INVESTIGATIONS ON SCOUR DEVELOPMENT AROUND A GRAVITY FOUNDATION FOR OFFSHORE WIND TURBINES

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Due to insufficient insights about the scour development around the STRABAG gravity foundation, the Franzius-Institute conducted small- and large-scale physical model tests in wave flumes on a scale of 1:50 and 1:17 in order to investigate the wave-induced scouring phenomena around the foundation and to design a scour protection system. The tests on scour development without a scour protection system show that the main areas which are vulnerable to scour are the contact areas of the foundation. Furthermore, the experiments show that a scour protection system is necessary for the given and investigated wave boundary conditions; the performance of the selected protection system using geotextile sand containers is verified. Additional numerical simulations indicate an amplification of the resulting flow around the foundation under combined loads (waves and current), but without significant change of the flow pattern.

Keywords: scour; gravity based foundation; scour protection; offshore wind turbines; CFD

INTRODUCTION

Engineers planning and constructing Offshore Wind Turbines (OWTs) often have to deal with the problem that the development and depth of scours especially around complex foundations different from simple pile structures (e.g. found in Sumer & Fredsøe 2002, Zanke et al. 2011), are not really predictable, which thus leads to oversized dimensions for the foundation structures due to this lack in knowledge of scour progression and its final effects on structures. The STRABAG gravity foundation is a further development of the classical, simple type of gravity foundation, consisting mainly of a reinforced and sand-filled concrete structure with a cross shaped base forming the foundation of the wind turbine.

The prefabricated foundation, including the pre-mounted wind turbine, is installed at its final location in an excavated and leveled pit. The excavation depth is around 3 to 6 m, depending on the soil condition. The installation of a scour protection system in the pit follows immediately. For the protection system geotextile sand containers are used, which are filled with material from the excavation. When required, the pit is backfilled with the remaining material above the scour protection system. Scour from the ground surface down to the scour protection system is accepted. It can only reach a depth up to the top of the scour protection system and therefore poses no threat to the stability of the foundation. Figure 1 shows the states of construction.

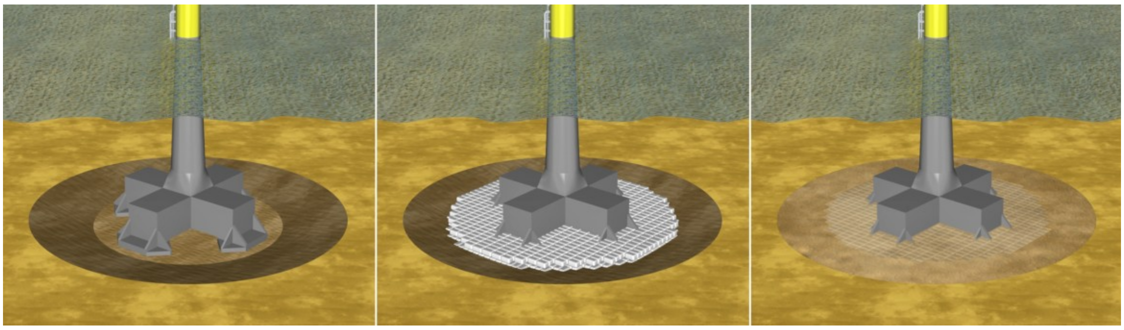

Figure 1. States of scour protection construction (from left to right): state after settling the foundation into the prepared pit; state after installation of the scour protection system in the pit; final state with backfilled pit (Wahrmund et al. 2011).

Without doubt, the foundation with dimensions of 40 m width and 8 m height (minus pit depth) constitutes a flow obstacle, which influences the flow in the near-field and the near-surface sediment transport. From the start, it is expected that without any special scour protection system, scour evolves at the structure edges under the wave conditions of the planned location in the North Sea, which might impair the position stability of the foundation. For the permanent preservation of the stability of the

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STRABAG gravity foundation it is necessary to prevent it from scour below the contact areas of the foundation. This requires a detailed knowledge of the current- and wave-induced sediment transport on the sea floor.

Due to insufficient insights about the flow and scour development around the STRABAG gravity foundation, the Franzius-Institute conducted small- and large-scale physical model tests in wave flumes on a scale of 1:50 and 1:17 in order to investigate the flow velocities and the wave-induced scouring phenomena around the foundation, as well as to design a scour protection system. The following questions are answered by the hydraulic model tests:

- What kind of scour phenomenon must be expected?
- Does the intended scour protection system meet the requirements?
- Is the dimension of scour protection system sufficient?
- What dimension and weight does the sand container must have?

It has to be noted that due to the set-up of the wave flume facilities, the model was solely loaded with wave boundary conditions; tide- or wind-induced current was not regarded here. However, under the given boundary conditions of an extreme event with a recurrence interval of 50 years, the influence of waves is considered as being the main load on the scour protection system installed around the gravity foundation. Nevertheless, to take into consideration the influence of currents on the scouring phenomenon, further scientific investigations using numerical CFD simulations are carried out using OpenFOAM® CFD code, were waves, currents and a combination of both load conditions are further regarded.

This paper focuses on the large-scale model tests dealing with the verification of the scour protection system. A numerical study is further presented in the end, investigating the influence of a combined load (waves and current) on the near-bed flow velocities compared to exclusive wave load.

HYDRAULIC MODEL TESTS

The test program in the small wave flume of the Franzius-Institute intend to phenomenologically analyze the flow velocities and wave-induced scour development around the structure by means of laboratory tests on a scale of 1:50, considering different values for the load parameters “water depth”, “wave height” and “wave period” as well as the orientation and embedding of the gravity foundation.

The subsequent large-scale experimental test program in the Large Wave Flume of the Coastal Research Center (FZK), Hanover, intend to quantitatively analyze the scour development around the foundation with and without scour protection systems using geotextile sand containers on a scale of 1:17 as well as the hydraulic stability of single geotextile sand containers on a scale of 1:10. As boundary conditions for the large-scale test series, the former determined load parameters from the small-scale tests leading to maximum scours are used. Firstly, tests using sand containers are carried out without the presence of the foundation in order to investigate the hydraulic stability of single containers against displacement subject to the parameters “size”, “weight” and “filling rate” and to finally determine the smallest and optimal dimensions of the sand containers, necessary to withstand the given load parameters. Furthermore, investigations of the wave-induced scour development around the structure without scour protection are carried out in order to validate the results from the former small-scale experiments. Afterwards, investigations of the scour development around the foundation using three different variations of a scour protection system are conducted in order to verify the effectiveness of the protection system. Figure 2 gives an overview of the physical model tests and their outputs.

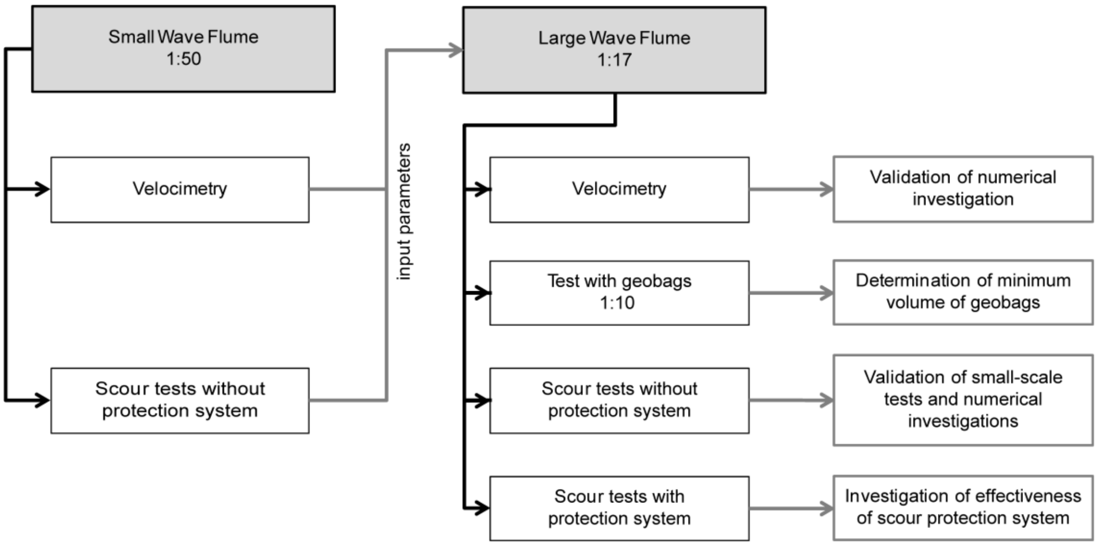

Figure 2. Overview of the physical model tests.

Test Setup

In the following, the test setup of the large-scale scour tests with and without a scour protection system is presented.

For the large-scale model tests in the Large Wave Flume fine sand (d_{50} = 0.15 mm) is installed as bottom material (movable bed) with a thickness of 1.20 m on a length of approx. 34 m. The front and back areas of the sand bed is profiled with an inclination of 1:20. This fine sand is also used as filling material for the geotextile sand containers. A 1:17 model of the STRABAG gravity foundation is manufactured and installed in the sand bed by a fixed connection to the bottom of the wave flume. Figure 3 schematically shows the profile and cross-section of the test setup in the Large Wave Flume which has a length of approx. 310 m, a width of 5 m and a depth of 7 m. It can be operated with a maximum water depth of up to 5 m, generating regular waves with a wave height H_m of up to 2.0 m and irregular waves with a significant wave height H_S of up to 1.3 m using a piston-type wave maker.

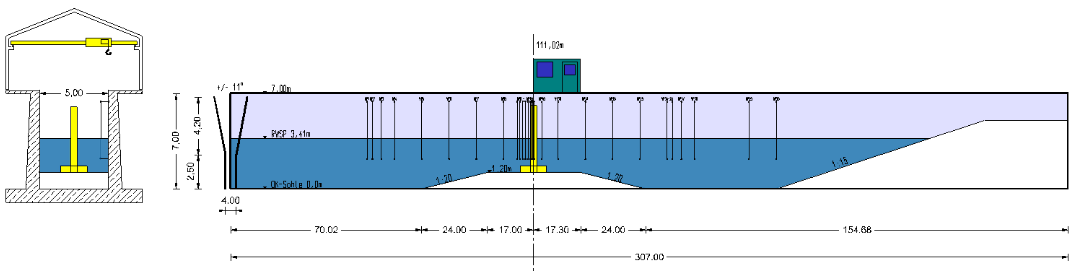

Figure 3. Cross-section and profile of the test setup in the Large Wave Flume (dimensions in meter).

During all tests, evolutions of the sand bed at the structure and in the near-field are measured by use of a multi-beam and several single-beam echo sounders as well as underwater cameras, which allow a highly-resolved three-dimensional and contact-free continuous monitoring of bottom profiles, i.e. scour depths or accumulation areas. The surface elevation is measured using 24 wave gauges.

Measurement Program

As a design basis for the wave parameters that are used as wave boundary conditions in the experimental setup, a typical storm event in the North Sea with a recurrence interval of 50 years is chosen in agreement with the client. During the hydraulic model tests, the foundation structure is successively loaded with 5,000 – 8,000 wave cycles per test series.

The hydraulic boundary conditions for the measurement program are given in Table 1.

Table 1. Hydraulic boundary conditions for the measurement program in the Large Wave Flume.

Parameter	Symbol	Nature	Model 1:17
Angle of wave attack	α	45°	45°
Water depth	d	37.5 m	2.21 m
Significant wave height	H_S	10.8 m	0.64 m
Peak period	T_P	13.8 s	3.35 s
Wave load	50-year extreme event		
Diameter of scour protection system	D_{sp}	52.5 m	3.09 m
Diameter of foundation (total length of hollow boxes)	D	32.5 m	1.91 m

To analyze the displacement of the sand containers and thereby the effectiveness of the scour protection system over time, the sand bed is measured after

- 0, 500, 1000, 2000, 3000, 4000 and 5000

single waves of the 50-year extreme event by use of the multi-beam echo sounder. After measurement of scour and scour protection systems, the water is drained slowly from the flume to make a visual assessment of the bed and scour protection state.

Variation of the scour protection system

Sand-filled geotextile containers made from needle-punched nonwovens are used as scour protection. The parameters "volume", "aspect ratio" and "type of textile" of the sand containers are given by the client. The sand containers have an aspect ratio of 1:1. As filling material, the fine sand used as sand bed material is chosen (d_{50} = 0.15 mm). The dimensions of the sand container type used are given in Table 2.

Table 2. Selected sand container type for the investigation on the design of scour protection system in the Large Wave Flume.

Typ N1	Dimensions	Filling volume	Weight
Prototype 1:1	2.05 x 2.05 m	1.50 m^3	2700 kg
Model 1:17	0.121 x 0.121 m	0.0003 m^3	0.550 kg

The investigations on the hydraulic stability of the single sand containers against displacement, which are not presented in detail in this paper (for more details refer to Wilms et al. 2011 and Werth et al. 2012), show that the sand container type N1 is hydraulically stable and represents the minimum dimensions to withstand the given hydraulic wave boundary conditions.

The amount of sand containers used for the scour protection system is determined by volumetric calculations. The calculation is based on a random, two-layer installation of the sand containers on the given area of the scour protection system with a diameter of 52.5 m (prototype scale). A total number of 1104 sand containers are used in the model tests.

The measurement program carried out to analyze the effectiveness and design of the scour protection system include a total of three different variants. Parameters of the test series are given in Table 3.

Table 3. Overview of the three variants of scour protection system (in prototype scale)

Variant	Sand container type	Fixing-in depth	Scour protection system
1	N1	0.0 m	Sand container
2	N1	3.0 m	Sand container + Fleece
3	N1	3.0 m	Sand container

The installation of the sand containers is carried out under water with a water depth of 0.45 m. The sand containers are installed randomly by being immersed in water and released afterwards in order to reach their final positions in free-fall. To achieve an even distribution of the sand containers around the gravity foundation, the circular area of the given scour protection area is divided into four sections. In each section 276 sand containers are distributed in a defined pattern.

In the scour protection system Variant 2 a fleece is used in addition to the sand containers. The fleece is for one half of the foundation attached between the cross-shaped hollow boxes and at the contact areas. The sand containers are then installed consecutively on top of the fleece. The pit is subsequently filled, so that the foundation was embedded 0.18 m (model scale) in the sand bed. In Figure 4 (left) the fleece is shown after its installation. Figure 4 (right) shows the foundation with a completed section of the scour protection system.

Figure 4. Foundation with installed fleece for Variant 2 (left) and foundation during installation phase of the scour protection system (right).

EXPERIMENTAL RESULTS

The tests on scour development without a scour protection system show that the main areas which are vulnerable to scour are the contact areas of the foundation. Furthermore, the experiments show that a scour protection system is necessary for the given and investigated wave boundary conditions.

In Figure 5 the state of scour and the result plots of the multi-beam echo sounder measurements of the test series with and without a scour protection system after 4000 and 5000 waves are given, respectively. The color coding of the result plots gives black for sediment erosion and white for accumulation of sediment, relative to initial bed. It can be observed that for the test series without a scour protection system, the largest scour occur at the four outermost bracings as well as in the luv and lee corners of the hollow boxes. In addition, a slight accumulation of sand can be observed in the lateral corners of the hollow boxes.

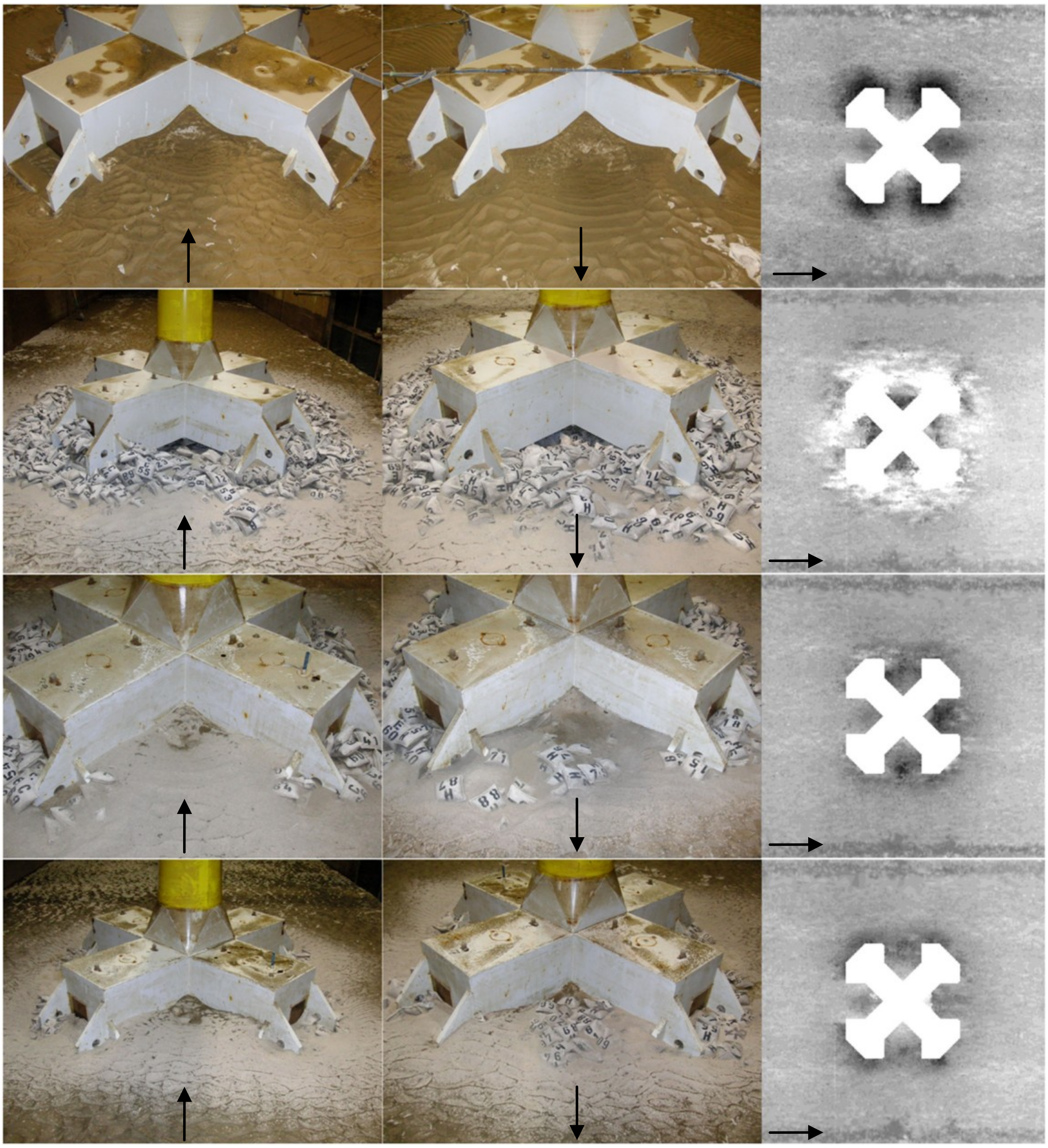

Figure 5. State of scour in front of (left) and behind the shaft (middle), result plot of multi-beam echo sounder (right). Arrow indicates incident wave direction. From top to bottom: tests without scour protection system, scour protection system Variant 1, Variant 2 and Variant 3.

For the test series with a scour protection system it is observed that the sand containers are hydraulically stable under the given boundary conditions of the 50-year extreme event. In Variant 1, however, the sand erodes under the foundation as a result of free space under the hollow boxes (note: fixing-in depth 0.0 m). Consequently, the sand containers slide into the resulting pit. Because of the considerable displacement of sand containers, the test series is terminated after 4000 waves. For the test series with scour protection system Variant 2 and Variant 3 it can be observed that light wave-induced sediment erosion occurs in front of and behind the shaft as well as at the lateral space of the foundation, but not as deep as in the test series without a scour protection system. Solely the sediment above the sand containers erodes.

In order to discuss and evaluate the measured data, the evolution of the relative scour depth is plotted against the number of waves for each test series at representative points in Figure 6. Those points are considered representative, which are located within a circular area with radius of the planned scour protection (r = 1.54 m, model scale) and have the deepest scour after being loaded with 4000 and 5000 waves, respectively. The location of the representative points is indicated with a red marker in Figure 6 (right). The representative points of the four test runs lie close to each other (max. 1.5 cm distance). The resulting maximum scour depths *S* are normalized with the structure diameter, which are taken as *D* = 1.91 m.

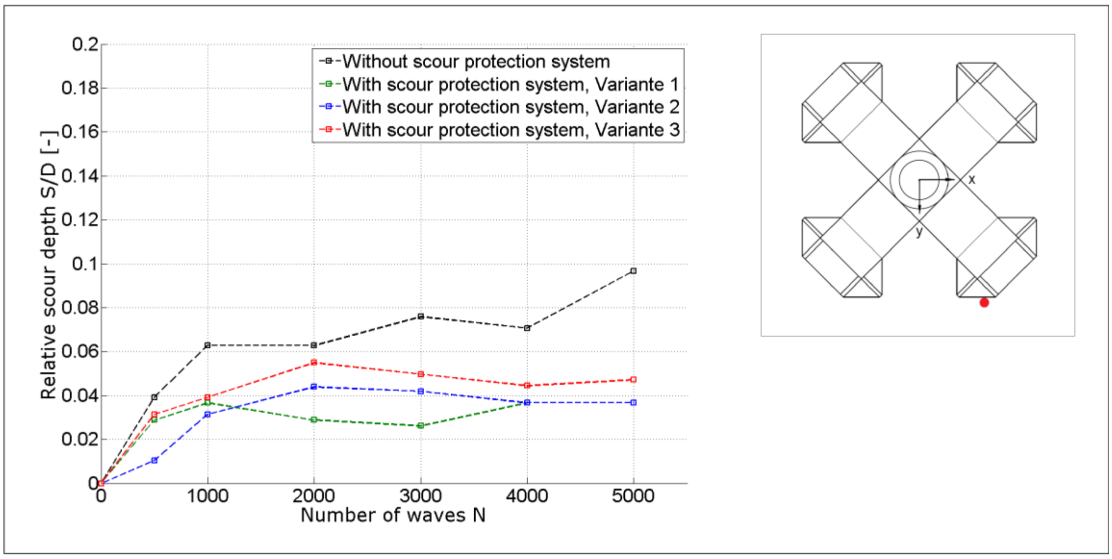

Figure 6. Rel. scour depth vs. number of waves (left) and foundation with measuring location (red dot).

The relative scour depths develop rapidly in the first 500 – 1000 waves and then increase insignificantly. In the test series without scour protection system, 50 % of the maximum, relative scour depth is already reached after the first 500 single waves. The relative scour depth afterwards increases slowly and has a depth of approx. 10 % of the diameter of the structure after 5000 waves. In the test series with scour protection system, the relative scour depths are lower, with approx. 5 % only half as large as without a scour protection. Based on the results of the test series for the scour protection system Variant 2 (sand containers and fleece) and Variant 3 (sand containers), no significant differences in scour evolution can be noticed by the additional use of a fleece. Under the given wave boundary conditions, the additional use of fleece therefore result in no significant benefit for the reduction of scour. Both variants, however, guarantee a blockage of the flow path under the hollow boxes and thereby prevent the occurrence of erosion under the foundation.

In addition to the temporal consideration of the scouring phenomena, the spatial evolution is considered using profiles of the above mentioned representative scour areas along the y-axis (flume width). Figure 7 shows the cross-section of the deepest scours for the tests with and without a scour protection system; the gravity foundation is depicted schematically with gray rectangles. It can be observed that the width of the scour has a maximum of 0.5 m and the scour is not influenced by the flume walls. It can be concluded that the existing degree of obstruction in the flume has no significant influence on the results of scour evolution. Furthermore, the previous observations can be confirmed:

- the scour develops rapidly under the first 500 –1000 single waves,
- the scour occurs at the contact areas and behind the shaft between the hollow boxes,
- as a result of the scour protection system, smaller scour depths and widths develop.

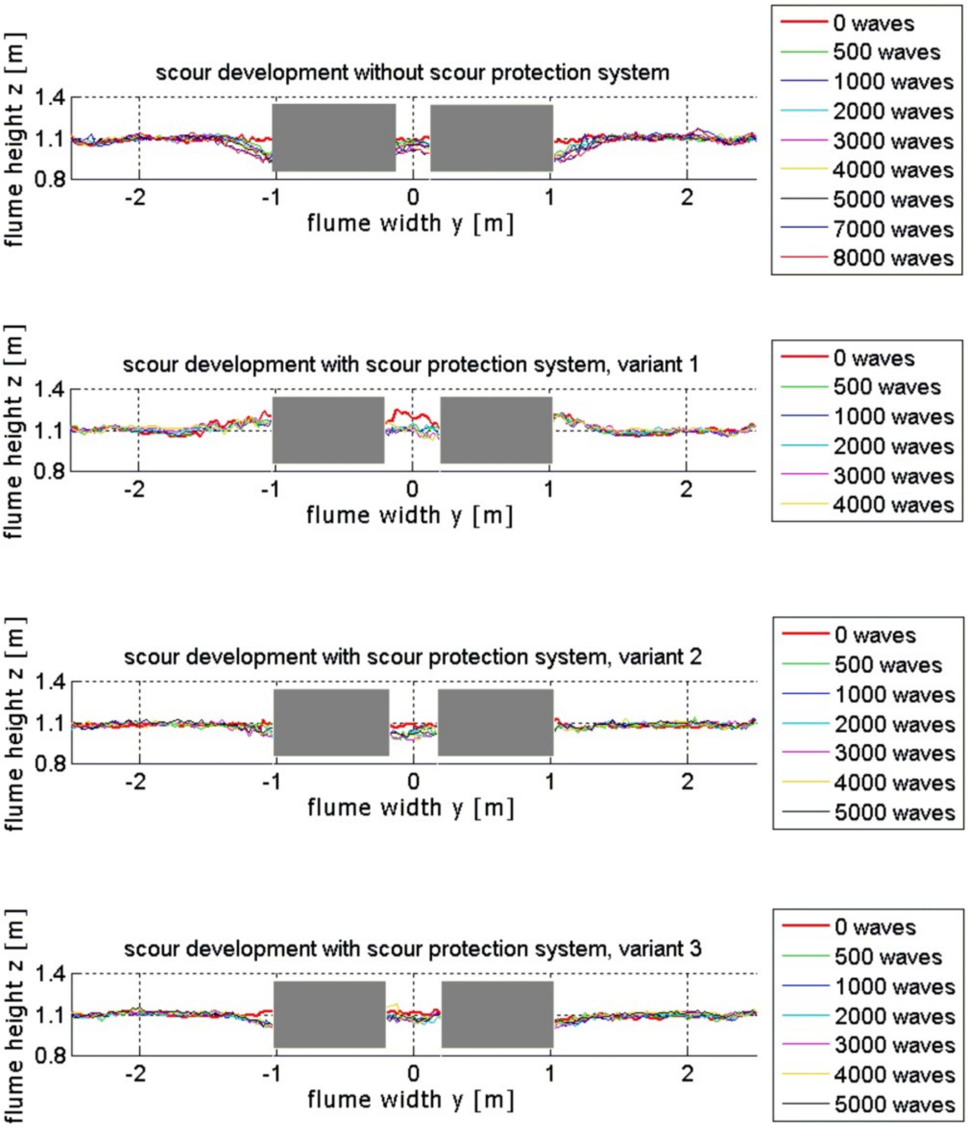

Figure 7. Cross-sections of the flume with measured sand bed surface for the position of the deepest scour.

NUMERICAL SIMULATIONS AND RESULTS

In order to further analyze the influence of a combined wave and current load on the near-bed flow velocities and shear stresses and the resulting local stability of the scour protection system, numerical studies have additionally been carried out. For the investigations, the OpenFOAM® CFD toolbox has been applied, using a Volume of Fluid (VOF) method with free-surface flow, whereas the Reynolds-Averaged Navier-Stokes equations (RANS) have been solved in combination with a modified k-ω SST turbulence model to account for surface roughness. Further details can also be found in Stahlmann & Schlurmann 2012. The model structure of the STRABAG gravity base foundation has been implemented into a numerical wave tank on a model scale of 1:50, i.e. the scale of the small-scale physical model tests in the wave flume.

Two different load cases using a rigid bed have been investigated: (a) a wave load case for the 50-year event from the physical model tests, and (b) a combination of this extreme event with an additional current in wave direction. The wave load has been modeled as regular waves using 5th order Stokes wave theory here, taking values of $H_m = H_s = 0.216$ m, $T_m = T_p = 1.95$ s and a water depth of $d = 0.75$ m. The current velocity of $v_m = 0.106$ m/s has been introduced at the domain inlet using a logarithmic velocity profile superimposed to the horizontal orbital motion.

Figure 8 gives the near-bed flow velocities in a distance of approx. 3 mm over ground at the time of passing wave crests for wave load (left) and combined wave-current load (right). The flow direction is depicted in the figures. As can be seen from the given velocity magnitudes and flow directions for the wave load case, increased flow velocities are present at the sides of the foundation due to blockage effects and flow separation with maximum velocities of 0.45 m/s, leading to enhanced sediment mobility (in case no scour protection is installed) or enhanced load on the protection material. On the other hand, areas of low mobility exist at the inner corners of the intersecting structural box parts all around the foundation. These findings coincide well with the transport processes observed in the physical model tests, in both the sediment transport and scour protection investigations. For the combined wave-current case, the overall load areas and flow pattern are similar to the wave load case; the effects are however more pronounced with larger maximum occurring near-bed velocities up to 0.6 m/s at the foundation sides. This effect therefore has to be accounted for in the final dimensioning of the scour protection system, both in the design of single protection elements against erosion as well as in the expansion of the overall protection system.

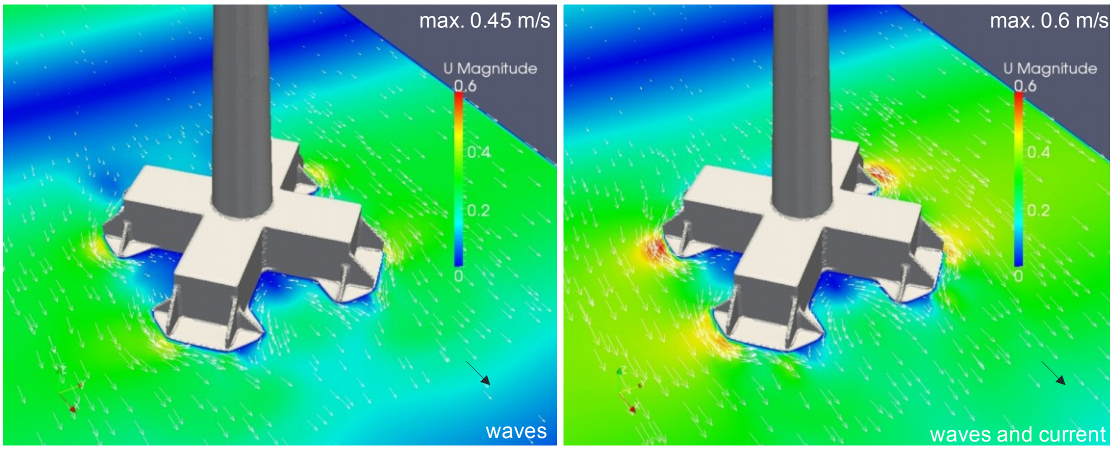

Figure 8. Simulated near-bed flow velocities (under the wave crest) for wave (left) and combined wave and current load (right). Model scale 1:50.

CONCLUSIONS

Experiences from the recently installed wind turbines in the German Exclusive Economic Zone (EEZ) in the North Sea show that scour is a very serious phenomenon concerning the stability of the OWT. So far, the existing calculation methods cannot describe any particular mechanism of action especially for geometrically complex foundation structures.

For the STRABAG gravity foundation there was no practical experience with scouring so far, which could be used as a basis for an appropriate design method for the scour protection system. Large-scale experiments were therefore essential to achieve a sufficient degree of planning certainty. The measurement program in the Large Wave Flume included test series to determine a scour protection system for the STRABAG gravity foundation. Test series with a movable bed, a direction of wave attack of 45° (relative to the horizontal base orientation) and a sea spectrum (50-year extreme event) according to the hydraulic, natural boundary conditions were performed. A test series without a scour protection system served as reference measurement. For the validation of the scour protection system, three different variants were examined. In all three variants the sand container type N1 were used (2.05 x 2.05 m, 1.5 m^3, prototype scale). The scour protection system was installed randomly in two layers.

Test series with scour protection system Variant 1 (fixing-in depth 0.0 m) was precocious terminated due to an already clearly discernible displacement after 4000 waves. Cause of the shift was an undercurrent through the open space on the underside of the hollow boxes. In Variant 1, the open space was particularly exposed by the lack of embedding of the foundation in the sand bed. The flow led to a mobilization of sediment and sediment erosion; the sand containers slided into the resulting pit.

In Variant 2 and Variant 3, the flow path under the hollow boxes was barred by embedding the foundation in the sand bed. Thus, erosions below the foundation could be prevented. In Variant 2, fleece was used as an additional scour protection. After the loading with 5000 waves, no significant scour was observed in the test series of Variant 2 and Variant 3. Under the given boundary conditions, the additional use of fleece results in no significant benefit for the reduction of scour.

The experiments have shown that a scour protection system is necessary for the given wave boundary conditions. The performance of the selected scour protection system using sand containers could be verified for Variant 2 and Variant 3 on a scale of 1:17 under the loading of 5000 waves of the 50-yearly extreme event. Further attention nevertheless has to be drawn to the final design of the scour protection system, as numerical investigations using OpenFOAM CFD software led to locally enhanced near-bed flow velocities and shear stresses for a simulated case wave-current load case.

REFERENCES

Stahlmann, A. and Schlurmann, T. 2012. Investigations on Scour Development at Tripod Foundations for Offshore Wind Turbines: Modeling and Application. *Proceedings of the Coastal Engineering Conference*, No. 33.

Sumer, B.M., and Fredsoe, J. 2002. The Mechanics of Scour in the Marine Environment, World Scientific Publishing Co. Pte. Ltd.

Wahrmund, H., Wilms, M., Stahlmann, A., Heitz, C., Schlurmann, T. 2011. Scour development and design of scour protection systems for a gravity based foundation for offshore wind turbines (Kolkbildung und Dimensionierung des Kolkschutzes eines OWEA-Schwerkraftfundaments), *8. FZK-Kolloquium – Maritimer Wasserbau und Küsteningenieurwesen, Forschungszentrum Küste*, S. 93-104, 10. March 2011, Hannover (in german)

Werth, K., Wilms, M., Peters, K., Stahlmann, A., Schlurmann, T. 2012. Offshore Wind Turbine Foundations - Hydrodynamic investigations, design, installation and durability of scour protection systems made of geotextile sand-fillled containers, *12th Baltic Sea Geotechnical Conference*, Infrastructure in the Baltic Sea Region, Rostock, Germany, pp. 310-316, 31.05.-02.06.2012.

Wilms, M., Wahrmund, H., Stahlmann, A., Heitz, C., Schlurmann, T. 2011. Scour development and design of scour protection systems for a gravity based foundation for offshore wind turbines (Kolkbildung und Dimensionierung des Kolkschutzes eines OWEA Schwerkraftfundaments), HTG-Kongress 2011, 07.-10.09.2011, Würzburg, published in: *Proceedings of the HTG-Kongress 2011*, Editor: German Port Technology Association, Hamburg (in german)

Zanke, U.C.E., Hsu, T.-W., Roland, A., Link, O., Diab, R. 2011. Equilibrium scour depths around piles in noncohesive sediments under currents and waves, *Coastal Engineering*, 58, 986-991.