INVESTIGATION OF SCOUR DEVELOPMENT UNDERNEATH OFFSHORE GRAVITY FOUNDATIONS DURING LOWERING

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Abstract

Lowering procedures of one leg of an offshore gravity foundation, e.g. offshore wind turbines or oil and gas platforms, were investigated in large-scale physical model tests in the Large Wave Flume (Großer Wellenkanal, GWK), Hannover, Germany. If for instance, the foundation of oil and gas platforms is composed of four legs the level difference between each leg must be very small and the evenness of the seabed directly underneath the base of the gravity foundation is crucial. The main objective of this study was to investigate changes in the seabed level, which consisted of crushed gravel stones, and the resulting scour development due to the high flow velocities in the gap between the foundation base and the surface of the seabed which were caused by wave-induced vertical oscillations. Displacements of the gravel stones were observed and measured by using photogrammetric measurement techniques. This paper will particularly focus on the results of the physical model tests and will show different stages of scour development due to regular and irregular structure motion. Furthermore, practical diagrams and formulae for design purposes based on the results will be provided.

1. Introduction

For the foundation of offshore structures like wind turbines or oil and gas platforms, gravity foundations are often favored due to their simplicity. Gravity foundations consist of a large, heavy base made of steel or concrete and filled with ballast material. The structures are usually constructed on land and transported by ships to their destination (either on the ship or as a floating body), where they are lowered to the sea floor. There are strong demands on the quality and evenness of the sea floor which in many cases require an additional graded layer of stones (rock blanket) on which the structure finally rests.

During the lowering of a gravity foundation, the transient motion of the structure is superimposed by oscillatory motions induced by the sea state. When the foundation structure approaches the seabed, the varying volume between the bottom side of the structure and the seabed will induce cyclic water flow underneath the foundation plate. Due to the large area of the base and the comparably small gap between the structure and the sea floor the induced flow velocities may reach significant values. These velocities may jeopardize the stability of the seabed or the rock blanket and lead to intolerable deformations, which may have a detrimental effect on the overall design of the structure.

The major objective of the present study is the investigation and quantification of rock blanket disturbance and scouring related to transient and oscillatory vertical motions of a gravity foundation during set down on the seabed. Although the actual sea state induced movement of the structure can have six degrees of freedom it is clearly the vertical motion having the largest impact. Large scale model tests of the lowering procedure of a square gravity foundation base were performed in the Large Wave Flume (Großer Wellenkanal, GWK) of Forschungszentrum Küste (FZK), Hannover, Germany.

2. Theoretical Background

2.1 Hydrodynamic processses

Hydrodynamic processes considered in this paper are due to the oscillating motion of the structure including the velocity and the acceleration of this motion which causes pressure changes at the bottom of the structure. Obviously, the maximum motion velocity will occur around the mean position s0 of the structure and the structure velocity v is zero in the trough smin and the crest smax of the structure motion. The resultant pressure p_{tot} underneath the bottom slab of the structure consists of three components and is given in Eq. [1]:

$$p_{tot} = p_s + p_v + p_a \qquad [1]$$

where p_{tot} is the resultant pressure, p_s is the pressure due to motion of the foundation structure s, p_v is the pressure due to velocity v and p_a is the pressure due to acceleration a.

2.1 Morphodynamic processses

Scour development depends mainly on the maximal structure velocity v and the minimal position above the gravel bed s_{min}, i.e. the minimal gap between gravel surface and bottom slab of the structure. Two morphological processes at and inside the gravel layer are relevant for its hydraulic stability and resistance against the aforementioned oscillating motion with the resulting horizontal flow velocities between the bottom of the foundation structure and the surface of the gravel bed: i) flow-induced shear stress at the surface of the foundation layer (SHIELDS concept) and ii) pore water flow inside the rock blanket. Both processes are responsible for the resulting scour development. The processes underneath the foundation plate are given in Figure 1 and described separately in the following for the downward motion (a) and upward motion (b) of the structure.

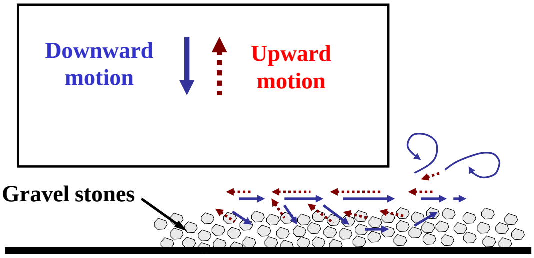

Figure 1. Flow direction in the gap underneath the gravity foundation induced by upward and downward structure motions

(a) Downward motion of the structure:

In the upper layer of the foundation underneath the structure the porous flow has a vertical component in the direction of the gravity force (inflow). This results in higher effective stresses in the grain skeleton and subsequently to a higher resistance force against the shear stress at the surface. Therefore the risk of grain transport is reduced. Beyond the structure edge the pore water flow is directed against the gravity force (outflow), which reduces the effective stress and thus the hydraulic stability of the skeleton. However, as the cross section for the flow is no longer restricted by the structure, the shear stress at the surface vanishes almost immediately. Hence, no displacement of gravels will take place.

(b) Upward motion of the structure

In that case, the pore water flow inside the upper layer of the foundation has a component, which is directed against the gravity force (outflow). This reduces the effective stresses and the hydraulic stability, respectively resistance, of the gravel stones, which are jeopardized by the shear stress at the surface. “Partial liquefaction” (reduction of effective stress due to unfavorable pore pressure gradient) occurs and the stones may be transported towards the centre of the gravity foundation. The most vulnerable area of the rock blanket to scour is located just underneath the edge of the gravity foundation which is also shown with the results later. The cross section for water flow decreases abruptly, resulting in high flow velocities and high shear stress velocities at the surface of the foundation soil. At this time, also a flow component against gravity reduces the effective stresses and increases scour development.

3. Materials and methods

3.1 Layout of the model

The large scale physical model tests were performed in the Large Wave Flume (GWK) of Hannover, although actually no waves were needed. However, the flume provided the necessary width of 5.00 m and allowed for a water depth during testing of about 1.30 m. The structure of the model was composed of a stiff frame and a quadratic stiff box as can be seen in the cross section (left) and plan view (right) in Figure 2, which represents one leg of the offshore gravity foundation.

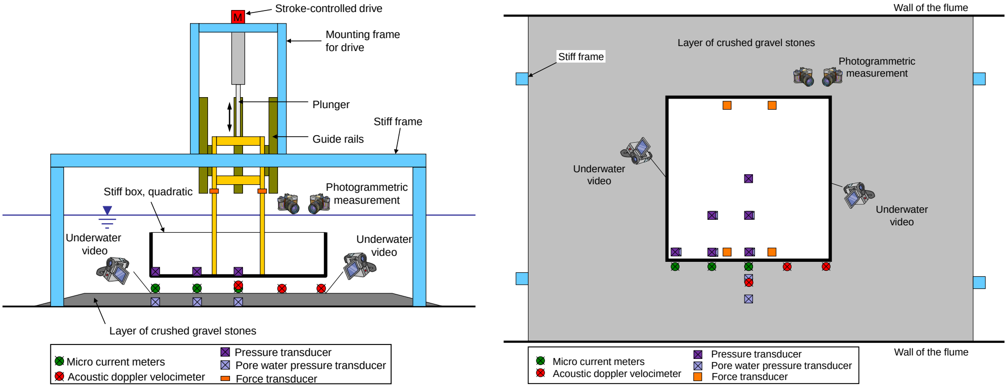

Figure 2. Cross section (left), plan view (right) of the model with measurement and observation devices

In order to realize the lowering procedure of the foundation structure, the stiff box fixed to the inner frame with plunger and guide rails was set in motion. Regular motions with different periods and amplitudes (sinusoidal waves) as well as irregular motion for several swell and storm conditions were generated and transferred to the converter which triggered the motor drive. The motion of the stiff box was observed with a displacement meter to compare the executed motion with the given motion.

The positioning of measurement devices is also given in Figure 2. As the foundation plates were quadratic and therefore point symmetric, the hydraulic processes and their impact on scour generation should be the same at each side of the gravity foundation. Consequently, the application of measurement devices was located only to one selected side of the structure.

Four force transducers with a measuring range of 2000 N were installed within each leg of the frame of the stiff box. The total resulting force can be calculated by adding up the results of each of the four force transducers. Additionally, six pressure transducers were integrated in the bottom of the stiff box in order to measure the pressure distribution at the base of the structure. With these results an integration of the pressure over the whole area of the bottom plate was performed in order to compare the results of the results of the force measurements.

Another six pressure transducers were fixed inside the gravel layer measuring the pore water pressure. The resulting currents and flow velocities induced by the motion of the structure were measured redundantly with three micro current meters and three Nortek Acoustic Doppler Velocimeters (ADV).

The incipient motions of the grains and the scour development were observed and recorded by using two underwater video cameras, which were installed near the edge of the structure. In order to quantify changes in the surface such as scour or crest development due to displacements of the gravel layer two SLR cameras were fixed at the stiff frame of the construction for photogrammetric measures of the surface before and after each test.

3.2 Test programme and methodology

Figure 3 sketches the aforementioned oscillating motion of the structure including the associated velocity and acceleration of structure motion. With this figure the mean position of the structure above gravel surface s_0 as well as the minimum (and the maximum) position of the structure and therefore the minimum (and maximum) distance above the gravel surface is defined as s_{min} and s_{max}, respectively. Due to different objectives of the investigations, the test program consists of four phases:

- Phase 1: Determination of damping forces.
- Phase 2: Investigation of scour development due to regular structure motion.
- Phase 3: Investigation of scour development due to irregular structure motion performed in a constant height above surface of the gravel bed.
- Phase 4: Investigation of scour development due to irregular structure motion with realistic lowering scenarios until touchdown to the surface.

First in phase 1, regular sinusoidal motions of the structure were performed above an impermeable concrete floor in order to measure the resulting forces which will be referred as the reference case. Later, these results were compared with the results obtained from tests with regular sinusoidal motions in phase 2 above the gravel bed to assess the influence of permeability on the damping forces. With these results the damping forces can be calculated. Overall 192 tests were performed by varying systematically the parameters of sea state condition such as wave height H and wave period T as well as mean position of the foundation above gravel bed s_0.

The main objective of phase 2 was the investigation of scour development under regular structure motion in order to get a first impression under which conditions grain motion can be expected and therefore, to obtain an understanding of the existing processes. The outcomes will be the fundamental basis to systematically establish equations for the scour development.

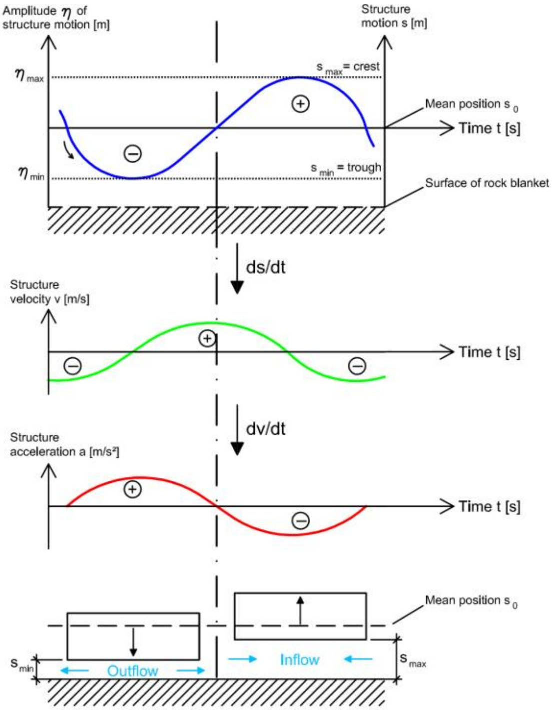

Figure 3. Principle sketch of structure motion s, structure velocity v and structure acceleration a

The parameters of sea state conditions were varied methodically similar to phase 1. In order to take into account the grouping of motion heights (comparable to the grouping of waves in natural sea states), the tests with regular motion were performed with three waves when scouring was expected, and with five waves, in which less scouring was expected. The behaviour of the gravel bed was observed by using underwater video cameras. If only small scouring was observed, additional five waves were performed before the absolute scour development was measured. Altogether, 75 tests were realized.

Phase 3 comprises irregular structure motion executed in a constant mean position above the bed surface s_0 by using time series which differ in terms of minimum and maximum sea states. Four mean positions of the foundation above the gravel bed s_0 were selected. In this phase six tests were realized.

In Phase 4 realistic lowering scenarios for the installation of the foundation were reproduced. For the tests "worst case wave packages" were extracted from the time series of phase 3. The tests started in a certain height above the gravel bed and the oscillating structure motions were superimposed by selected constant lowering velocities coming out from the "worst case wave packages". These tests were run until touchdown at the surface. Also, in this phase six tests were performed.

3.3 Test procedure

In order to obtain a first impression of the scour development, after a test the displacement of the gravel stones was surveyed first by a manual measurement (tape measure) whereby depth, length and width of the erosion as well as accretion length and the position of the scour related to the position of the structure were measured. To estimate the depth of scouring a white plastic board with centimeter scale was installed in the gravel bed

Additionally, before each test the surface of the gravel bed was smoothed and pictures were taken with the two single lens reflex (SLR) cameras for photogrammetric processing. The water was filled in the flume and the test was performed. Afterwards, the water was discharged and the surface was surveyed again by taking pictures with the SLR cameras. The 3-D surfaces were generated by computational methods programmed in MATLAB®.

4. Test results

4.1 Initiation of motion

In order to investigate systematically the start of gravel motion (i.e. initiation of motion) tests with regular structure motions were performed above gravel bed.

The results imply that the initiation of motion of the gravel stones depends on the structure velocity v and the minimum position s_{min}. The relationship is plotted in Figure 4. The observations during tests with irregular structure motions are also shown with smaller grey rhombi, while the results of tests with regular motion are indicated by larger blue rhombi.

The results show that a certain threshold of structure velocity v must be exceeded for any begin of gravel displacement. It can be assumed that this threshold depends on the mean diameter and the density of the gravel material.

For the selected material the velocity threshold is $v_1 = 0.01m/s$. This threshold remains constant up to a gap width of $s_1 = 0.01m$. The straight lines represent the envelopes which define the range were gravel displacement starts.

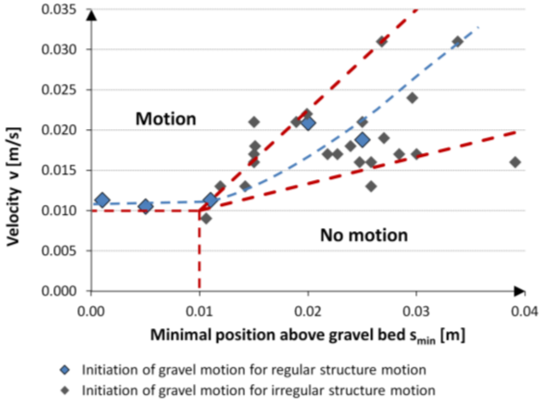

Figure 4. Incipient gravel motion as a function of the structure velocity v and the minimum position above surface smin

4.2 Scour pattern

Directly underneath the edges of the structure a scour developed, while under the foundation structure accretion could be observed due to the fact that the mobilised gravels were transported towards the centre of the foundation as can be seen from the principle sketch in Figure 5. Depending on the geometrical conditions (quadratic structure) the shape of the scour which develops underneath the foundation structure, remains constant for all tests.

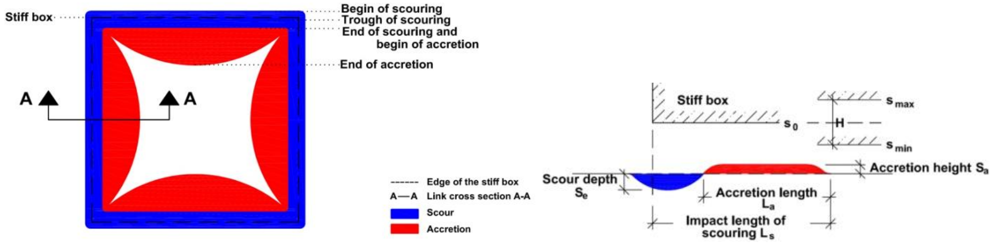

Figure 5. Principle sketch of gravel displacement with a plan view (left) and a cross section (right)

For further analysis following morphological parameter were defined: i.) Scour depth S_e (maximum scour depth underneath the edges), ii.) Accretion height S_a (maximum height underneath the foundation plate) and iii.) Impact length L_s (extension of the surface disturbance relative to the structure edge). The morphological processes underneath the foundation, which lead to this type of pattern, are discussed in chapter 2. From the results it could be seen that mainly three aspects have an influence on the development of the scour pattern which are explained in the following:

- Development of shapes depending on different periods T of structure motion
- Development of shapes depending on number of cycles of structure motion
- Development of shapes depending on position above surface s0 of the structure

First, the motion period T has an influence on the impact length of scouring L_s which increases when the values for period T becomes smaller and therefore the velocity and also the acceleration of structure motion becomes larger.

Secondly, the number of cycles of structure motion is important. The final scour depth underneath the edge of the structure develops under very few oscillations and remains nearly constant until the end of the test. There are only small changes in scour depth of 5 mm. It was observed that for large motion amplitudes and small gaps s_{min} the maximal scour depth is already reached after one single oscillation. Whereas, the impact length Ls increases with additional number of cycles due to the fact, that there is a continuous transport towards the centre of the foundation area. In order to enable a direct comparison of the measured data, always the values after 8 oscillations are selected for data analysis.

The third aspect which has an influence on scour development depends on the structure position above the bed surface s_0. It could be seen from the scour pattern that in a high position of the structure above the ground the gravel surface is less influenced by structure motion. Afterwards, the structure is lowered and the displacement of the gravel stones increases. If the structure comes closer to the gravel surface the main displacement of the gravel stones occurs. Whereby, as mentioned before, the scour depth is nearly the same from the beginning until touchdown, but the length of the accretion underneath the structure increases significantly.

Depending on the conclusions an empirical relationship for the processes is developed.

4.3 Parameterization of scour development due to regular structure motion

In order to develop empirical relationships, the values for each morphological parameter are normalised by the structure width B and plotted against the maximal structure velocity v, which is normalized by g·T (gravitational acceleration, period of oscillation). As mentioned before, the motion of the gravel stones depends on the velocity v and the minimal gap s_{min}. In Figure 6 the relationship for the normalized scour depth is shown, exemplarily. From the results several conclusions can be drawn:

- A certain velocity threshold must be exceeded for the development of scour.
- This threshold depends on the minimum position of the structure above surface s_{min}.
- For each s_{min} a linear relationship may be adopted between structure velocity v and the impact length of scouring L_s.
- The increase of scour with velocity v (the slope of the aforementioned linear function) also depends on the minimal gap s_{min}.

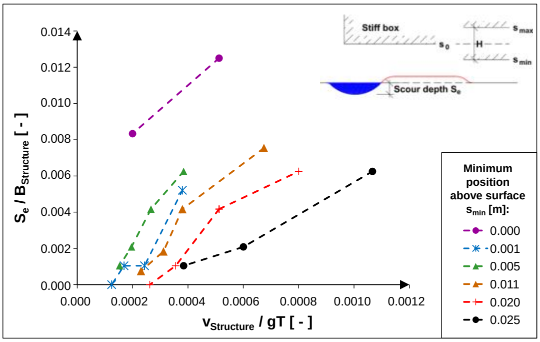

Figure 6. Normalized scour depth S_e after 8 cycles of regular structure motion as a function of v and smin

For design purposes a simple linear approach defined by the slope a and offset b for the results of the normalized scour depth S_e in Figure 6 as well as for the impact length of scouring L_s and the scour accretion is expressed by Eq. [2]. The linear fit functions for a and b for the results of the scour depths given in Figure 6 are shown in Figure 7:

$$\frac{S_e}{B}, \frac{S_a}{B}, \frac{L_s}{B} = \frac{v}{gT} \cdot a\left(\frac{s_{min}}{B}\right) + b\left(\frac{s_{min}}{B}\right) \qquad [2]$$

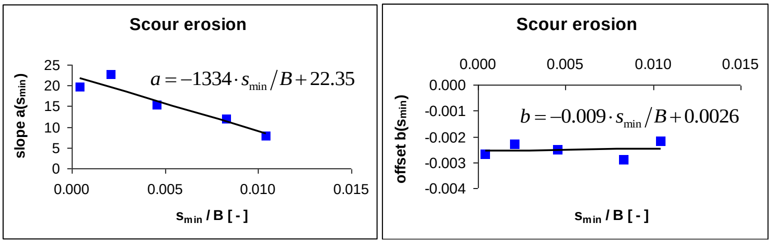

Figure 7. Equation for the slope a (left) and for the offset b (right) of the scour depth S_e

The following Eq. 3 is established on the basis of the aforementioned linear approach in Eq. [2] and the linear fit equations in Figure 7:

$$\frac{S_e}{B} = \frac{v}{gT} \cdot \left(-1334.3\frac{s_{min}}{B}\right) + 22.35 + 0.009\frac{s_{min}}{B} + 0.003 \qquad [3]$$

The same procedure has been done for the relationships of the impact length L_s and the accretion height S_a and the linear fit equations are given in the following Eq. [4] and Eq. [5]:

$$\frac{S_a}{B} = \frac{v}{gT} \cdot \left(-63.51\frac{s_{min}}{B}\right) + 9.275 - 0.35\frac{s_{min}}{B} \qquad [4]$$

$$\frac{L_s}{B} = \frac{v}{gT} \cdot 1466 \cdot \exp\left(-257.7\frac{s_{min}}{B}\right) + 0.307 \cdot \exp\left(-298.3\frac{s_{min}}{B}\right) \qquad [5]$$

In the following Figure the design formula expressed in Eq. [3] is visualized for selected values of s_{min}/B (straight lines) together with the measured scour depth S_e (individual symbols).

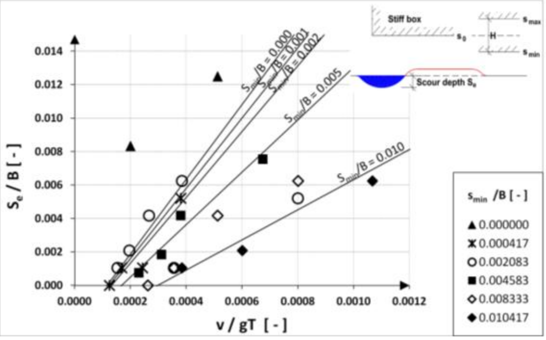

Figure 8. Scour depth S_e as a function of v and s_{min}

In the left diagram of Figure 9 the design formula expressed in Eq. [4] for the scour depth S_a and in the right diagram the design formula expressed in Eq. [5] for the impact length of scouring L_s is visualized.

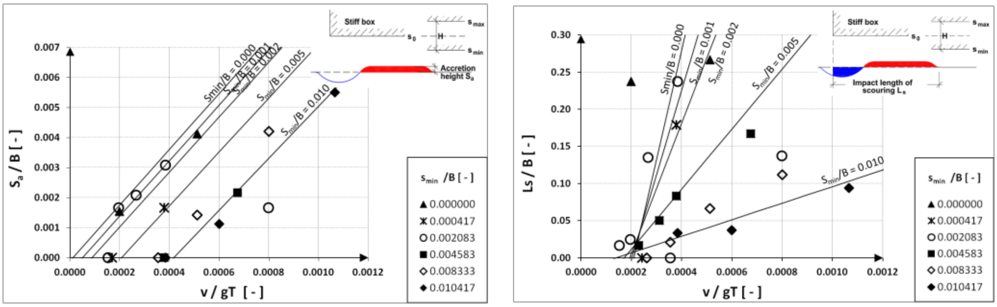

Figure 9. Impact length of scouring L_s (left) and scour accretion S_a (right) S_e as a function of v and s_{min}

The deviations between the empirical formula and the measurements must be considered in regard to the measurement accuracy, which is in the range of the mean diameter of the gravel material.

5. Conclusions and Outlook

During the lowering of a gravity-based offshore structure the wave-induced vertical oscillations of the structure induce significant currents underneath the foundation plate when approaching the seabed. Depending on the selected foundation material, serious deformations may occur, which jeopardize the structural stability of the construction or its usability. In order to investigate the impact of structure motions on the deformation of a gravel bed, model tests were performed with a sample quadratic structure on a gravel layer.

From the results of the experiments following conclusion could be drawn: i.) When approaching the seabed the amplitude of structure oscillation is damped. This effect is significantly smaller for a porous gravel layer than for an impermeable bottom ii.) Characteristic parameters for describing the scour development were defined and systematically investigated under regular structure motions, iii.) Empirical relationships were established to assess the scour development as a function of maximal structure velocity and minimal gap between structure and foundation layer.

The application of the obtained results is restricted to the selected geometry with its special boundary conditions, including the range of tested conditions. The structure width and the gravel material were kept constant during the investigation. For a more general application of the developed formulae the parameters and boundary conditions should be varied systematically. Also the structure velocities should cover a wider range. For further investigations another focus should be set on the scour development under irregular structure motion in order to improve the accuracy of the developed formulae for realistic scenarios.