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EXPERIMENTAL STUDY ON THE EROSION STABILITY OF COARSE GRAIN MATERIALS UNDER WAVES

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EXPERIMENTAL STUDY ON THE EROSION STABILITY OF COARSE GRAIN MATERIALS UNDER WAVES

Alexander Schendel[1], Nils Goseberg[1, 2], and Torsten Schlurmann[1]

Key words: scour protection, hydraulic model test, wide-graded grain material, erosion stability.

ABSTRACT

Large-scale hydraulic model tests were carried out by the Leibniz University of Hannover, Germany to investigate the performance of wide-graded grain materials (0.1-200 mm) as scour protection system tested under spectral wave loads. The model tests were conducted in the Large Wave Flume (GWK) of the Forschungszentrum Küste (FZK) assuming a length scale of 1:4. The experimental setup consisted of a single layer material bed protecting a monopile (D = 1 m) as often used as offshore supporting structure. In order to measure the structure-induced scour development around the monopile acoustic backscatter systems (ABS), single-beam echosounder, and a 3D laser scanner were used. Matching environmental conditions of the North Sea, the model tests were carried out with spectral wave load (JONSWAP-spectra) and successively increasing significant wave heights up to H_s = 1.3 m. As result, a maximum scour depth of S/D = 0.161 was found after 9000 waves which resembled a synthetic storm duration of 20 h. The results indicate high stability against spectral wave load and demonstrate the capability of wide-graded material to perform reasonably well under wave loads, particularly applied in a dynamic design of scour protection.

I. INTRODUCTION

As a result of the advancing expansion of Offshore Wind Energy Converters (OWEC), the need for innovative and flexible scour protection systems increases in order to guarantee long-term operation of supporting structures in various locations. Due to their versatility and cost efficiency wide-graded material mixtures, mainly composed of natural, crushed quarry stone material, are considered as a potential scour protection system, which meet the desired requirements. To date fundamental research studies, which can verify the stability of these wide-graded material mixtures under offshore conditions as well as their actual performance as scour protection system, are however limited. The applicability of existing approaches and guidelines for the design of scour protection for offshore supporting structures has not yet been proven. The numerous studies on the erosion stability of wide-graded material mixtures (e.g. Kuhnle, 1993) are mostly based on fluvial erosion and sedimentation processes and still considering the classic Shields approach (Shields, 1936). Due to the restrictions associated with the single grain approach proposed by Shields (1936) in contrast to the large variability of the newly scrutinized material presented herein, his results cannot be transferred directly to the stability of wide-graded quarry stone materials under offshore conditions. In light of this situation, industry-funded large-scale hydraulic model tests were conducted by the Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz University Hannover, Germany, in order to fundamentally investigate erosive potentials, bed stability and the performance as scour protection of wide-graded material mixtures. On this basis safer and more economic design criteria for scour and bed protection may be accomplished. The two phase test program contained the quantitative determination of bed stability of a wide-graded grain material under unidirectional flow conditions (phase 1, cp. Schendel et al., 2015) and, in addition, the assessment of the performance as adaptable and "low-regret" scour protection for maritime structures under typical wave loads (phase 2).

This paper focuses on the second test phase, which contained hydraulic model tests in the Large Wave Flume (GWK) of the Forschungszentrum Küste (FZK) in Hannover.

II. EXPERIMENTAL SETUP

The hydraulic model tests were carried out in the GWK of the FZK in a length scale of 1:4. This model scale was chosen to account for scaling and model effects, particularly with regard to the unique sediment properties. The investigated

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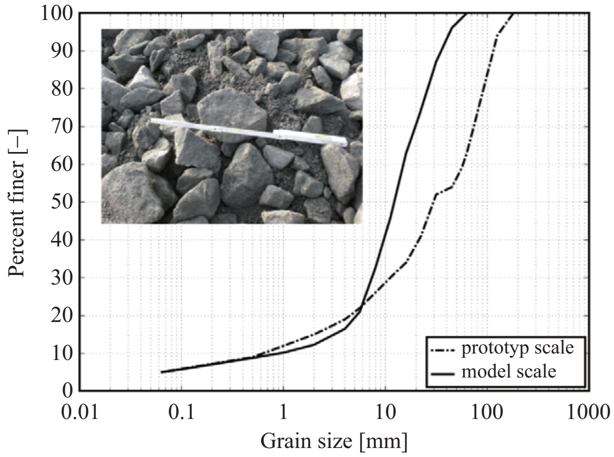

Fig. 1. Prototype and scaled-down grain size distribution of the tested wide-graded grain material.

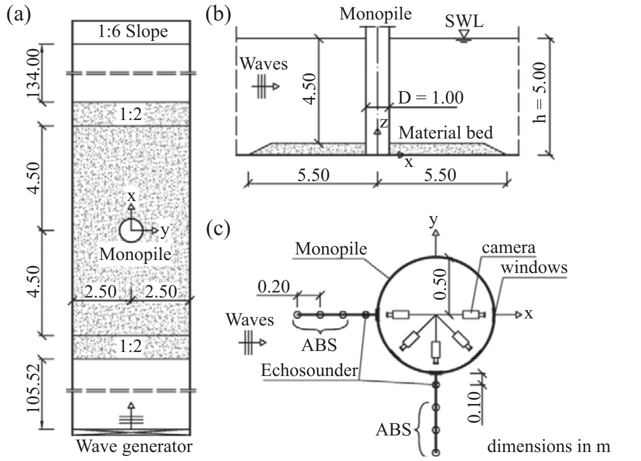

Fig. 2. Sketch of the experimental setup: (a) Top view; (b) Side view; (c) Placement of measurement devices around the monopile.

material was a homogeneous wide-graded quarry stone material made of Jelsa-Granodiorite with a grain size distribution of 0.1-200 mm. Due to the abundance of finer fractions within the grain size distribution and the sharp-edged grain shapes, the tested material differed significantly from material mixtures used in previous studies. Fig. 1 shows the grain size distribution of the prototype material and of the scaled material, according to the model scale of 1:4.

Dimensions of the GWK are 307 m in length, 7 m in height and 5 m in width. Waves are generated by a piston type wave generator with a maximum stroke of ± 2.1 m. Regular waves up to a height of 2.00 m and wave spectra with a maximum significant wave height of H_s = 1.3 m can be generated under prototype conditions. Furthermore, the wave maker is able to filter re-reflections by an active absorption system.

The experimental setup consisted of two independent sections. While the first section provided the assessment of the general bed stability of the wide-graded material under spectral wave load, the second section (Fig. 2 and Fig. 3) followed the investigation of the structure-induced scour and protection around a monopile-support structure. The present paper only refers to the results of the second section; the setup of the first part is neglected for space restrictions. The setup for the second section included a monopile as offshore foundation structure with a diameter of D = 1 m. The monopile was placed in the middle of a single layer material bed made of the wide-graded material mixture. The material bed was installed with a layer thickness of 0.50 m over a length of 9 m and ended on both sides of the wave flume. It should be noted that with this setup the negative effects of secondary scours at the edge of the scour protection, winnowing failure and material sinking to the underlying sediment were prevented (Chiew, 1995; Whitehouse, 1998; Sumer and Nielsen, 2013). Considering the intended application of the wide-graded material as one-layer scour protection system the filter stability and the associated failure mechanism, winnowing and sinking, are of major importance and should be investigated in future studies.

Fig. 3. Picture of experimental setup. Waves are propagating in viewing direction.

For the continuous measurement of water surface elevation a total number of 20 wire-type wave gauges were installed along the flume side. The measurement of the scour process and the general material displacement around the monopile was accomplished by the combination of acoustic backscatter systems (ABS), single-beam echosounder and the first-time application of a high resolution 3D laser scanner (FARO Focus^{3D}). The high resolution scans (accuracy up to ± 2 mm, depending on the distance to the object) by the laser scanner enabled the determination of smallest displacement processes on the bed, which is a very useful feature when dealing with coarse grain materials. In addition, the bed movement during the tests could be observed with five underwater cameras in the monopile. The experimental setup as well the placements of the measurement devices are shown in Fig. 2.

Table 1. Test conditions for scour tests under spectral (JONSWAP) wave loads in model scale. U_m is calculated by linear wave theory with $H = H_s$ and $T = T_p$.

Spectrum	Wave length L [m]	Significant wave height H_s [m]	Peak wave period T_p [s]	Maximum horizontal orbital velocity at the bed U_m [m/s]	Keulegan-Carpenter number KC [-]
1	53.1	0.7	8.0	0.51	4.1
2	53.1	1.0	8.0	0.73	5.9
3	53.1	1.3	8.0	0.96	7.6

In order to simulate environmental conditions of the North Sea, the model tests were carried out with spectral wave load (JONSWAP-spectra with $\gamma = 3.3$). The significant wave height H_s was successively increased in three steps from 0.7 m to 1.3 m with a constant peak period T_p of 8 s. For each spectrum a total amount of 3000 waves was generated. The water depth d remained constant throughout the entire test program at 5 m above the flume bed. The ABS and echosounder devices allowed a continuous measurement of the scour development, but only at fixed positions close to the monopile. On the other hand, the laser scanner captured the whole setup, but in order to use the 3D laser scanner the water had to be drained. Therefore, only three laser scans became available for each wave spectrum. Table 1 lists the test conditions used for the subsequent experiments.

III. QUALITATIVE MATERIAL PERFORMANCE

In this chapter qualitative observations of the general material behavior under wave load are presented based on camera coverage during the model test.

While the scour development induced by the first wave spectrum was relatively small and a distinct position of a maximum scour could not be determined visually, the scour development increased significantly during the second wave spectrum along with the higher H_s values. Despite the further development of the scour depth during the third spectrum an overall high stability under wave loads can generally be attributed to the material. To demonstrate this observation the minor scour development at the end of the test is shown in Fig. 4. Moreover, tendencies of a developing armour layer on the bed surface were already visible after the first wave spectrum with $H_s = 0.7$ m (cp. red circle in Fig. 5), which is consistent with results from previous model tests with unidirectional flow conditions (Schendel et al., 2015). Related to this a moderate sorting of material fractions, especially around the monopile, was found. As illustrated in Fig. 5, a deposition of finer material fractions occurred directly at the sides of the monopile (blue circle). In contrast, coarser material fractions concentrated in a wider radius around the monopile (yellow circle in Fig. 5).

The development of the deposition of finer fractions at the sides of the monopile could also be followed closely by the cameras mounted in the monopile (Fig. 6).

Fig. 4. Final scour development around the monopile after 9000 waves and maximum significant wave height $H_s = 1.3$ m. Waves are propagation in viewing direction.

Fig. 5. Tendencies of an armour layer development (red circle), deposition of finer fractions on the sides (blue circle) and coarser fractions (yellow circle) around the monopile after 3000 waves with $H_s = 0.7$ m. Waves are coming from the left side.

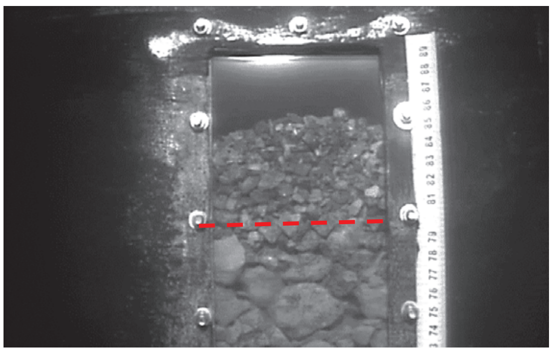

Fig. 6. Deposition of finer fraction at the sides of the monopile after 3000 waves with $H_s = 0.7$ m. Red line indicates initial bed level.

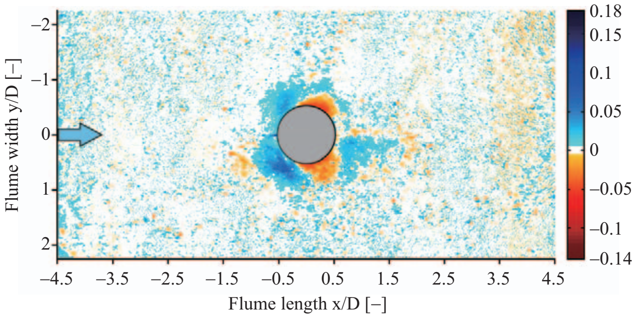

Fig. 7. Scour development in S/D after 3000 waves with H_s = 0.7 m (spectrum 1).

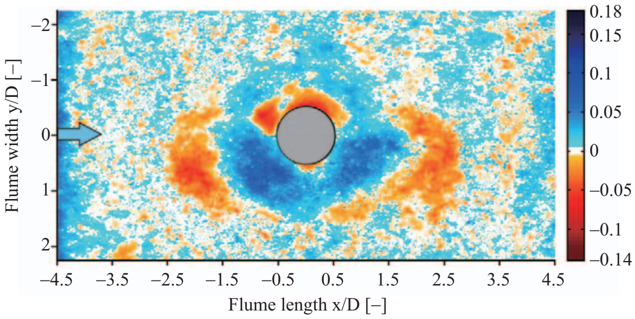

Fig. 8. Scour development in S/D after additionally 3000 waves with H_s = 1.0 m (spectrum 2).

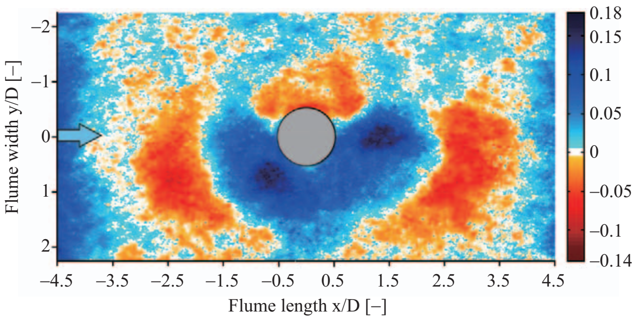

Fig. 9. Final scour development in S/D after additionally 3000 waves with H_s = 1.3 m (spectrum 3).

IV. SCOUR DEVELOPMENT

The Figs. 7-9 exemplarily show the scour development around the monopile based on the laser scans. In these figures erosion is represented with blue colors, while deposition is plotted in red colors. In order to account for potential measuring uncertainties, only changes in bed topography greater than ± 5 mm were considered.

Within the first spectrum (H_s = 0.7 m) a symmetrical scour developed around the monopile with maximum scour depths in front and depositions and both sides of the structure (Fig. 7). As a result of the second spectrum (H_s = 1.0 m) the maximum scour depth diagonal in front of the monopile increased. In addition, a second concise scour was formed on the back side

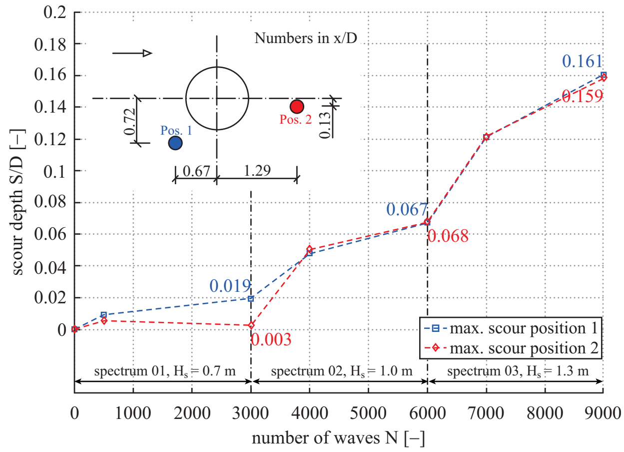

Fig. 10. Combined development of maximum scour depth for position 1 (blue) and position 2 (red), combined for all wave spectra.

of the monopile. Furthermore, the increased load lead to an asymmetrical scour pattern in wave direction. The inhomogeneous material composition as well as an unavoidable spatially varying compaction during the installation of the material in the flume may be possible explanations for the asymmetrical scour pattern. Apart from that, a typical radial scour around the monopile evolved in the course of the third wave spectrum with H_s = 1.3 m. Moreover, two positions with almost identical maximum scour depth could be identified. The first position (pos. 1, cp. Fig. 10) is located diagonal in front of the monopile at x/D = 0.67 and y/D = 0.72 in relation to the center of the monopile. The second (pos. 2, cp. Fig. 10) is placed behind the monopile at x/D = 1.29 and y/D = 0.13. The increase of the maximum scour depth for all three wave spectra is presented in Fig. 10 and in detail in Table 2. Since the ABSs and echosounder were not able to measure the maximum scour depth the displayed development of the maximum scour depth is based on the laser scanner data only. Due to the successive wave load with increasing H_s, the combined development of the maximum scour depth for all three spectra is given in Fig. 10.

In the beginning of each spectrum, and thus with every step up of H_s, the maximum scour depth increased considerably. In the further course of a spectrum the increase of scour depth slowed down. In summary, a maximum scour depth of S/D = 0.161 could be concluded after 9000 waves and a simulated storm duration of 20 h with a maximum significant wave height of H_s = 1.3 m. Thus, the maximum scour depth is found to be an order of magnitude below practical design approaches for scour depth estimation at monopiles with S/D = 1.3 (DNV, 2010) or S/D = 2.5 (GL, 2005).

However, it should be noted that a wave load of 3000 waves for each wave spectrum has proven to be insufficient to achieve an equilibrium scour depth, so that a further increase of scour depth with ongoing wave load has to be assumed. Since no reliably data for the scour protection potential of such material was available, the determination of the required amount of

Table 2. Maximum scour depth and accumulated maximum scour depth for position 1 and position 2 for every measurement based on laser scanner data.

Spectrum	Number of waves	Position 1: Maximum scour depth S/D_{max} [-]	Position 1: Cumulative maximum scour depth $\Sigma\ S/D_{max}$ [-]	Position 2: Maximum scour depth S/D_{max} [-]	Position 2: Cumulative maximum scour depth $\Sigma\ S/D_{max}$ [-]
1	500	0.009		0.006	
	2500	0.010	0.019	-0.003	0.003
2	1000	0.029		0.048	
	2000	0.019	0.048	0.017	0.065
3	1000	0.054		0.054	
	2000	0.040	0.094	0.037	0.091
Σ	9000		0.161		0.159

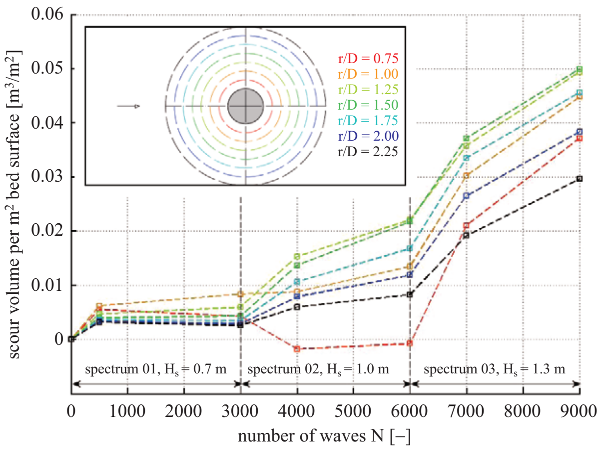

Fig. 11. Development of scour volume around the monopile with increasing number of waves based on laser scanner data.

waves in order to reach an equilibrium state was based on the temporal scour development in sand beds. As a result of internal time constrains an increase in the number of waves was not feasible during and after the experiments. The detailed development of scour depth for each wave spectrum can be taken from Table 2.

By cumulating the scour processes over the considered bed surface around the monopile the displaced scour volume is calculated. Fig. 11 shows the cumulated scour volume in dependency to the radial distance r/D to the monopile center. As before with the development of the maximum scour depth, the amount of eroded scour volume increased at the beginning of each wave spectrum. Here, the highest displaced scour volume per m^2 surface area could be determined within a distance of r/D = 1.5 to the center of the monopile. Beyond this distance the scour volume decreased, due to the deposition of material at a distance of r/D = 2 (Fig. 8 and 9).

The development of the scour volume at a distance of r/D = 0.75 (red curve in Fig. 11) indicates the described deposition of finer material fractions directly at the sides at the monopile. The maximum scour volume after 9000 waves is 0.05 m^3/m^2, so that an average scour depth of 5 cm (model scale) within a radius of r/D = 1.5 can be found as a result of the successively increasing wave load with a significant wave height H_s up to 1.3 m. At this point, the asymmetric scour pattern has to be pointed out again, which influences the calculation of the radial scour volume around the monopile.

V. DISCUSSION

When comparing the results of this study to practical design guidelines for the scour depth estimation at monopile foundation (GL, 2005; CERC, 2006; DNV, 2010) it has to be taken into account, that these guidelines refer to combined current and wave conditions and to an already obtained equilibrium scour depth. In this present study the wave loads exerted to the monopole and bed supposedly did not act long enough to achieve an equilibrium scour depth. Whether the results can be considered as an additional stability criteria or whether the measured scour development is a sole result of the applied wave load has to be clarified in further studies. Yet, the upscaled storm duration matches typical North sea storm events indicating that our results provide unique guidance unless more detailed research becomes available.

A direct comparison of the results to approved approaches from the literature on maximum scour depth (Sumer et al., 1992; Melville and Coleman, 2000; Sumer and Fredsøe, 2001; Zanke et al., 2011) or time scale of scour development (Sumer and Fredsøe, 2002) is problematic due to highly divergent material properties and the successive wave load. Additionally, the hydraulic model tests were conducted in the GWK with a relatively large model scale, so that different scaling and model effects have to be considered compared to small scale model tests.

VI. CONCLUSIONS

In order to assess the stability and the performance of coarse grain materials as scour protection large-scale hydraulic model tests were carried out in the Large Wave Flume (GWK) by the

Franzius-Institute. The experimental setup consisted of a single layer material bed and a monopile (D = 1 m), which enabled the investigation of structure-induced scour development under wave load. To simulate North Sea environmental conditions, the model tests were carried out with spectral wave load (JONSWAP-spectra) and subsequently increasing significant wave height up to H_s = 1.3 m. In summary, the following results on the stability and scour performance of wide-graded grain materials under spectral wave load can be concluded:

- Tendencies of a stabilizing armour layer development could be observed along with general small changes of the bed topography under wave load.
- Development of a radial structure-induced scour pattern around the monopile, with two positions of almost identical maximum scour depth diagonal in front and on the back side of the monopole was observed.
- A maximum structure-induced scour depth of S/D = 0.161 was found after 9000 waves and a simulated storm duration of 20 h with a maximum significant wave height of H_s = 1.3 m. However, it has to be noted that this scour depth does not represent a final equilibrium scour depth.
- The final eroded scour volume yielded 0.05 m^3/m^2 within a radial distance from the center of the monopile of r/D = 1.5, which corresponds to a mean scour depth of 5 cm around the monopile. The calculation of the scour volume might be influenced by an asymmetrical scour pattern around the monopile in wave direction.

For the first time, this experimental study provides insights in the behavior of coarse grain materials under wave loads and into the capability of this material as scour protection system. The results indicate high stability against spectral wave load for the investigated material and the given test conditions. It demonstrates the capability of wide-graded material to perform reasonably well under wave loads, particularly applied in a dynamic design of scour protection (De Vos et al., 2012), which allows the limited movement of finer stone fractions for certain sea states.

However, a final assessment of the scour performance of wide-graded coarse grain materials requires further fundamental investigation under wave as well as under steady flow conditions. In the case of scour performance under wave load model test with higher KC numbers and longer load duration are needed in order to achieve an equilibrium scour depth and to allow a quantitative comparison with other scour protection systems.

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