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By

Klaas Jan Bos[1], Henk J. Verheij[1], Gijsbert Kant[1], Arno C.H. Kruisbrink[1]

ABSTRACT

This paper presents results of research onto scour around large scale submerged offshore structures (Gravity Based Structures) subjected to the combined effect of loads related to wind waves and currents. The research comprises small-scale model tests with a GBS, numerical simulation of the flow field around the structure, and the derivation of a scour prediction equation for practical engineering purposes. The physical model tests were carried out with a GBS protected by thick layers of various rock sizes, different hydraulic conditions and structure configurations. The flow field around a GBS was computed in order to increase the insight into the observed scour phenomena. Finally, as prediction formulas for structures like a GBS loaded by combined wave and current action do not exist, the obtained test data have been used to develop a scour prediction formula enabling designers to determine the scour depth and required minimum thickness of the rock protection.

INTRODUCTION

Little is known about scouring due to combined wave and current action around a GBS with a structure height of less than 50% of the water depth as well as the required rock as scour counter measure. The combined wave and current influence induce scour of an unprotected seabed, in particular near the corners of a GBS. Under North Sea conditions scour holes of 5 to 10 m can easily develop depending on the loading conditions. Then, a proper bed protection to ensure the stability of the GBS will be required. One of the possibilities is a thick layer of small-sized rock which extents up to a certain distance out of the GBS side walls. The design philosophy of this 'dynamic scour protection' is that, in principle, scouring of the rock is allowed as long as the full thickness of the layer is not eroded. Dynamic scour protections are environmental-friendly and can easily be constructed and maintained by using proven fall pipe technology and, therefore, they provide a good alternative to other types of GBS scour protections such as mattresses. However, design rules about the required minimum rock size and layer thickness in relation to the expected scour are not available.

In addition to the above mentioned lack of design rules for a dynamic scour protection, no scour prediction equations are available about GBS scour due to the combined wave and current action. Even observed data in physical models or

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prototype conditions about this combined scour are very scarce. In design manuals (Hoffmans and Verheij, 1997, Whitehouse, 1998) only scour prediction equations are presented for current-induced scour or wave-induced scour. Examples are the well-known formulas for current-induced scour of Khalfin (1983) and Teramoto (1973), of which the latter is applicable, even for submerged structures. With respect to wave-induced scour the formulas of Sumer et al. (1993a, 2001b) are well known. The only data on combined wave and current induced scour at large scale structures mentioned are those presented by Rance (1980). Data on combined wave and current induced scour at slender structures are presented by Sumer and Fredsøe (2001a).

Based on the above mentioned lacunas in scour knowledge the underlying study was initiated and carried out. The aim of the research was to collect data and, if possible, to derive a scour prediction formula in order to enable in the future a proper conceptual design of the scour protection for a GBS subjected to the action of combined waves and currents. Therefore, data were collected by carrying out small-scale model tests. Combined with literature data, amongst others of scour surveys at a GBS located in the F3 field in the North Sea, it was possible to derive a scour prediction equation. The equation allows to determine the expected scour and the required scour protection for conceptual design purposes.

PHYSICAL MODEL EXPERIMENTS

Description of the model

Physical model tests were carried out at in a basin with a length of 35 m and a width of 7 m at WL | Delft Hydraulics. In the facility waves and flows can be generated simultaneous. In the basin a test section was constructed comprising a bed protection over the total width of the basin with a length of about 4.5 m and a thickness of 0.1 m. On top of the bed protection a GBS model was placed with dimensions of 1.0 x 1.0 m^2. The local water depth at the bed protection was 0.65 m. A total of 12 tests were carried out in four main test series.

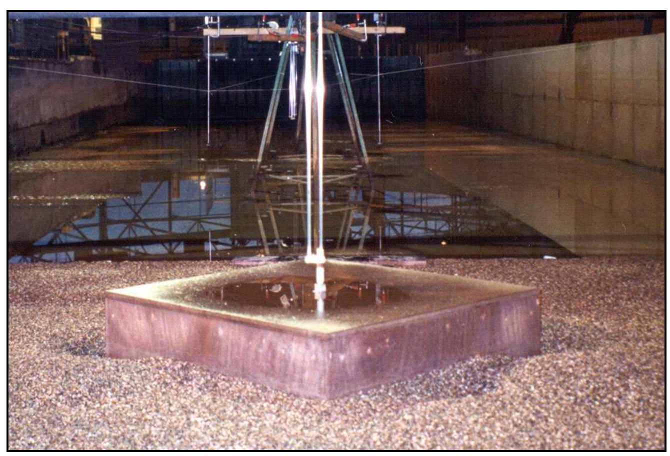


Figure 1: Physical model test on GBS scour

Test series

Four main test series were carried out, each focussing on a different parameter of the scour process. In Test series 1 the influence of the bed protection diameter was studied for a basic layout (square GBS with a height of 0.15 m, 45° orientation). The grain size was varied in three steps from d_{50} = 0.028 m to 0.085 m. In addition a test with increased wave load was carried out for the protection with the largest grain size.

For these tests the scour development in time was determined. In Test series 2 the hydraulic conditions were varied to study the influence of the hydraulics conditions on the scour. Tests were carried out for wave heights in the range H_s = 0.14 - 0.27 m and depth average flow velocities u_c varying from 0 - 0.25 m/s. These tests concentrated on the equilibrium scour depth. The development in time was not measured. In Test series 3 one test was carried out in which the height h_c of the GBS was varied from 0.15 m to 0.40 m. Test series 4 comprises two tests. One test was carried out with rounded corners of the GBS. In the second test the orientation of the GBS was changed from 45° to 90° relative to the wave and flow direction.

Test	d_{50} (cm)	h_c/h_0 (-)	H_s (m)	T_p (s)	$\hat{u}_\delta$ (m/s)	KC^* (-)	u_c (m/s)	u_{cw} (-)	u_*/u_{*cr} (-)	S_e (m)
1.1	2.8	0.23	0.22	2.0	0.33	1.02	0.21	0.38	1.05	0.064
1.2	3.7	0.23	0.22	2.0	0.33	1.02	0.20	0.38	0.99	0.065
1.3	8.5	0.23	0.22	2.0	0.33	1.02	0.21	0.38	0.78	0.048
1.4	8.5	0.23	0.27	2.3	0.44	1.56	0.19	0.30	0.87	0.062
2.1	3.7	0.23	0.27	2.3	0.44	1.56	0.20	0.31	1.12	0.081
2.2	3.7	0.23	0.22	2.0	0.33	1.02	0.00	0.00	0.95	0.091
2.3	3.7	0.23	0.23	2.0	0.34	1.05	0.09	0.21	0.99	0.062
2.4	3.7	0.23	0.16	1.6	0.20	0.49	0.00	0.00	0.76	0.033
2.5	3.7	0.23	0.14	1.6	0.18	0.44	0.25	0.59	0.77	0.024
3.1	3.7	0.62	0.14	1.6	0.18	0.44	0.25	0.59	0.77	0.071
4.1	3.7	0.23	0.22	2.0	0.33	1.02	0.24	0.42	1.00	0.036
4.2	3.7	0.23	0.22	2.0	0.33	1.02	0.25	0.43	1.00	0.046

d_{50} = median grain size, h_c = construction height GBS, h_0 = water depth, H_s = significant wave height, T_p = peak wave period, $\hat{u}_\delta$ = peak orbital velocity, KC* = modified Keulegan-Carpenter number (Eq. 2), u_c = depth average flow velocity, u_{cw} = nondimensional flow parameter (Eq. 1), u_* = bed shear velocity, u_{*cr} = critical bed shear velocity, S_e = equilibrium scour depth

Table 1: Overview of test parameters

Test conditions

From the measured hydraulic conditions various test parameters have been computed which are summarised in Table 1. Following Sumer and Fredsøe (2001a) a non-dimensional flow parameter has been used:

$$u_{cw} = \frac{u_c}{u_c + \hat{u}_\delta} \tag{1}$$

With u_c the depth average current speed and $\hat{u}_\delta$ the peak orbital velocity at the bed. Bed shear stresses and Shields values have been computed following well-known methods (see for instance van Rijn, 1993).

The Keulegan-Carpenter number, KC is defined by $KC = \hat{u}_\delta T_p / D$ in which D is the characteristic length of the structure and T_p the peak wave period. However, for large structures such as GBS it seems that not the dimensions of the structures are the determining factor but the water depth (see also the next section about the new scour formula). Therefore, in the present study a slightly modified KC number has been used defined as:

$$KC^* = \frac{\hat{u}_\delta T_p}{h_0} \tag{2}$$

With h_0 the water depth. The test parameters for the tests are summarised in Table 1. In the final column of Table 1 the maximum observed scour depth S_e are included.

Physical model results

In Test series 1 the influence of the grain size has been studied as well as the scour development in time. Figure 2 shows the scour development in time. From the results it can be concluded that the scour develops relatively fast. In the first 50 minutes about 70% of the scour has already been developed. Hereafter the scour develops on a much smaller rate.

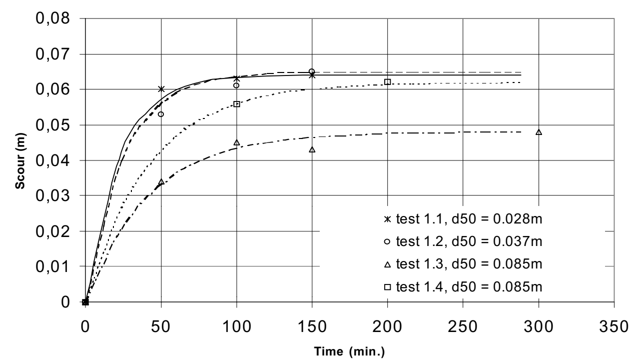


Figure 2: Scour development in time

Furthermore it can be concluded that the scour rate slows down with increasing grain size. However, after 150 minutes the scour was similar for the tests with d_{50} = 2.8 mm and 3.7 mm. A further increase of the grain size to d_{50} = 8.5mm results in a smaller scour depth even after an extension of the test series from 150 min. to 300 min. The smaller scour depth is explained by the flow velocities being less close to the critical flow velocities (see low ratio of u_* / u_{*cr} in Table 1). Test 1.3 has therefore been repeated with a higher wave height (Test 1.4). Although the ratio of u_* / u_{*cr} is still lower than those of Tests 1.1 and 1.2 the resulting erosion increased to similar values as measured for Tests 1.1 and 1.2.

Test series 2 focussed on the influence of the hydraulic conditions. Two typical examples of measured scour are shown in Figure 3. All tests clearly show that the scour is concentrated at the two side corners of the structure. The material from the scour holes has been deposited downstream, relatively close to the scour hole and the structure. The exception to this is Test 2.1 (see Figure 4) where probably due to the more severe hydraulic load the material is spread over a larger area outside the measured area.

The most striking from these results are the larger scour depths for tests with waves only compared with tests with both waves and currents (see for example Test 2.2 versus 2.3 and Test 2.4 versus 2.5). The scour depth reduces with about 40% when a current is added to the hydraulic loads. A possible explanation for this phenomenon might be that eddy formation by the wave orbital motion is suppressed by the flow conditions imposed onto the wave action. This phenomenon is not yet fully understood and therefore further research is required to study the wave-current interaction and to explain the observed smaller scour for combined waves and currents.

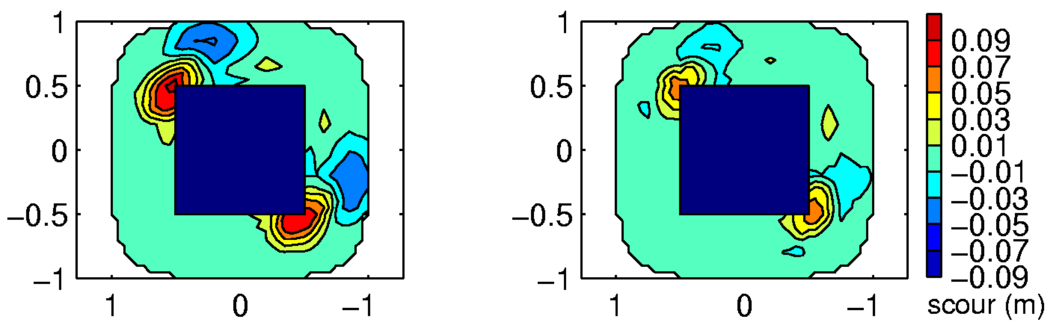


Figure 3: Scour results of Test 2.2 (left) and Test 2.3 (right), wave and flow direction is from lower left to upper right

Apart from the scour at the side corners the test results indicate secondary scour hole formation downstream of the primary scour holes at the GBS corners. This is the most pronounced in Test 2.1 (see Figure 4) but also visible in Tests 2.2 and 2.3.

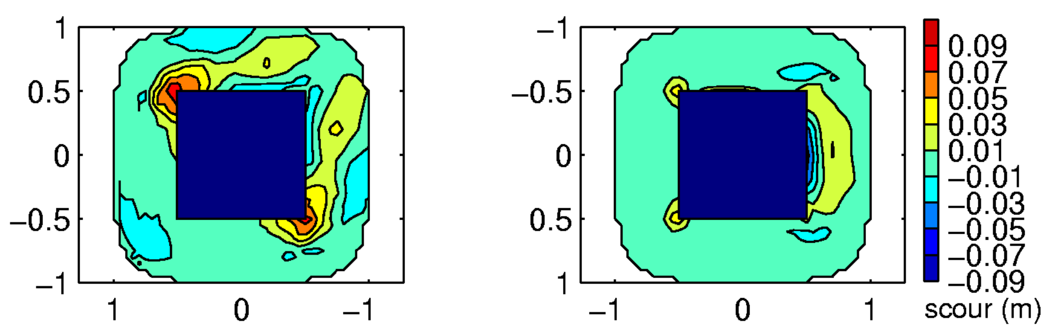


Figure 4: Scour results of Test 2.1 (left, wave and flow direction is from lower left to upper right) and Test 4.2 (right, wave and flow direction is from left to right).

In Test 3.1 the influence of the height of the structure has been studied by repeating Test 2.5 with increased structure height. The resulting scour clearly indicates the importance of the structure height. An increase of the structure height from 23% to 62% of the local water depth resulted into an increase of the scour depth with about 200%.

In Test 4.1 the shape of the structure has been modified by removing the sharp edges of the square structure. A comparison with Test 1.2 with similar hydraulic conditions indicates a reduction of the scour with about 50%.

The results for a test situation with a 90° orientation of the structure relative to the wave and flow direction is shown in Figure 4 (Test 4.2). The test results indicated a reduction of the scour holes with 30% compared with Test 1.2 which was carried out with similar hydraulic conditions. The scour pattern for this test is different from the other tests. The largest scour is found at the front corners of the structure. Scour also occurred downstream of the structure. Scoured material has been deposited immediately at the back of the structure.

NUMERICAL FLOW MODELLING

From the observed scour in the physical model it was concluded that adding a flow velocity to the hydraulic load enforced secondary scour at the back of the structure (see Figure 4, Test 2.1). This secondary scour might be explained by eddy formation in the lee of the structure. Similar to the flow over a sill the current over the submerged GBS might generate an eddy with a horizontal axis at the back of the structure. The nearbed flow velocities in the eddy are directed opposite to the main flow direction. When the flow velocities are high enough, gradients in the transport capacity occur and hence erosion of the seabed. The maximum erosion occurs just downstream of the re-attachment point where the velocities diverge and the local horizontal velocity is zero. At the wall of the structure the bed velocities will be zero causing deposition of the bed material directly near the structure. These effects are visible in Figure 4.

In order to verify the above hypothesis, numerical flow simulations was carried out for the tested GBS geometry and a typical flow condition in the absence of waves. The simulations were carried out with the flow modelling software CFX, which enables the simulation of three-dimensional flows. Figure 5 shows the bed shear stress components in flow and lateral direction. The results illustrate that in the lee of the structure bed shear stresses are directed towards the structure. Furthermore, the bed shear stress pattern correlates well with the secondary scour pattern of Test 2.1.

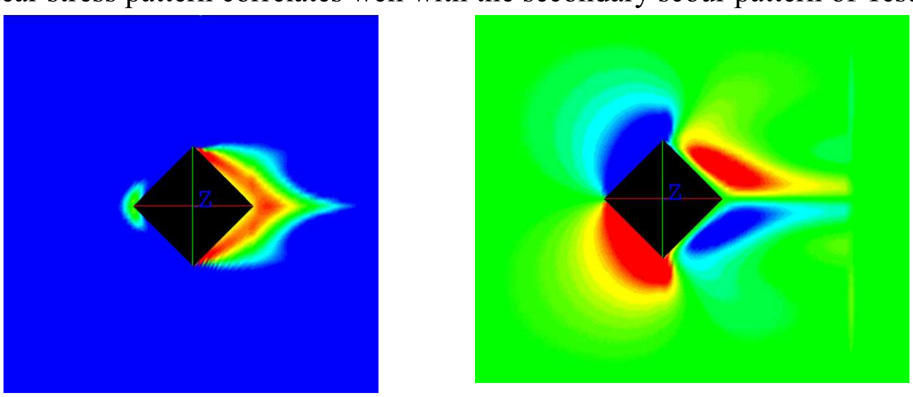


Figure 5: Bed shear stresses in flow direction (left) and in lateral direction (right), flow direction is from left to right.

From the above results it may be concluded that the flow simulations support the hypothesis of eddy formation and subsequent scour in the lee of the structure.

It should be noted that the presented results are representative for a situation with currents only (not tested in the physical model). The combined action of waves and currents will generate a much more complicated dynamic 3-dimensional flow field around the submerged structure. Further research is required to study the wave-current interaction around these type of structures.

SCOUR FORMULA

General shape

In order to develop a new formula for the prediction of the scour depth for large scale submerged structures the general concept presented by Breusers et al, (1977) has been applied, which describes the scour depth as the product of various influences:

$$S = S_e\, f(t) \quad \text{with} \quad S_e / L = \prod f_i \quad \text{and} \quad \prod_1^n f = f_1 \cdot f_2 \cdots\cdots\cdots\cdots f_n \qquad (3)$$

in which S = time-dependent scour, S_e = maximum scour, *f(t)* = function describing the time dependent scour, L = characteristic length, f_i = coefficients for various influences. These influences account for the wave characteristics, the ratio structure diameter - water depth, the influence of initiation of motion, the shape of the structure, the angle of wave and flow attack, sediment/rock diameter and gradation, etcetera.

This concept has been presented by Breusers et al, (1977) and has been adapted by various researchers (e.g. HEC-18, 1995; Escarameia & May, 1999; Melville & Coleman, 2000) to predict the scour around all types of structures. However, most of these formulas focus on one dominant process in particular situations, see for instance the formulas of Sumer et al. (1993, 2001b) for wave-induced scour only. In addition the time factor *f(t)* is not defined in many equilibrium scour formulas.

The underlying study was focused on large diameter structures, e.g. structures with a ratio diameter - water depth larger than 1.5. Scour around these type of structures depends less of the horizontal dimensions of the structure, but more of the water depth. Therefore, the characteristic length L has been replaced by the water depth h_0 and not by a characteristic or equivalent diameter of the structure D. Bridge piers may be considered as slender structures with $D/h_0 < 0.5$ and, subsequently, the characteristic length is the pier diameter. Breusers et al. (1977) presented a factor that takes this aspect into account automatically for slender and large structures, but also for intermediate range of $0.5<D/h_0<1.5$ (see also next section on influence of the ratio structure diameter-water depth).

The various parts of the total formula are discussed in the next section.

Influence of waves

The function f_1 describes the wave related scour. A linear relation between the modified Keulegan-Carpenter number KC* and the dimensionless scour depth S_e/h_0 could be derived from experimental data presented by Sumer and Fredsøe (2001b). If all other influences may be ignored the factor f_1 reads:

$$f_1 = 0.044 KC^* \qquad (4)$$

The water depth is the characteristic length in the modified KC^*-number and not the diameter.

Influence currents

The function f_2 describes the influence of a current on the scour depth. Recent work of Sumer and Fredsøe (2001a) resulted in the diagram given in Figure 6 showing the influence of a flow velocity on the scour depth for several KC numbers. The influence of the flow is the ratio between the scour depth at $u_{cw} = 0$ (waves only) and the scour depth for a given value of u_{cw}.

Sumer and Fredsøe (2001a) do not present a mathematical formulation and, therefore, an expression has been determined which approximates the given data points:

$$f_2 = \frac{A \tanh(3.5(u_{cw} - B)) + 1.9 - A}{A \tanh(-3.5B) + 1.9 - A} \qquad (5)$$

$$\text{with } A = \frac{0.95}{1 + 0.005KC} \quad \text{and} \quad B = \frac{0.8}{1 + 0.005KC^2}$$

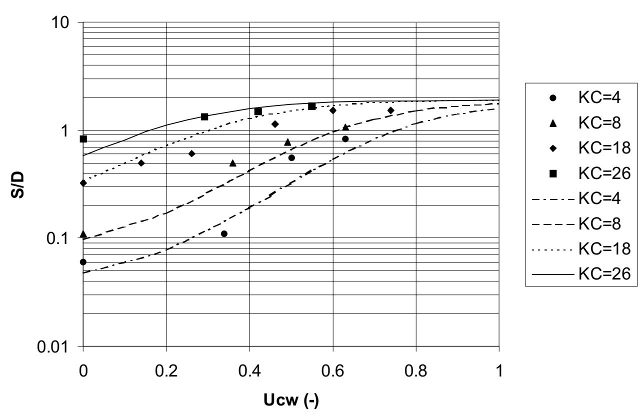


Figure 6: Influence of currents on scour depth (data points after Sumer and Fredsøe, 2001a).

Note that this formula has been derived from tests comprising slender structures, and as a consequence the formula is expressed in KC instead of KC^*. Future research should be carried out to confirm the suitability of this relation for large diameter structures.

Influence initiation of motion

The factor f_3 describes the influence of the critical flow velocity. In the literature two types of formulations are found for this function: for clear water scour $f_3 = (2.u/u_{cr} - 1)$ for $0.5<u/u_{cr}<1.0$ (Breusers et al, 1977; Khalfin, 1983) or $f_3 = u/u_{cr}$ or $u_*/u_{*,cr}$ (Hoffmans and Verheij, 1997; Teramoto, 1973) and for live bed scour $f_3 = 1$ for $u/u_{cr} > 1$. Note that for $u/u_{cr} < 0.5$ no scour will occur. Escarameia and May (1999) presented similar influence factors, but made a difference between circular and square structures. As the tests carried out in this study were all clear water scour tests the formulation has been adapted with the bed shear velocities, because it is difficult to decide which value of u, e.g. depth-averaged value or the value at for instance 1 m above the bed, should be applied. So, f_3 reads:

$$f_3 = \frac{u_*}{u_{*,cr}} \tag{6}$$

The critical bed shear stress velocity was computed from the critical Shields parameter. The latter was computed following Soulsby and Whitehouse (1997).

Influence structure height

All other influence factors are derived for structures extending through the water surface (emerging structures). A GBS, however, is a submerged structure and this affects the scouring. The influence of the height is included in the f_4 function.
Theoretically the value of the factor should be equal to 1 for h_c/h_0 approaching 1. The structure then becomes emerged and the influence of the height will be negligible. From the measured data it appeared that the f_4 value depends on the value of u_{cw}. For the tests without a current a value for f_4 is required in the order of 1, while for tests with combined waves and currents a value smaller than 1 was required.

On the basis of the now available data the following relation could be determined to assess the influence of the structure height:

$$f_4 = 1 \quad \text{for} \quad u_{cw} = 0 \quad \text{or} \quad h_c/h_0 = 1 \tag{7}$$

$$\text{else} \;\; f_4 = \tanh\left[3.5U_{cw}\left(\frac{h_c}{h_0} - 1.4\right)\right] + 1$$

It should be noted that most tests were carried out with a GBS height of about 25% of the water depth and only one test has been conducted with a larger structure height of about 60%. Another possibility should have been to investigate whether the relationship is applicable presented by Khalfin (1983): $S_e/D \therefore (h_c/D)^{1.43}$. However, this was not investigated because the parameter u_{cw} appeared to be relevant in our data set.

Influence structure shape

The function f_5 represents the influence of the shape of the construction. The other factors are all derived for circular piles, therefore the f_5 function is an influence factor for the shape relative to a circular shape. For slender structures various influence factors are presented in the literature (Melville & Coleman, 2000; Hoffmans and Verheij, 1997; HEC-18, 1995). However, for large structures these data are very limited, in fact only experimental results of large emerged objects presented by Rance (1980) are available. From the presented results the following values have been derived:

$f_5 = 1.0$ *for circular structures* (8)
$f_5 = 2.0$ *for square structures* (90^0 *orientation)*
$f_5 = 2.8$ *for square structures* (45^0 *orientation)*

Note: the influence of the angle of attack or alignment with respect to the flow direction is implicitly included in the f_5 value.

Influence ratio structure diameter-water depth

The function f_6 describes the effect of the length scale of the structure (usually the pier diameter) relative to the water depth. The function has been expressed by Breusers et al., (1977) as $f_6 = 1.5 \tanh(D / h_0)$ (Note that the ratio D/h_0 has been reversed to account for the change of the characteristic length compared to the original Breusers formula), or in the HEC-18 formula as $f_6 = (D / h_0)^{0.65}$, while Escarameia and May (1999) presented a reverse function $f_6 = (h_0 / D)^{0.6}$.

In principle, all those formulas could be applied, but having chosen the water depth as characteristic length (see previous section on general formula shape), a factor including the diameter of the structure is not longer important. Therefore, the value of the factor f_6 has been set at 1 for the present application of large scale offshore structures. However, in situations it is not clear whether D or h_0 is the decisive parameter, the function of Breusers is recommended, because it is valid for the whole range of h_0/D.

Influence time

In literature various equations are presented for the time-dependent development of the scour. Most of these formulations are of the form (Whitehouse, 1998; Sumer et al., 1993; Cardoso & Bettess, 1999; Melville & Coleman, 2000):

$$S = S_e \left[1 - \exp\left(-a \left(\frac{t}{T} \right)^b \right) \right] \tag{9}$$

with t the time in hours, T a characteristic time scale and a and b being coefficients.For simplicity a and b have been set at 1.0. Assuming the maximum measured scour depth for each test as the equilibrium scour depth only a value for T needs to be determined. In the literature various expressions for T are found. In most of these formulas T is expressed as a function of the grain size, relative density, structure diameter or water depth, KC number and flow velocity. As the data in the present study was limited a very simple relation for T was adopted which assumed a linear relationship between T and the sediment size d_{50}. The relation was derived from a fit through the data points and reads:

$$T = 0.2 + 60d_{50} \quad (10)$$

Resulting curves for the time variation of the scour for the various tests are presented in Figure 2. Further research is required to assessed a more generic formula expressing the time dependent scour.

Validation

For all test conditions the scour has been computed with the newly developed formula and compared with the measured scour depth in Figure 7b. From the results it can be concluded that for most tests the observed scour depths are within 80 - 120% of the predicted ones (computed value ±20%).

With respect to Test 4.1 with a square GBS with rounded corners a shape factor f_5 = 2.0 is required to match predicted and measured scour. As expected this value is between the value for a circular structure and square structure with a 45° orientation.

The developed formula to predict the scour depth has been verified with other relevant data sets available. They are summarised in Table 3.

GBS	origin data	h_0 (m)	h_c (m)	length x width (m^2)	H_s (m)	T_p (s)	u_c (m/s)
Case A*	model	41.8	12	63 x 56	12.4	15.6	1.3
F3	model	42.3	16	70 x 80	11.2	14.25	1.0
F3	field	42.3	16	70 x 80	9.5	13.25	0.64-0.82

* Data of tests carried out within framework of consultancy

Table 3 Validation data (all measures are prototype dimensions)

Data used for validation were from small-scale model tests for platforms in the North Sea and from a scour evaluation for an existing platform in the F3 field. The physical model tests for Case A were carried out on scale 55 for a 1/100 years storm event. The scour protection consisted of a thick layer of small size rocks at the corners of the GBS. For the two corners which face the most severe attack different grain sizes of respectively d_{50} =2.8 mm (model) and d_{50} = 3.7 mm (model) were used. Maximum measured scour depths and predicted values are summarised below and it may be concluded that the predicted scour is about 15 to 20% larger than the observed one.

rock size (mm)	Observed scour (mm)	predicted scour (mm)
2.8	85	97
3.7	78	91

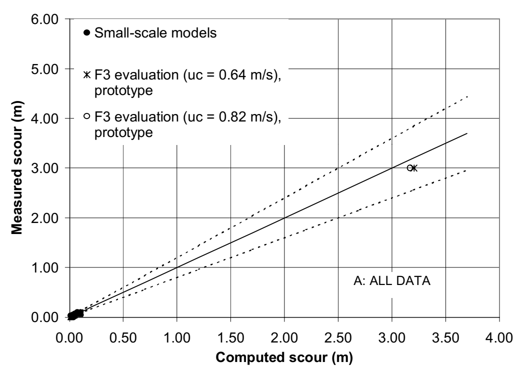
Table 4: Comparison of measured and predicted scour, Case A

The tests for the F3 platform were carried out on scale 40 and also for a 1/100 years storm event. The bed consisted of sand with a characteristic grain size d_{50} = 0.210 mm. From the observed measurements the equilibrium scour depth was estimated at 100 mm, while the predicted scour is also 100 mm.

Yearly scour surveys were carried out at the GBS in the F3 field in the North Sea. Since the installation in 1992 the observed scour is about 3.0 m (sand diameter d_{50} = 0.150 mm). In Bos et al (2002) the environmental conditions which occurred after the installation of the GBS have been estimated on the basis of a hindcast and measured data. The wave conditions are used to determine the orbital flow velocities for 1/1 year and 1/10 year storm event. The comparison between observed and computed scour is presented below.

observed scour: 3.0 m
computed scour: 3.2 m

Note: In Bos et al (2002) a comparison has been made between the scour computed with a modified Khalfin formula (see Hoffmans and Verheij, 1997) for current-induced scour and the observed scour. The computed values predicted a scour of 3.6 m, which is an overestimation of the scour depth.



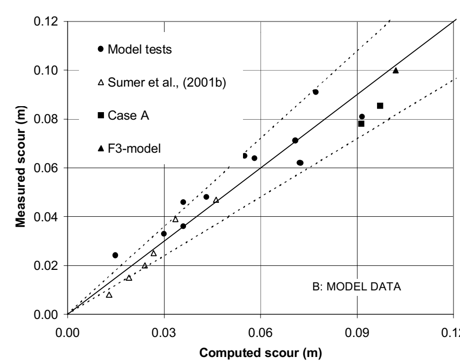


Figure 7: Comparison of measured and predicted scour depth

All scour data (computed and observed) are summarised in Figure 7. It can be concluded that for both model and prototype data most data points are within 20%. These results confirm the reliability of the developed formula. Although the amount of data is limited, obviously the formula predicts both prototype scour and model scour very well. The figure includes the data that has been used to develop the formula, e.g. data in Table 1 and the Sumer data. It should be noted that, in principle, these data may not be used for verification as they have been used to develop the formula. However, with respect to the data of Sumer, the data show that the formula is also able to predict the scour for large emerged structures. Furthermore, it should be noted that all available cases are more or less similar e.g. GBS structures in North Sea conditions. More heterogeneous data are required for further verification and validation of the formula.

PRACTICAL APPLICATIONS

When using the present formula for practical applications the following is noted:

- Application of the formula in engineering practise should be restricted to conceptual design studies within the limits of the test conditions, as the available data were limited (North Sea conditions, little variation structure height). For final design purposes physical model testing is recommended to verify and optimise the design.
- The formula has been developed for a symmetrical GBS. Although we expect that the influence of an a-symmetrical structure is negligible, this has not been verified.
- The scour depth might be influenced by elements placed on the vertical walls of the GBS structure, especially when placed near the corners of the GBS. These effects are not included in the formula.

Finally, the new formula as described above has been summarised below:

$$S = S_e\, f(t) \text{ with } S_e / h_0 = \prod f_i$$

with:

$$f(t) = 1 - \exp(-t/T) \text{ with: } T = 0.2 + 60 d_{50} \text{ (Note: t in hours)}$$

$$f_1 = 0.044 KC^* \text{ with } KC^* = \frac{\hat{u}_\delta T_p}{h_0}$$

$$f_2 = \frac{A \tanh(3.5(u_{cw} - B)) + 1.9 - A}{A \tanh(-3.5B) + 1.9 - A}$$

$$\text{with: } A = \frac{0.95}{1 + 0.005KC} \text{ and } B = \frac{0.8}{1 + 0.005KC^2} \text{ with } KC = \frac{\hat{u}_\delta T_p}{D}$$

$f_3 = u_* / u_{*,cr}$ (clear bed scour) and $f_3 = 1$ (live bed scour)

$f_4 = 1$ *for* $u_{cw} = 0$ *or* $h_c/h_0 = 1$ *else* $f_4 = \tanh\left[3.5U_{cw}\left(\frac{h_c}{h_0} - 1.4\right)\right] + 1$

f_5 = 1.0 for circular structures
f_5 = 2.0 for square structures (90^0 orientation)
f_5 = 2.8 for square structures (45^0 orientation)

$f_6 = 1.5\tanh(D/h_0)$ (Note: 1.5 is a safety coefficient)

CONCLUSIONS

On the basis of the work presented in this report the following is concluded and recommended:

- A new design formula has been developed for large scale submerged offshore structures subjected to wave or combined wave and current attack. Using the formula the maximum and time dependent scour depth can be predicted. For the available model and prototype data sets the predicted scour depth has been shown to be within 20% of the observed scour.
- Maximum scour occurred during tests with waves only and a 45° orientation of the GBS. The main scour occurred at the corners of the GBS structure.
- The test results have shown a reduction of the scour depth when a flow is added to a situation with waves only. This observed phenomenon for submerged structures differs from results presented previously for emerging structures (see Figure 6) and is not yet fully understood. Furthermore it is noted that at the back of the GBS secondary scour formation is likely to be caused by enforced eddy formation in the lee of the structure due to the current flowing over the submerged GBS structure.
- It is recommended to improve and verify the formula on the basis of other data sets from either prototype measurements and results from new physical model testing programmes.
- Numerical model studies are recommended to increase our knowledge on the hydraulic and morphologic behaviour on submerged structures.

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