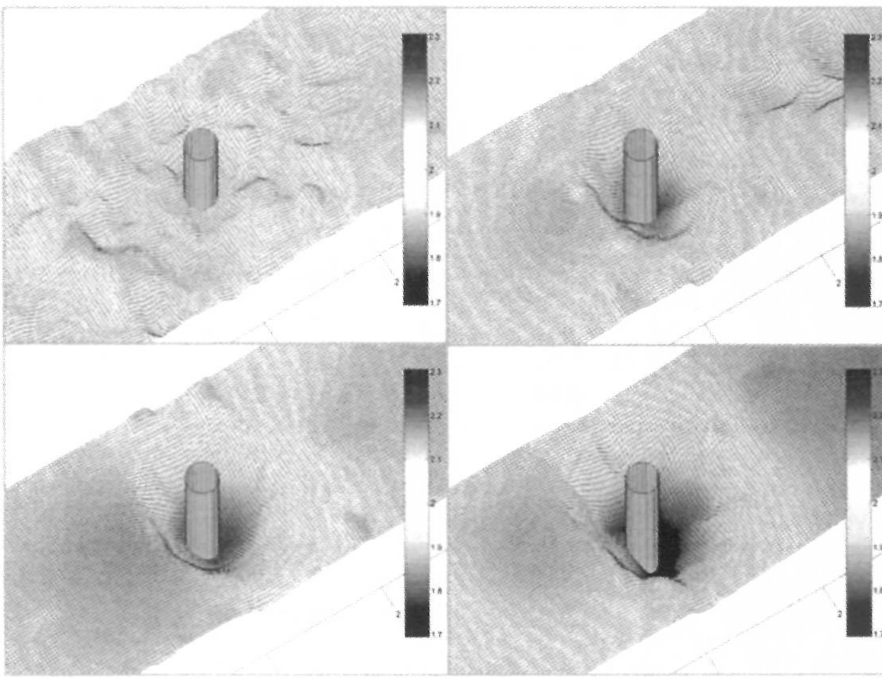

Figure 4: Profiles of the sand bed for all test series (up left – test series 1 after 6,000 waves, up right – test series 2 after 6,000 waves, down left – test series 3 after 6,000 waves, down right – test series 4 after 6,500 waves)

During the tests increasing sand transport processes from the slope in front of the monopile were observed with increasing wave parameter values. Thus, a correction of the initial state of the sand bed level was required. For each test the elevation of the sand bed was determined and the according reference level for the final evaluation of the scour depth was modified as shown in Figure 5 exemplarily.

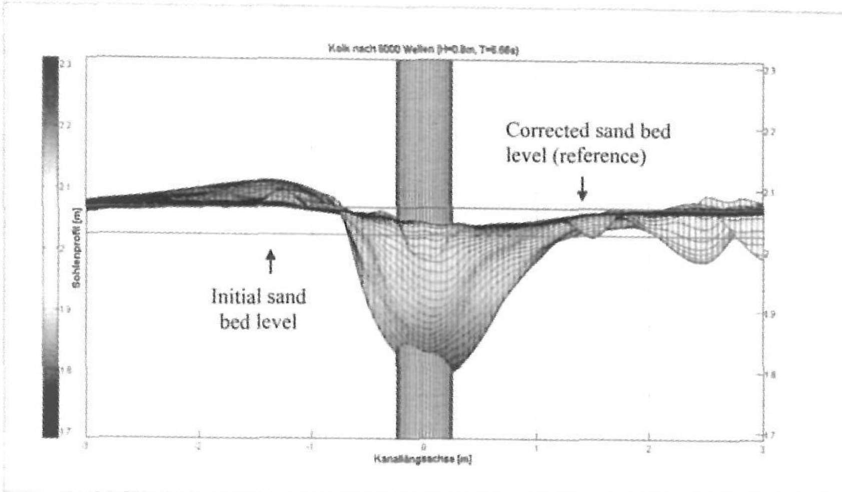

Figure 5: Modification of the initial state of the sand layer to find the correct reference level for evaluating the scour depth.

TEST RESULTS AND DISCUSSION

Some results of the test series are presented in Table 2. It was observed that for the design wave conditions of the test series 1 in Table 1 the scour depth remains relatively small, so that it was difficult to distinguish the scour hole from the ripple development around the pile. For the further test series increasing scour depths with increasing incident wave conditions were observed.

Table 2: Measured wave parameters, scour depths and sand profiles during the Tests (see also table 1)

Test series number	No. of waves N	$H_{1/3}$	$V_{+1/3}$	T_p	mod. scour depth S	mod. scour depth S/D	Profile of sand bed
	[-]	[m]	[m/s]	[s]	[m]	[-]	[-]
Test series 1	Sand bed back to the initial state (07.11.2006)						
15110602	3,000	0.84	0.83	5.31	0.08	0.1500	X
20110604	6,000	0.86	0.86	5.01	0.08	0.1495	X
Test series 2	Sand bed back to the initial state (28.11.2006)						
29110606	3,000	1.03	1.05	6.39	0.22	0.3986	X
04120603	6,000	1.03	1.02	6.90	0.23	0.4264	X
Test series 3	Sand bed back to the initial state (06.12.2006)						
07120607	3,000	1.21	1.22	8.16	0.29	0.5214	X
11120606	6,000	1.21	1.21	7.60	0.27	0.4977	X
Test series 4	Sand bed back to the initial state (14.12.2006)						
20120607	6,500	1.40	1.44	8.93	0.33	0.6023	X

The measured and modified scour depths were related to the pile diameter D as proposed for instance by Sumer et al. (1992). To compare the test results with previous reported small-scale tests results, the Keulegan-Carpenter number was calculated with different characteristics of the orbital velocity and wave period. Selected results are shown in Table 3.

First the characteristic values as used by Sumer and Fredsøe (2001) with v_{rms} and T_p (Eqs. 4 and 5) are adopted to calculate KC. Furthermore, KC was calculated from the measured velocities v_{+max}, $v_{+1/3}$ and v_{+m} plus the measured wave periods T_m and T_p. The velocity parameters were evaluated from the time domain with v_{+max}= the highest velocity value during the test, $v_{+1/3}$= the mean value of the one third highest velocities during the tests and v_{+m}= the mean velocity value as well as T_m = mean wave period, whereas T_p= spectral peak wave period was evaluated from the frequency domain. The results for KC vary significantly with increasing wave energy as shown in Table 3.

Table 3: Calculation of the KC number using different characteristics of the incident wave parameters

Test series	$v_{+max}*T_p/D$	$v_{+m}*T_p/D$	$v_{rms}*T_p/D$	$V_{+max}*T_m/D$
Test series 1 3,000	12.20	4.92	4.90	10.74
Test series 2 3,000	22.69	8.26	6.93	18.97
Test series 3 3,000	26.22	10.68	9.07	21.70
Test series 1 6,000	12.18	4.91	4.82	10.85
Test series 2 6,000	22.20	8.06	6.80	18.88
Test series 3 6,000	26.34	10.50	8.98	22.19
Test series 4 6,500	38.95	14.66	11.02	33.26

To identify the appropriate KC-number the relative scour depths were calculated with the formula of Sumer et al. (1992) (Eq. 2) and compared with the measured related scour depths. Figure 6 shows the calculated relative scour depth S/D using the parameter definition of Sumer and Fredsøe (2001) and the best agreement with the measured scour depths (v_{max}, T_m). A strong deviation of the Sumer/Fredsøe parameter can be identified; i.e. the formula underestimates the scour depth for most of the wave conditions tested.

Based on these results it can tentatively be concluded that the characteristic values used for the KC number by Sumer and Fredsøe (2001) are not appropriate. A more appropriate choice would be the maximum orbital velocity v_{+max} and the mean wave period T_m instead of the characteristic values used for the small-scale tests carried out by Sumer and Fredsøe (2001).

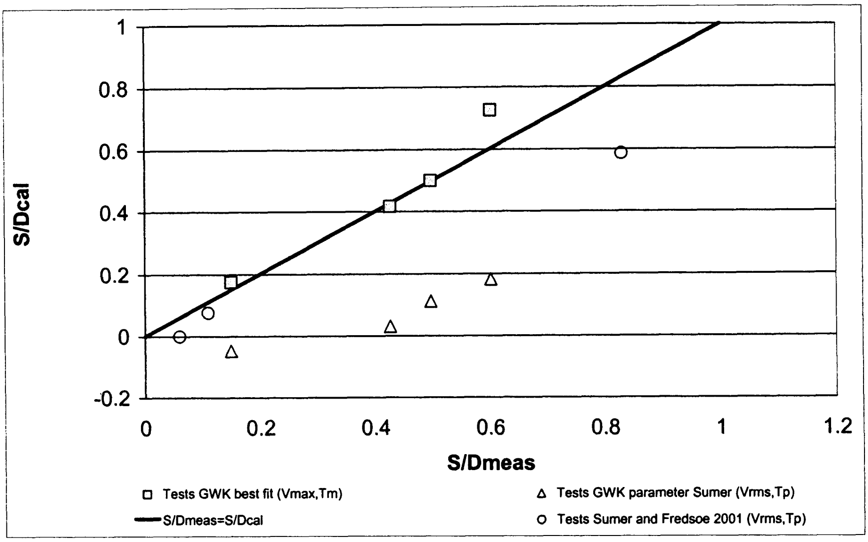

Figure 6: Comparison between calculated and measured scour depths from GWK tests and small-scale tests of Sumer and Fredsøe (2001).

The relative scour depth *S/D* measured in GWK and in small-scale tests by Sumer and Fredsøe (2001) are compared with calculated values using different definitions of the *KC* number in Figure 7, where the deviations of the KC number calculated by the formula of Sumer and Fredsøe (2001) using different velocity and wave parameter come out clearly.

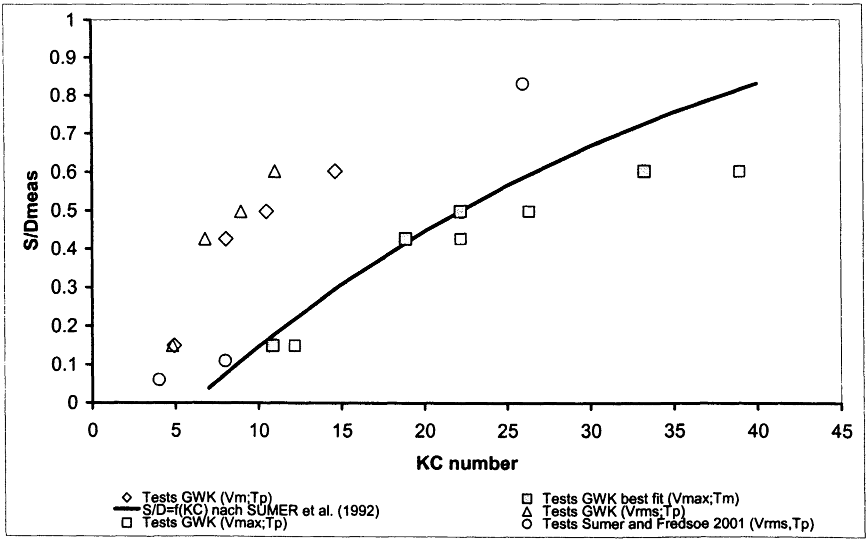

Figure 7: Measured S/D of GWK tests and small scale tests of Sumer and Fredsøe (2001) for different definitions of KC number.

Generally, scale effects could be expected. However, the analysis related to scale effects is still in progress and the results will be published in a forth coming paper.

CONCLUDING REMARKS

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

- As expected the relative scour depth *S/D* increases exponentially with *KC*, thus confirming the scour formula by Sumer and Fredsøe (2001).
- A good agreement with the Sumer and Fredsøe formula was achieved with the measured date using v_{+max} and T_m for the *KC* number instead of the values v_{rms} and T_p adopted by Sumer and Fredsøe (2001).
- The development of the scour hole depends on the initial seabed conditions around the pile. The effect of the initial conditions on the scour depth increases with the incident wave energy.
- The published results of small-scale tests compared to the large-scale tests are affected by scale effects, but before stating final conclusions the still ongoing analysis has to be finished.

A comparison with further large-scale tests in the GWK is being continued. The initial sea bed conditions were modified, so that in the additional tests the scour development with an existing scour before starting the tests can be analysed. Furthermore these tests will also be used additionally to analyse scale effects.

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REFERENCES

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

Rudolph, D., K.J. Bos. 2006. Scour around a monopile under combined wave-current conditions and low KC-numbers. *Proceeding 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), 403-411.

Sumer, B.M., R.J.S. Whitehouse, A. Tørum. 2001. Scour around coastal structures: a summary of recent research, *Journal of Coastal Engineering*, 44, 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), 15-31.