Conference Paper, Published Version

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Abstract
This paper describes selected results of the scale model tests on scour around a triangular spud can under combined wave and current conditions with oblique direction. Physical modelling experiments were carried out using structures with two orientations, three different heights and variable hydraulic conditions. The observed scour depths were analysed. A new formula was developed for the prediction of scour around a triangular structure in non-cohesive material (sand) for typical North Sea design conditions.

1 Introduction

In connection with the site evaluation for jack-up drilling rig operations, scour assessments are usually carried out. The scour assessment comprises the potential of scour and a scour depth prediction for given hydraulic design conditions. Often, some scour is allowed depending on the spud can penetration depth. If the predicted scour depth is too high (more than penetration depth), scour protection measures need to be applied. As these measures are time and money consuming, the decision making on the necessity of scour protection measures must be based on a reliable and not too conservative scour depth prediction.

In principle, scour depth predictions can be based on a comparison with similar field cases, empirical scour depth prediction formulae and scale model testing. In general, field experiences are difficult to transfer to new situations and the degree of uncertainty of scour development remains high. Empirical scour prediction formulae do not exist for spud cans. Spud cans have different shapes, dimensions and penetration depths. Typical spud can designs are summarised by Rapoport & Young (1987).

In cooperation with Shell Netherlands, NAM and AJS a research project was set-up in order to investigate the scour development around triangular spud cans. The triangular spud cans represent the footings of a jack-up rig which is under contract in the North Sea. Jack-up operations are characterised by different operation periods, hydraulic design conditions and spud can penetration depths.

Scale model tests were carried out in order to investigate the effects of spud can orientation, hydraulic design conditions and penetration depth on the maximum scour depth for typical situations in the southern North Sea. Based on the test results a scour prediction formula was derived.

In this paper we first present typical prototype conditions which were considered (Chapter 2). Then we shortly summarise available literature for the prediction of spud can scour (Chapter 3). Next, the model set-up (Chapter 4) and selected test results are presented (Chapter 5). In Chapter 6 the data analysis and the scour prediction formula are provided. Finally, conclusions and an outlook are given (Chapter 7).

2 Typical prototype conditions

The model set-up and the validity range of the scour depth prediction formula were guided by typical prototype conditions. The considered jack-up is operated in water depths of about 20 to 40m in the southern North Sea. The leg and footing structure are schematised in Figure 1.

For the purpose of scale model tests, the structure was schematised by a fully submerged block with triangular base. The spud can forms a huge flow obstruction with a width of b_{obst}=10m and a height depending on the penetration depth. The leg bracings and the chords were not considered further, since it was judged that these structural members do not contribute significantly to the scour development.

The seabed of the southern North Sea generally consists of fine, medium dense to dense non-cohesive sand. Typical hydraulic design conditions are usually in the range between the 1/1 year condition and 1/100 years condition, depending on the operation period and scour management philosophy.

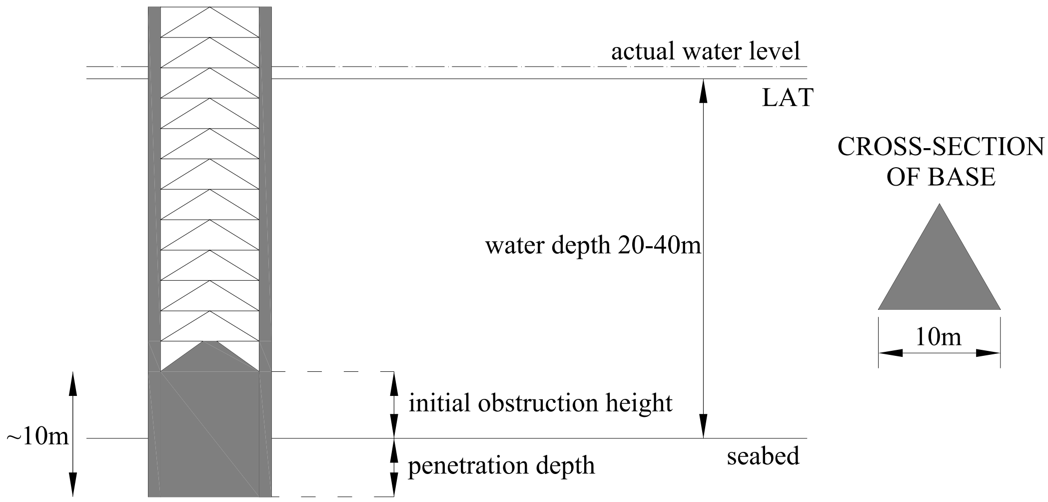

Figure 1 Leg and footing structure of the considered jack-up unit

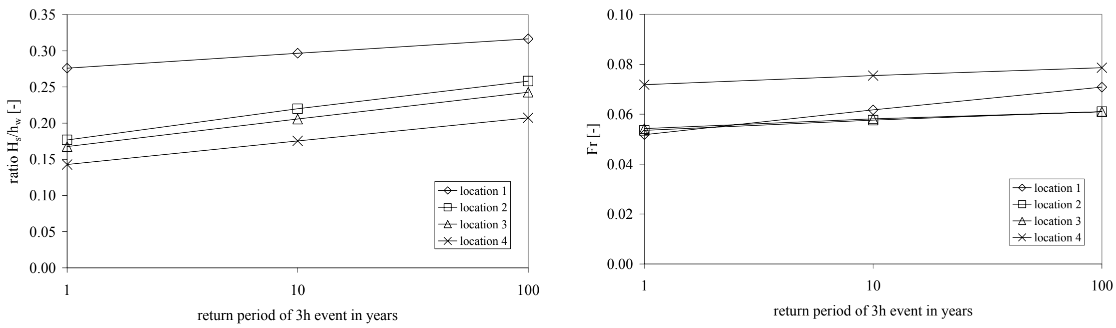

Figure 2 Typical prototype conditions (non-dimensional). Left: return period versus H_s/h_w; Right: Return period versus Froude number

A selection of typical non-dimensional hydraulic design conditions are presented in Figure 2. The significant wave height H_s was related to the water depth h_w, the depth-averaged current velocity was expressed in terms of the Froude number $Fr=u_c/(g*h_w)^{0.5}$. The central peak wave period T_p can often be approximated by $T_p=3.6…4.6*H_s^{0.5}$.

These prototype conditions were used to improve the understanding of scour development around triangular structures and to derive a scour prediction formula for fully submerged triangular structures in general.

3 Short literature review

Literature on scour around angular and especially triangular fully submerged structures is very scarce. Melville & Sutherland (1988) give shape factors for triangular emerged piles in current-only situations for design purposes. Sweeney et al. (1988) carried out two scale model tests with triangular fully submerged structures in current only situations. Rudolph et al. (2005) analysed inhouse data from scale model tests and field experiences and developed a rule of thumb for a rough estimate of the maximum scour depth for spud cans. Assuming that the obstruction height is smaller than the obstruction width, scour is determined by the shape and the obstruction height. The rule of thumb reads:

$$S_{\max} = K \cdot h_{obst}$$

with
K … influence factor, mainly depending on spud can shape [-]
h_{obst} … initial obstruction height of the structure [m]

For angular structures (blocks, triangles) a K factor between 1 and 2 was found for the available data.

Based on the available literature it was concluded that there are no data on scour around a fully submerged triangular structure under offshore conditions.

4 Model set-up

All tests were carried out in Delft Hydraulics' Scheldt basin (see Figure 3). Irregular waves were used in all tests (Jonswap spectrum with γ=3.3). The cross-current was generated by a continuous discharge from a pumping system. The angle between waves and current was between 60º and 90º. Velocity and wave height measurements were performed at various positions in the test section.
Scaling of spud can dimensions was guided by the Froude law with a scale factor of 1:50. In each test run we investigated 6 triangular spud cans at the same time. The applied structures were fixed at the floor of the facility and had a width of $b_{obst,m}$=0.20m. The obstruction height varied between $h_{obst,m}$=0.06m, $h_{obst,m}$=0.18m and $h_{obst,m}$=0.30m above the undisturbed surrounding seabed. The water depth was h_w=0.50m.
The spud can surface was smooth (material: wood). The bed of the facility was covered with a 0.20m non-cohesive sand layer (d_{50}=0.13mm). The scour depths were measured after drainage of the basin using a ruler. The maximum scour depth was defined as the maximum vertical difference between the bed level close to the structure and the surrounding undisturbed bed level.

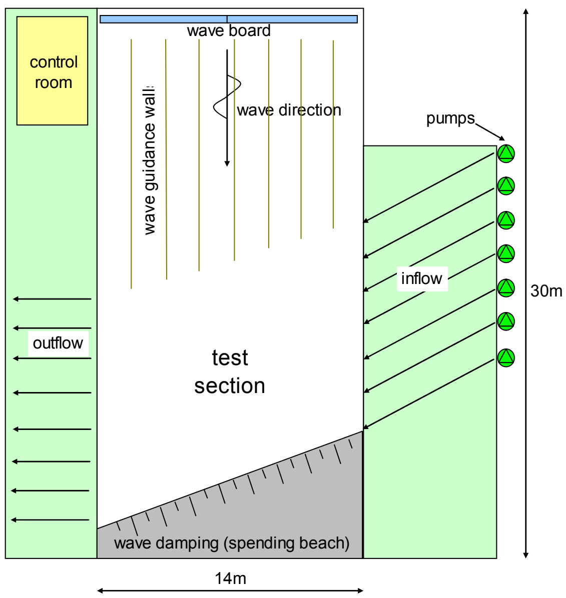

Figure 3 Schematisation of the test facility layout

The hydraulic conditions varied between

- H_s/h_w=0.2…0.4
- T_p=4.5*$H_s^{0.5}$
- Fr=0.04…0.2

As a measure of the relative magnitude of the current compared with the wave orbital velocity, the relative velocity U_{rel} was defined:

$$U_{rel} = \frac{u_c}{u_c + U_w} \qquad \text{(Equation 1)}$$

with
U_{rel} … relative velocity [-]
u_c … current velocity at z=0.5*h_{obst} [m/s] but with a maximum of z=b_{obst} or z=δ with δ being the height of bed boundary layer
U_w … peak orbital velocity at the bed as a function of H_s, T_p, h_w [m/s]

Under the considered hydraulic design conditions, the relative velocity U_{rel} is usually in the order of 0.3 to 0.4. The tests focussed on this range of U_{rel}. In addition to this narrow U_{rel} range, tests were carried out with variable U_{rel} (U_{rel}=0…1) in order to check the effects of waves only (U_{rel}=0), current dominated situations (U_{rel}>0.5) and flow only (U_{rel}=1).

All test conditions represented the live-bed situation (undisturbed wave and current induced bed shear stress > critical bed shear stress).

Prior to the test runs, the current velocity profile was determined for a range of conditions. It was found that in case of current only, the velocity profile follows a logarithmic shape with a bed roughness of k_s=0.01m and z_0=k_s/30.

5 Visual impressions of test results

After test execution and drainage of the basin, the scour patterns were inspected visually and scour depths were measured along several rays depending on the scour pattern and the scour extent. Figure 4 shows typical test results of current only situations. If the current hits at first the tip (here: point B), little scour occurs. If the current hits the face (here: face A-B), significant scour occurs. The spud can dimensions and the Froude numbers were the same.

In case of waves only, the scour pattern and scour depths were the same for waves hitting the tip and waves hitting the face. An image from a test with waves only hitting the tip at first is shown in Figure 5, left side. The difference with the current only situation can be explained by the oscillatory water particle motion: in every wave cycle, the flow hits the face in perpendicular direction which causes a much higher disturbance at the bed than hitting the tip at first.

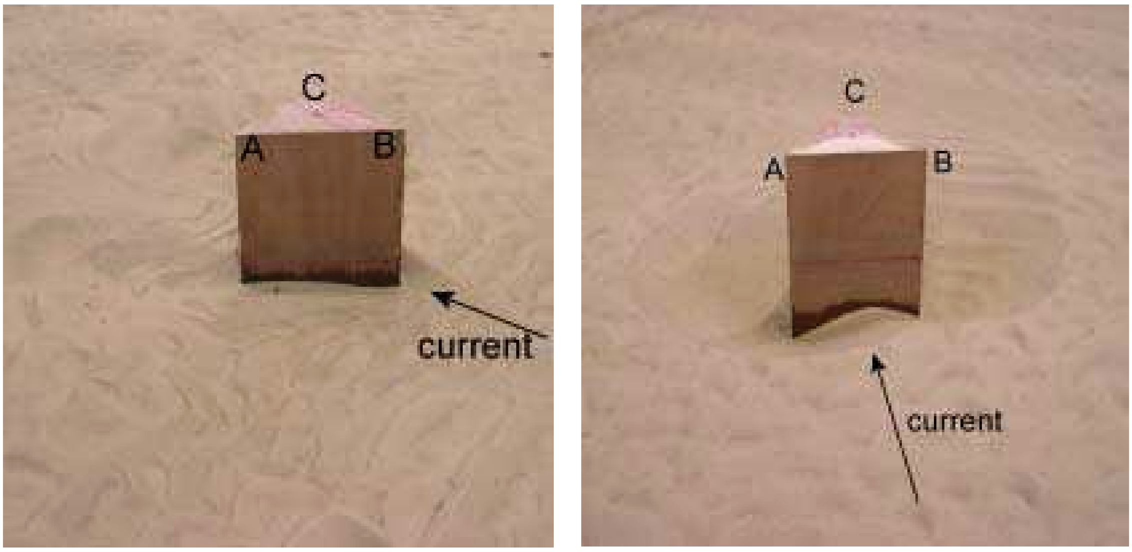

Figure 4 Scour patterns in case of current only; Left side: current against tip leads to little scour; Right side: current against face leads to significant scour. Note: Very high current velocities (Fr=0.15) were used to generate significant scour patterns. These are not representative for the considered typical design conditions.

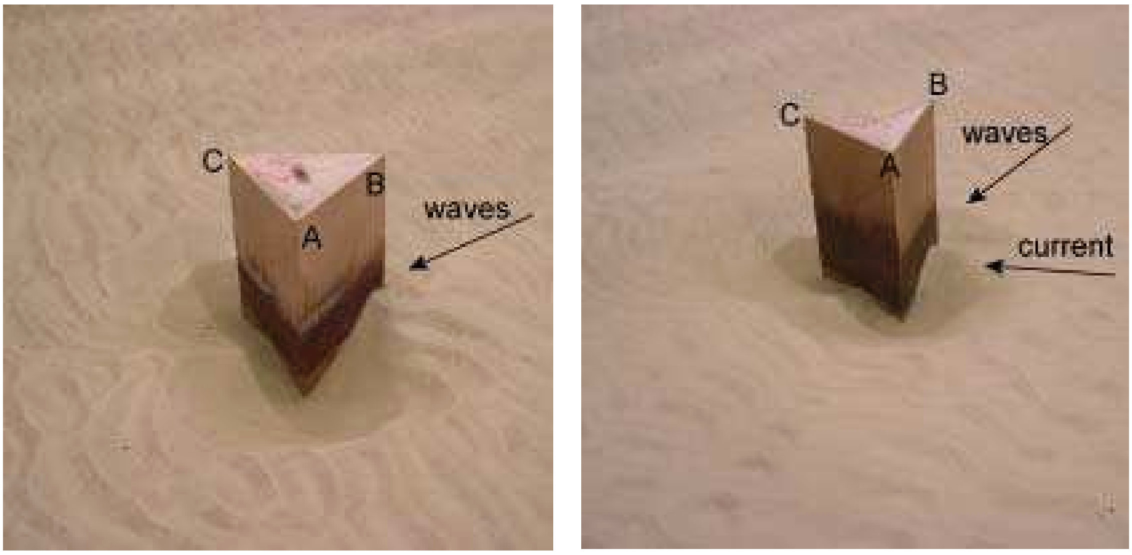

Figure 5 Scour patterns in case of waves only (left side) and wave dominated (right side)

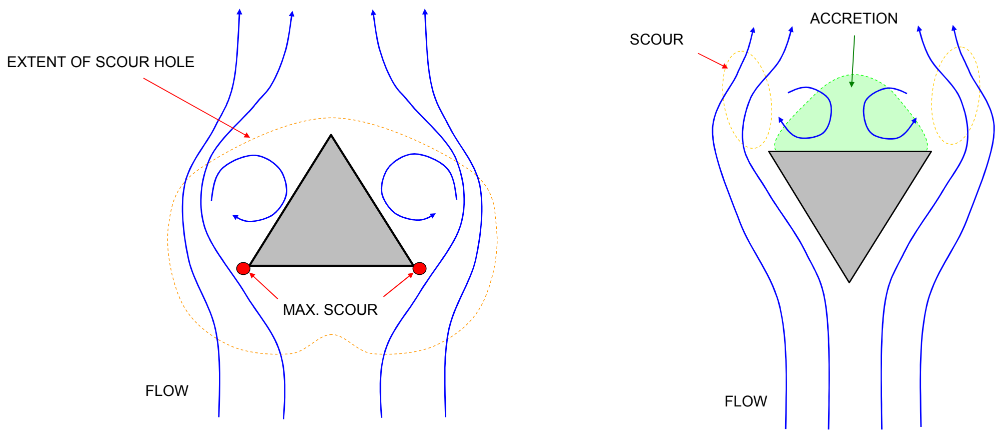

Figure 6 Schematisation of flow patterns and scour patterns in case of flow perpendicular to the face (left side) and flow hitting the tip (right side)

In case of a current superimposed on waves, the scour pattern starts to change. In case of wave domination, the change of scour depths at the corner points is marginal. A scour pattern of a wave dominated situation is shown in Figure 5, right side. The applied conditions are representative for typical prototype conditions (U_{rel}=0.4). A further increase of the current velocity (wave conditions constant) leads to scour patterns gradually changing towards the flow-only scour pattern with flow hitting the face. However, the maximum scour depths did not change significantly in the tests.

Schematisations of typical flow and scour patterns are indicated in Figure 6. In case of wave dominated conditions, the flow patterns are expected to be similar to current only, however, the flow patterns and scour patterns reverse during each wave cycle. In case of wave dominated situations, an accretion zone does not build up.

6 Analysis

Data selection

In total, 10 test runs were carried out with 6 structures each (3 heights, 2 orientations). In the analysis we focussed on the maximum and time-equilibrium scour depths measured around the perimeter. The scour hole extent and the scour hole slopes were not analysed in detail. The scour development in time was investigated by interrupting selected tests and measuring the scour depth. The development with time followed an exponential curve. The characteristic number of waves was determined at about $N_{char} \approx 1200$.

$$\frac{S}{S_{eq}} = 1 - \exp\left(-\frac{N_{waves}}{N_{char}}\right) \qquad \text{(Equation 2)}$$

with

S … scour [m] measured after N waves

S_{eq} … time-equilibrium scour depth, maximum around perimeter [m]

N_{waves} … number of waves [-]

N_{char} … characteristic number of waves [-], for $N_{waves}=N_{char}$ about 63% of the equilibrium is reached

Choice of non-dimensional parameters

The following general trends were expected which also determine boundary conditions for the set-up of the scour prediction formula.

- The scour depth generally increases with the width of the structure b_{obst}. If b_{obst} reaches the order of magnitude of the water depth, the effect of b_{obst} on S reduces and reaches an equilibrium. A further increase in b_{obst} does not lead to a further increase of S.
- The scour depth generally increases with h_{obst} but less than linearly. The increase of h_{obst} from e.g. $h_{obst}=0.1h_w$ to $0.3h_w$ has more effect on scour than the increase between $h_{obst}=0.8h_w$ to $h_{obst}=1h_w$.
- If $h_{obst}<b_{obst}$ then h_{obst} is the most important structural dimension affecting scour. If $b_{obst}<h_{obst}$ then b_{obst} is the most important structural dimension affecting scour.
- Scour generally increases with wave conditions. The wave conditions are best represented by the amplitude of the wave orbital motion.
- Scour generally increases with the current velocity.

In the analysis the following non-dimensional parameters were chosen:

- Dimensionless equilibrium scour depth S_{eq}/b_{obst}.
- Keulegan-Carpenter number KC. The KC number as defined in Equation 4 describes the relation between wave-induced load and a characteristic dimension of the structure. It was chosen to relate the amplitude of the wave orbital motion A to the spud can width.
- Relative structure height h_{obst}/h_w.

The current velocity was not considered in this analysis because of limited data with current only. Furthermore, test results indicated that the current velocity did not increase the wave-induced scour significantly within the range of interest (U_{rel}<0.5). Of course, theoretically, it would be more sound to define a combined wave and current parameter instead of the wave dependent KC number. In the near future, it is envisaged to obtain additional current-only data and to extend the validity to current-only and current-dominated situations as well.

Data fitting

Based on the above given considerations, the following principal formula set-up was chosen:

$$\frac{S_{max}}{b_{obst}} = c_1 \cdot \left\{1 - \exp\left[-c_2 \cdot KC \cdot \left(\frac{h_{obst}}{h_w}\right)^{c_3}\right]\right\} \qquad \text{(Eq.3)}$$

$$KC = 2 \cdot \pi \cdot \frac{A_w}{b_{obst}} \qquad \text{(Equation 4)}$$

with

S_{max} … maximum scour depth [m]

b_{obst} … width of structure [m]

KC … Keulegan Carpenter number [-]

h_{obst} … obstruction height [m], $h_{obst} \leq h_w$

h_w … water depth [m]

c_1, c_2, c_3 … empirical coefficients [-]

Based on the analysis of the selected data, the best fit was obtained if all three coefficients equal unity (c_1=1, c_2=1, c_3=1).

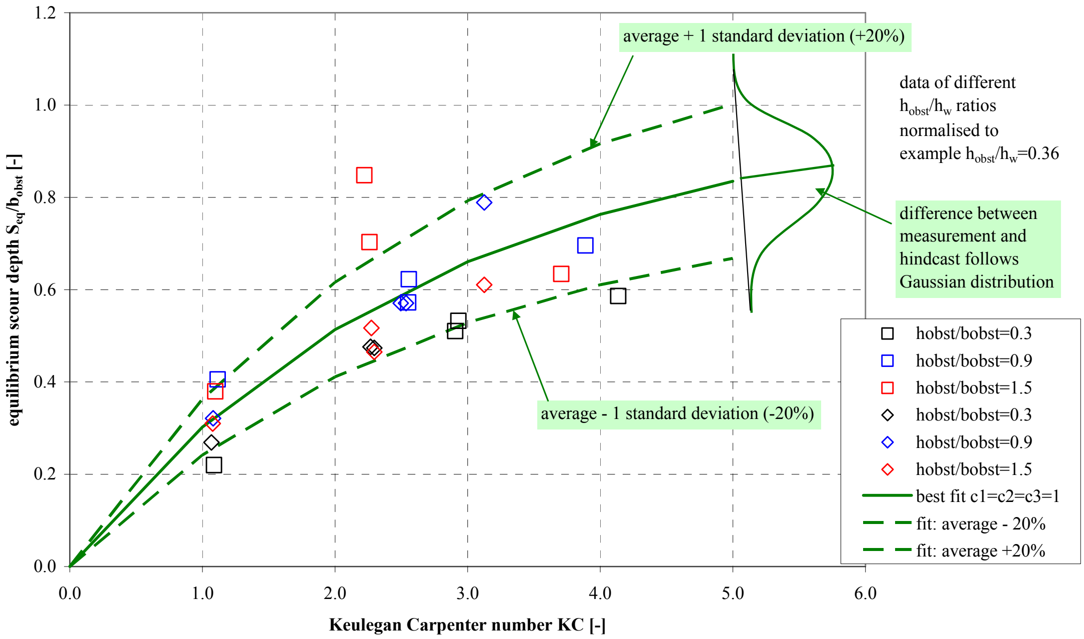

Figure 7 Relation between KC and scour depth prediction for an arbitrarily chosen example (h_{obst}/b_{obst}=0.9, h_{obst}/h_w=0.36)

For illustration of the data fit and the accuracy range, an example is provided in Figure 7. The scour depth prediction (green line) is given in terms of the KC-number for arbitrarily chosen values of h_{obst}/h_w=0.36, h_{obst}/b_{obst}=0.9.

<u>Quality of data fit</u>

The empirical coefficients presented above correspond with a standard deviation of about 20% for the ratio scour depth hindcast/ scour depth measurement (S_{hind}/S_{meas}). The 95% confidence interval was about 7%.

The quality of the data fit was assessed by comparing scour depth measurements with scour depth hindcasts for the test conditions. The results are presented in Figure 8.

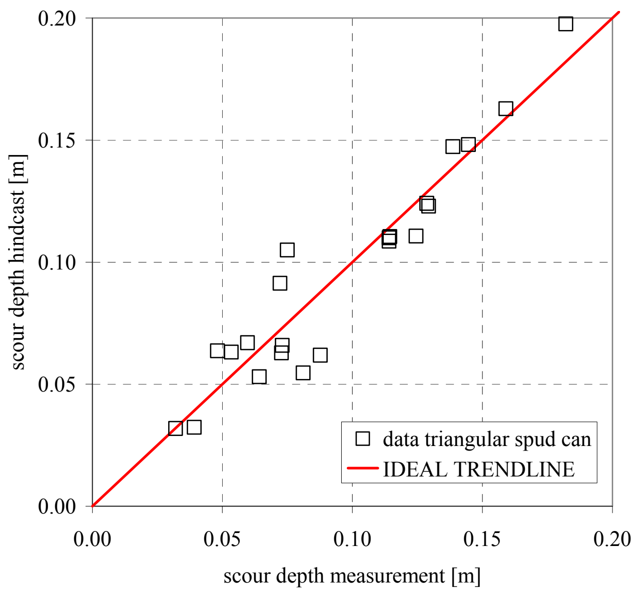

Figure 8 Quality of data fit: measurement versus hindcast, based on selected test results

Validity range of new formula

The new formula was derived based on scale model test data representing typical North Sea design conditions. The range of validity is approximately:

- $0<KC<5$
- $U_{rel}<0.5$
- $b_{obst}/h_w<1$; $h_{obst}/h_w<0.6$
- seabed material: non-cohesive mobile sand ("live-bed situation")
- shape of structure: triangular base

Recommendations for application for design purposes

Various scale factors may exist which should be taken into account when using the results of this study for design purposes: In practice, waves and currents might also approach from the same direction which might increase the hydrodynamic load and consequently the scour depth. Taking also into account the standard deviation of the measurements, we suggest applying a safety factor γ.

7 Conclusions and outlook

Scale model tests were carried out to study the scour development around a triangular fully submerged structure in combined wave and current situations. The tested situations were representative for typical design conditions of the southern North Sea. The practical application of the scale model tests is related to triangular footings of jack-up drilling rigs (spud cans).

The analysis of the test results led to a scour prediction formula for a fully submerged structure with triangular base in a live-bed situation. It was found that the KC-number, the structure height and the structure width are the dominating factors for the prediction of the scour depth. The orientation of the structure and the current velocity were of minor importance in the considered range of conditions.

The new formula represents a best fit and reads:

$$\frac{S_{\max}}{b_{obst}} = \gamma \cdot c_1 \cdot \left\{ 1 - \exp\left[-c_2 \cdot KC \cdot \left(\frac{h_{obst}}{h_w} \right)^{c_3} \right] \right\} \quad with\ KC = \frac{2 \cdot \pi \cdot A_w}{b_{obst}} \quad and\ c_1 = c_2 = c_3 = 1$$

For design purposes it is recommended to apply a safety factor γ in order to account for scale effects and limitations of the model set-up (e.g. tests: current perpendicular to waves; prototype: current and waves possibly unidirectional).

The test results indicated that significant scour can occur around a triangular structure in wave dominated situations. The scour development differs from the situation with a cylindrical pile (for cylindrical piles see e.g. Sumer & Fredsøe, 2002; Rudolph & Bos, 2006).

Therefore, we suggest not to apply a general shape factor on scour prediction formulae for cylindrical piles to account for the difference in shape between triangular structure and cylinder.

For more general use of this scour prediction formula, additional scale model tests need to be carried out. These tests should focus on:

- Current and waves unidirectional
- Variation of structure width (b_{obst})
- Scour in flow dominated situations ($0.5<U_{rel}<1$)

Acknowledgements

The authors are thankful to the Dutch Ministry of Foreign Affairs for co-financing this research project.

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