Scour protection of spud cans - a new design approach

Tim Raaijmakers (WL | Delft Hydraulics, The Netherlands)
Daniel Rudolph (WL | Delft Hydraulics, The Netherlands)

ABSTRACT

For jack-up operations in sandy seabed conditions, the assessment of scouring is often an important aspect. In recent operations where significant scour was expected, dumping gravel has proven to be an attractive measure for various reasons. To improve the prediction of scour and the design of scour protections around offshore structures a research program was executed including physical model testing. Besides the structure dimensions, also the orientation, the hydraulic conditions and the scour protection design (rock size, rock volume and layout) were varied in model tests. It was found that scour protections, consisting of small size rocks, performed well and that even small amounts of stones, dumped at the correct position, could significantly reduce the scour depth. The findings were quantified in a new formula for scour development around offshore structures with bed protection. In this paper, the research results are presented and their practical application is demonstrated for an imaginary field case.

KEYWORDS

Scour, scour protection, design formula, spud can, jack-up

1. INTRODUCTION

For jack-up operations in areas with an erodible seabed (e.g. sandy seabed), the assessment of scour development is an important aspect in planning and management of a rig operation. Excessive scour around spud cans might lead to settlement, tilting of legs or possible unsafe situations. If considerable scour is to be expected combined with small spud can penetration depths, it is often decided to apply a scour protection. The need for scour protection is illustrated in Figure 1. Various measures are available comprising mattresses, gravel bags or loose gravel. In recent operations, dumping loose gravel or cobbles has proven to be an attractive measure because of the low risk on damaging nearby structures, less harm to future jack-up deployment and an easy construction method. Application of scour protection consisting of small size rock is possible both before and during jack-up deployment, even after initial scour development. This paper focuses on the use of small size rock for scour protection.

A possible disadvantage of smaller stones, like gravel, compared to larger rocks, is the fact that these stones may become mobile under more severe weather conditions resulting in scour development in the scour protection material. However, if the scour depth remains limited during the operation period, this type of scour protection will prove adequate. Besides the size of rock, jack-up operators, contractors, risk managers and engineers often deal with other questions regarding scour protection, like: where should the protection be applied, which volume is needed, what is the structure stability during occurrence of the design storm, which survey interval is required etc.

All these subjects require accurate prediction techniques for the expected scour depth during drilling rig operations. In view of the above a research program including physical model testing was carried out by Shell and WL | Delft Hydraulics, aiming at the derivation of a proper design formula for scour protections consisting of small size rock (e.g. gravel, cobbles). Besides the dimensions of the spud cans, also the orientation of the spud can and the scour protection design (rock size and layout) were varied in laboratory experiments.

In this paper, first a brief overview of executed laboratory experiments of recent years (2004-2006) is presented. All test results were analyzed and important scour parameters are addressed. Subsequently a new design formula was derived. This formula is compared to earlier published formulae. To illustrate the application of the new design approach, an imaginary jack-up operation is considered. In this imaginary case, a jack-up will be deployed in summer season, but there is a potential risk that the operation will not be finished before winter season. The penetration depth is uncertain and it appears that scour protection is needed. Two sizes of gravel are available for purchase. The example illustrates the required gravel volume. The case yields valuable input for the scour management strategy and can be used in all stages of a drilling rig operation.

2. LABORATORY EXPERIMENTS

In recent years (2004, 2005 and 2006) numerous physical modeling experiments were executed by WL | Delft Hydraulics in the Schelde Basin, which has a length of 30m and a width of 15m, see Figure 2. The basin is equipped with a wave generator, several pumps to generate a cross-flow of up to $2m^3/s$, and a bed of fine, non-cohesive sediment (d_{50} = 130μm). The tested structures varied both in dimensions (width, height) and in shape (circular, triangular, square etc). Most structures were fully submerged, but some structures extended over the entire water depth.

This paper focuses on spud cans with triangular base, for two reasons. Firstly, most tests were executed on triangular structures (183 tests in total); and secondly, additional tests are planned on other structure shapes, while the triangular test data base is considered more or less sufficiently comprehensive.

The hydrodynamic conditions varied between waves-only, current-only and combined-current-and-waves conditions. However, the majority of the tests were based on typical storm conditions, which are normative for scour protections consisting of gravel. Typical wave height/water depth ratios were between H_s/h_w = 0.25 – 0.40. The relative flow velocity (ratio between current velocity and combined-current-and-wave velocity) is typically 0.3-0.6, which is representative for storm conditions.

Different scour protection layouts were tested, varying from no protection to abundant protection. The dimensions of the scour protection varied in height (number of layers from 0 to approximately 20), in extension (from 0 to 1 times structure width) and in location. Some of the tested layouts of scour protection are shown in Figure 3 and Figure 4. The left-hand side of each set of pictures shows the initial layout, the right-hand picture shows the situation after test execution. Additional information on the tests and selected preliminary results can be found in [1].

3. ANALYSIS OF EXPERIMENTS

After test execution, the Schelde basin was drained and the scour holes that developed around the structures were measured. The analysis of these scour holes focused on a few parameters, i.e. horizontal extent of the scour hole, maximum slope steepness and the maximum scour depth. This paper focuses on the maximum scour depth, which occurs close to the structure, because this parameter is most important for jack-up stability. Maximum scour depth is governed by the following topics.

<u>Structure characteristics</u>
It was already known that the maximum scour depth is very much dependent on the obstruction height. Based on analysis of laboratory experiments and field measurements, the following simple 'rule-of thumb' was proposed $S_{max}=K*h_{obs}$ [2]. This easily applicable formula provides a first rough estimate. In this formula, it is assumed that the bed material is mobile and the structure width is smaller than the obstruction height. A more comprehensive formula should of course also take into account influences such as hydrodynamics (currents, waves), mobility of the seabed/protection material and structure width/diameter.

The most favourable structure shapes with respect to scour are streamlined (e.g. circular and square, when aligned to the flow). The sharper the corners, the deeper the scour holes. Triangular structures, as studied in this paper, may be very logical with respect to the (also triangular) shape of the superstructure, but is not the most scour-friendly shape. Because of the back-and-forth wave motion, it is not possible to align a triangular structure with the hydrodynamic load to reduce scour. In the tests it was found that the orientation of the triangular structure has minor influence on the maximum scour depth, but only determines the location of the deepest scour hole.

<u>Hydrodynamics</u>
In current-only conditions, the actual hydrodynamic load (current velocity) is often not taken into account, when the scour depth is calculated. In waves-only conditions often the Keulegan-Carpenter number (KC-number) is used, which is a measure for the wave orbital motion at the bed relative to the structure width. In combined current-and-waves conditions also the relative velocity ($U_{rel} = u_c / (u_c+\hat{U}_w)$) is included, which is a measure to indicate whether the current action or the wave action is dominant.

Because for dynamically stable bed protections wave action is more important than current action and because the relative velocity is fairly constant during storm conditions (U_{rel} = 0.3-0.6), only the KC-number is used to express the hydrodynamic load. A clear relation between KC-number and maximum scour depth was found in the laboratory tests.

Time

The question whether maximum scour depth (equilibrium scour depth) will be reached during a design storm can only be answered if the scour rate is known. Time scales in laboratory tests are often difficult to compare with time scales in the field. However, the number of waves can be scaled very well. For example, a design storm with a duration of 6 hours and a mean wave period of 9s counts approximately 2400 waves. The same design storm can be modelled in the laboratory on a scale of 1:50 with a mean wave period of 1.3s. Therefore, the time effect was studied based on the number of waves.

The timescale of scour development was found to fit the following relation well:

$$S(N_{\mathrm{w}}) = S_{\mathrm{eq}}\left[1-\exp\left(-\frac{N_{\mathrm{w}}}{N_{\mathrm{char}}}\right)\right] \tag{1}$$

in which S = the scour depth as a function of number of waves; S_{eq} = the equilibrium scour depth; N_w = the number of waves and N_{char} = the characteristic timescale. After N_{char} waves approximately 63% of the equilibrium scour depth is reached; after $3*N_{char}$ about 95% of the equilibrium scour depth is reached.

Typical values for N_{char} found in laboratory tests are between 500 and 800 waves, which is approximately 1½ - 3 hours in prototype conditions. This illustrates that the equilibrium scour depth can indeed be reached during storm conditions.

Stone size

Larger stones are more stable during severe conditions. Statically-stable bed protections are based on no movement of the top layer (armour layer). If the design storm is more severe, larger armour stones are chosen. To create a smooth transition between large armour stones and fine grains in the seabed one or more filter layers are applied.

The objectives of a dynamically stable bed protection are totally different. Only one gradation of stones is applied. This one layer of stones combines the functionality of a filter layer and an armour layer. Therefore, the stone size cannot be too large (too permeable) and not be too small (too mobile). Therefore, often gravel-like material will be used with nominal stone diameters (D_{n50}) around 0.05 to 0.10m. These stones will generally be stable during normal conditions (tidal current + small to moderate waves), but will be redistributed during design storms. Deformation will occur, which has both negative and positive consequences. Negative, because still a scour hole will develop, although less deep than in the unprotected case. Positive, because initially unprotected parts of the seabed will become protected due to redistribution of the protection material.

When the redistribution is considered to be unacceptable, or in other words the scour hole becomes too deep, dumping somewhat larger stones can be effective. However, dumping a larger volume is often far more effective.

Applied gravel volume

Because the gravel volume is an important parameter in dynamically stable bed protections, attention should be paid to the method of scaling between laboratory and prototype scale. Translating a certain bed protection layout into a dimensionless characteristic number is not straightforward, as protection width, layer thickness, shape of structure and applied stone size can be different for different types of structures.

In order to come to a dimensionless parameter, describing the applied volume, two important conclusions were drawn from the model tests:

I. Not the absolute thickness of the protection is considered important, but the number of applied layers. Because protection material is redistributed during design conditions, the total volume of protection material may be translated to a uniformly applied number of layers. According to this assumption, heaps of dumped stones may be spread out as if there are uniform layers that cover the entire seabed around the structure. This rather crude assumption was confirmed by the model tests. Both Figures 3 and 4 show that this redistribution indeed occurs. During severe conditions, an initial scour hole develops, gravel becomes trapped in the scour hole and covers the side slopes. The pictures clearly show that the protection material is spread out over the scour holes, while hardly any loss of gravel volume occurs.

II. Not all dumped material may be taken into account. If gravel is dumped too far from the structure to be protected, this gravel will not be redistributed and transported to the scour hole, where it is most effective in reducing scour depth. Whether gravel is dumped at an 'effective location' depends on the horizontal extent of the scour hole. A significant relation between extent and obstruction height was found. Depending on the hydrodynamic conditions, the extent varies between approximately 1 to 2 times the obstruction height. This means that for small storms gravel, dumped within a distance of $1*h_{obs}$, is effective, while for the largest storms gravel, dumped within a distance of $2*h_{obs}$, can even be effective.

Based on these two conclusions, the following formula for the dimensionless number of protection layers is defined.
For safety reasons, the effective area extends to only $1*h_{obs}$ of the structure (see Figure 1).

$$n_{\text{layers}} = \frac{V_{\text{bed protection}}}{A_{\text{eff}} D_{\text{n50}}} \qquad \text{for triangular structures: } A_{\text{eff}} = (3b_{\text{obs}} + \pi h_{\text{obs}}) h_{\text{obs}} \qquad (2)$$

in which n_{layers} = the number of stone layers, $V_{bed\ protection}$ = total applied volume of scour protection within a distance of $1*h_{obs}$; A_{eff} = effective area, D_{n50} = nominal stone diameter. The number of layers n_{layers} in fact describes the amount of stone layers that would be present if the total applied stone volume is spread out over the effective area.

The laboratory tests showed that with sufficient layers scour depth reductions between 40 and 60% could be obtained.

5. DESIGN FORMULA FOR SCOUR PROTECTION

Based on the above described parameters that affect scour depth, the following formula was derived, which seems rather complicated at first sight, but in fact it consists of three simple components (terms between [ ] brackets).

The first part describes the interaction between hydrodynamics and structure dimensions. The fitting coefficients 'α_{L1}', 'α_{L2}', 'α_{L3}' and 'α_h' are structure-dependent. In future, it is intended to fit these coefficients for different structure shapes. The second part describes the time effect, while the third part describes the characteristics of the applied scour protection, both volume and stone size.

Another way to look at this formula is to imagine that the resulting scour depth is a combination of load and strength. The terms in the first line describe the storm impact (= load), dependent on structure characteristics, wave load and storm duration. The terms in the second line describe the resistance of the seabed against scouring (= strength), dependent on mobility of the scour protection material and the amount of scour protection material.

$$\frac{S}{b_{obs}} = \overbrace{\alpha_{L1} \cdot \left[1 - \exp\left(-\alpha_{L2} \cdot (KC - \alpha_{L3}) \cdot \left(\frac{h_{obs}}{h_w}\right)^{\alpha_h}\right)\right]}^{\textit{hydrodynamics and structure characteristics}} \cdot \overbrace{\left[1 - \exp\left(-\frac{N_w}{N_{char}}\right)\right]}^{\textit{time effect}} \cdot \ldots$$

$$\ldots\ldots\ldots \underbrace{\left[\alpha_{n1} + (1-\alpha_{n1}) \cdot \exp(-\alpha_{n2} \cdot n_{layers}) \cdot \left\{1 - \exp\left(-\left(\frac{MOB}{\alpha_{m1}}\right)^{\alpha_{m2}}\right)\right\}\right]}_{\textit{characteristics of applied scour protection}} \qquad (3)$$

in which S = scour depth; b_{obs} = obstruction width *or* width of spud can *or* face diameter; KC = Keulegan-Carpenter number = $\hat{U}_w * T_p / b_{obs}$; $\hat{U}_w$ = maximum orbital velocity of waves with significant wave height H_s and peak period T_p; h_{obs} = obstruction height *or* spud can height; h_w = water depth; N_w = number of waves; N_{char} = characteristic number of waves; n_{layers} = characteristic number of layers of protection material; MOB = relative mobility = mobility according to Soulsby (as described in [3]) due to combined current-and-waves divided by critical mobility.

The fitting constants α_{L1}, α_{L2} and α_{L3} describe the dependency on hydrodynamics; α_h accounts for the structure height; α_{n1} and α_{n2} describe the influence of amount of applied material; α_{m1} and α_{m2} account for the relative stability or mobility of the applied gravel. All fitting coefficients were optimized using a Nelder-Mead simplex algorithm to reduce the Mean Least Square Error of the difference between prediction and measurement.

The recommended values for all constants in formula (1) are: $\alpha_{L1} = 1.08$, $\alpha_{L2} = 0.53$, $\alpha_{L3} = 0$, $\alpha_h = 0.64$, $\alpha_{n1} = 0.40$, $\alpha_{n2} = 0.09$, $N_{char} = 630$, $\alpha_{m1} = 0.72$, $\alpha_{m2} = 2.22$. These values are only valid for a triangular shape.

The goodness of fit can visually be deduced from the right-hand graph of Figure 5. To account for 95%-confidence, coefficient α_{L1} should be set to 1.35. The probability that the predicted value is exceeded is then only 5%.

It is emphasized that although the hydrodynamics are solely described by the wave action (through the KC-number) and that the current action is implicitly assumed to be present (because the formula is fitted for storm conditions with $0.3 < U_{rel} < 0.6$), the effect of the current is also incorporated through the relative mobility number.

6. SPECIAL CASES OF DESIGN FORMULA FOR SCOUR PROTECTION

No scour protection

If no scour protection is applied, the number of layers of the protection reduces to zero ($n_{layers} = 0$), the mobility rapidly approaches 1 because coefficient $\alpha_{m2} > 1$ and the entire last part between brackets, reduces to 1. The formula reduces to a formula for scour around unprotected triangular structures, only dependent on the KC-number (measure for hydrodynamic load) and number of waves (measure for time).

No scour protection and very long storms

If the storm lasts sufficiently long, the equilibrium scour depth is reached. Only the first part between [ ] remains and the design formula reduces to

$$\frac{S_{eq}}{b_{obs}} = \alpha_{L1} \cdot \left[1 - \exp\left(-\alpha_{L2} \cdot (KC - \alpha_{L3}) \cdot \left(\frac{h_{obs}}{h_w} \right)^{\alpha_h} \right) \right] \quad (4)$$

A formula of this shape was published earlier [4]. Based on the available data, coefficients $\alpha_{L1} = \alpha_{L2} = \alpha_h = 1$ and $\alpha_{L3} = 0$ were found (only valid for triangular shapes). For this particular case of no protection and equilibrium scour depth the predicted scour depths are very similar.

Comparison of formula with formulae for other shapes

To compare this formula (fitted for triangular structures) with scour formulae of Sumer et al. [5, 6, 7] and Rudolph et al. [4, 8], required number of input data for the new formula was further reduced: the structure height h_{obs} was taken equal to the water depth, which means that the structure extends over the entire water column.

Sumer et al. investigated scour development around various structure shapes in waves-only and combined-current-and-waves conditions. In waves-only conditions [5, 6], three different structure shapes were studied: circular, square with the side towards the waves (°90) and square with the tip towards the waves (°45). They concluded that in absence of a current, wave-induced scour only occurs above a certain threshold of KC-number. In combined-current-and-waves conditions, Sumer and Freds¢e [7] published a formula that is only valid for circular piles. In presence of a current, the KC-threshold decreases and scour also occurs for smaller KC-numbers. Rudolph and Bos [8] focused more on KC-numbers between 0 and 10, which is a typical range for structures in the North Sea and adapted the formula to these circumstances.

To visualize the predicted scour depths by the present design formula in relation to earlier published formulae, all mentioned formulae are plotted in the left-hand graph of Figure 5. This comparison is based on equilibrium scour depth (live-bed scour) for piles of different shapes extending over the entire water column, with a relative velocity 'U_{rel}' of 0.5.

It should be realized that the black lines are based on waves-only conditions, the red lines on combined-current-and-waves (formulae in principle valid for $0 < U_{rel} < 1$) and the blue lines especially on storm conditions with $0.3 < U_{rel} < 0.6$ (U_{rel} is not a parameter in formula 1).

Based on Figure 5 it can be concluded that triangular structures induce more scour than circular structures in comparable conditions. The results for triangular structures are especially sensitive for the KC-range from 0 to 20, which was indicated as the typical range for North Sea storm conditions. Predictions for waves-only conditions around circular and square piles are clearly smaller, but also considered to be hardly applicable in practice, since waves-only conditions are purely theoretical.

Because the present test data set is not well covered for large KC-numbers (very long waves), the asymptotic value of $S_{eq}/D = 1.1$ may not be very accurate. It is assessed that this does not influence the application of this formula in offshore engineering practice.

Application of very large gravel volumes

The main purpose of this research was to investigate whether relatively small volumes of relatively small material (like gravel) are effective in reducing scour depth around offshore structures, like spud cans. This purpose comprises two essential elements:

I) this approach should be adopted when reducing scour depth is an adequate solution. Most of the time some scour development is acceptable as long as a certain limit is not exceeded;

II) this approach is based on gravel-like material and it should be realized that stones of this size will generally be mobile during design storm conditions. Consequently, a scour hole will always develop, although it will be less deep than in the original seabed material.

Therefore, aiming at no scour development at all by dumping large amounts of rock is not an efficient solution. This is incorporated in the new design formula (3). When the number of layers becomes large, the last part between [ ] reduces to α_{n1}. This means that even if many gravel layers (of suitable size) are applied still a scour hole will develop with a depth of $100^*\alpha_{n1}$ % ≈ 40% of the unprotected scour depth.

This coefficient was bounded during the fitting procedure of all coefficients, because larger reductions in scour depth were not observed during the laboratory tests. It may be possible that for other configurations of scour protection larger reductions can be obtained.

Application of very large stones

Larger stones will be more stable during design conditions. In the design formula, this is taken into account through the relative mobility. When the relative mobility becomes smaller (stones become more stable), the last part between { } decreases faster and the scour depth reduces. However, when stones become too large, the filter characteristics of the scour protection deteriorate and seabed material will be washed through the relatively large pores between the stones. Then one (or more) filter layer(s) need to be applied. The scour protection becomes more like a statically stable protection, which is based on no movement/redistribution of the protection material. As explained above, large stones are often not feasible in drilling operations.

It is emphasized that this formula does not account for the filter characteristics and it is not recommended to apply this formula for large stones. The formula includes some safety, because even for very stable stones the scour depth will never become smaller than 40% of the unprotected scour depth.

7. EXAMPLE OF APPLICATION OF NEW DESIGN APPROACH

The new design formula has a very flexible set-up. Depending on the shape of the spud cans, design storm conditions (e.g. summer or winter conditions), duration of operation (e.g. weeks, months or years) and available scour protection material a scour management plan can be made. At present, additional tests are executed by Delft Hydraulics to extend this approach to other structure shapes such as square and circular structures.

This new design formula is illustrated for triangular structures. The following imaginary case illustrates the functionality of the formula for three important phases in a drilling operation.

Phase I: planning of drilling operation

In summer season, a new borehole needs to be drilled at a gas platform. The jack-up drilling rig that is available for the operation has four legs and footings with a triangular base. The width and height of this triangular base are both 10m. Because the triangular footing is the main scour-inducing structure of a platform leg, formula 3 is considered to be suitable for the scour assessment.

The drilling operation is planned in 15m water depth. Due to uncertainty about the local soil conditions, the penetration depth can not be calculated very accurately. It is estimated that the penetration depth will be between 2.5 and 3.5m. The hydrodynamic design condition is based on a 1/20 year storm. The significant wave height H_s is 3.8m, the peak wave period is 8.8s and the current velocity is 0.7m/s. The expected storm duration is 6 hours, which means almost 2500 waves.

No scour protection

First, it has to be assessed whether scour will be problematic. Therefore formula 4 is applied to calculate maximum scour depth without scour protection during the 1/20 year design storm. The scour depth after occurrence of the 1/20y design storm is estimated at 2.8m (95%-confidence = 3.8m) if a spud can penetration of 3.5m was achieved. In case of 2.5m penetration, the scour depth would be about 3.1m (95%-confidence = 4.1m).

However, it is emphasized that in the unprotected situation current-only or current-dominated conditions may cause larger scour holes than wave-dominated conditions during storms. Because unprotected sand particles can already be transport by currents, the normal tidal situation may be normative. The unprotected scour depth in current-only or current-dominated conditions is estimated in the order of the structure height, which will be approximately 6-7m.

It can be concluded that due to the relatively large spud cans, shallow water and severe conditions, scour protection is necessary, both in normal tidal conditions and extreme storm conditions.

Scour protection

For scour protection, two gradations of rock are available. The first gradation consists of 1-3" gravel, with an estimated D_{n50} of 0.05m; the second gradation is somewhat coarser: 2-6" cobbles with an estimated D_{n50} of 0.09m. Both gradations have a solid density of ρ_s = 2650 kg/m^3 and a bulk density of ρ_{bulk} = 1600 kg/m^3.

In Figure 6, the scour depth is plotted against useful applied 1-3" gravel volume per platform leg. In total, four lines are drawn, representing the 'best estimates' and the '95%-confidence' for two different penetration depths. It can be concluded from the left graph that when sufficient gravel is applied, the scour depth can be reduced to 1.5-2.0m (best estimate). When better penetration is achieved, the scour depth is slightly smaller.

For very small gravel volumes, a sharp bend in the trend line can be observed (see attached figures). This bend is located at the transition between complete coverage of the seabed with precisely one layer and coverage of only a few places. If only a very small amount of stones is dumped, the scour depth returns to the unprotected scour depth. Predicting scour development for such small amount of stones is hardly possible.

The right graph of Figure 6 shows the predicted scour depth divided by the penetration depth. As a rather simple criterion it is stated that, when the scour depth becomes equal to the penetration depth, failure occurs (S/d_{pen} = 1). This graph clearly shows that, although the scour depth is only slightly larger for smaller penetration, the safety against failure is much larger for good penetration. An increase of penetration depth works twofold: a larger penetration depth means a smaller obstruction height above the seabed and a larger safety against scour development.

When safety is included (95%-confidence), a gravel volume of approximately 20m^3 at each leg of the drilling rig should suffice, assuming penetration of 3.5m can be achieved. When the penetration depth is less (d_{pen} = 2.5m), the graph shows that much larger volumes of gravel (about 190m^3) need to be dumped.

A similar figure can be drawn for scour protection consisting of 2-6" cobbles, see Figure 7. It can be noticed that small volumes of 2-6" cobbles are very effective in reducing scour depth, because 2-6" cobbles are less mobile during design storm conditions than 1-3" gravel. Gravel is especially effective when dumped in large volumes, since large volumes imply many layers.

Summarizing, for this particular case scour development would become too severe, when no scour protection is applied. Both 1-3" gravel and 2-6" cobbles can be used as scour protection. When 2-6" cobbles are used smaller volumes are sufficient. Although 1-3" gravel will be more mobile during storms, it can still be used as scour protection as long as many layers are applied. The penetration depth is a very influential parameter, because a larger penetration depth means a smaller obstruction height, thus less scour, while deeper scour holes can be allowed.

Phase II: installation of drilling rig

Based on the calculations made in the planning phase, it was decided to proceed with the operation. A nearby quarry can deliver 1-3" gravel for a reasonable price and a side stone dumper with a loading capacity of 1000 tons is available in this period. With an estimated dry bulk weight of 1600 kg/m^3 this means that this ship can carry about 625 m^3 of gravel. The drilling rig operator wants to know which penetration should minimally be achieved for sufficient safety (95% confidence) against scour. The operator is aware that gravel should be dumped within the effective area (A_{eff} in equation 2) and estimates the loss due to badly placed stones outside this area at 25%. Therefore, about 125m^3 of gravel volume will be available for each of the four legs.

The left graph of Figure 8 depicts the scour depth against the penetration depth, given the fact that 125m^3 of 1-3" gravel is dumped within the effective area around each leg. It can be observed that larger penetration depths cause smaller scour depths. In the special case that the spud can penetration is equal to the spud can height, no scour is predicted. Generally, some kind of superstructure will be present on top of the spud can. Although, most of the time, this structure is more slender than the spud can, some scour will probably occur.

The right graph of Figure 8 shows that the safety against failure is even more sensitive to penetration depth. The safety rapidly increases when the penetration depth increases from 1.5 to 3m. The drilling operator concludes from this graph that a penetration depth of 2.1m may be just sufficient (best estimate value), but that when a larger penetration depth than 2.8m can be achieved, scour exceeding the penetration depth is not very likely (95% confidence).

The company decides to deploy the drilling rig and fortunately a penetration depth of 3.5m is reached. The side stone dumper dumps one ship load of 1-3" gravel around the legs of the rig. Subsequently, the risk manager has to assess quickly whether the platform is sufficiently protected against scour or more gravel needs to be dumped. When he studies the as-built surveys of the gravel pads, he discovers that at leg IV only 40% (ca. 62.5m^3) of the gravel volume is located within a distance of the obstruction height (spud can height minus penetration depth) away from the side of the spud can (i.e. effective area A_{eff}). The risk manager makes the calculation once again, and he concludes that due to the successful penetration the present scour protection at leg IV is sufficient to withstand the design storm.

Phase III: delay of operation and changing design conditions

The scour protection was considered fit for purpose during the summer season. However, due to delays, the drilling operation will be continued in the winter season. The 1/20year design storm in winter season is more severe: a significant wave height of 5m and a peak period of 10.1s. The drilling rig operator wants to know whether the scour protection can withstand the winter storms. Because the protection around leg IV is clearly different from the other legs, the calculations were made both for legs I, II and III and for leg IV.

In Figure 9 the scour depth against significant wave height is shown. It can be observed in the left graph that at legs I, II and III a scour depth of 2.5m (best estimate) or 3.3m (95% confidence) is expected during occurrence of the 1/20 year design storm. At leg IV, however, the best estimate is 2.9m and the 95%-confidence value is 3.9m. The right graph shows that a 95%-safety can not be guaranteed at leg IV, when the 1/20 year design storm occurs. Additional dumping of gravel may be considered to increase the safety level.

This example shows that once the scour-related characteristics (shape, dimensions, penetration properties, etc.) of a certain jack-up footing are known, relatively accurate computations can be made that are extremely helpful in the process of planning and risk management. For each drilling rig, an easily applicable calculation module can be made, which can be used both in the planning process and during operation. Deviations from the planned installation of the drilling rig and the scour protection can also easily be assessed and mitigating measures can be proposed.

Finally, it is emphasized that this example is not based on economic considerations like operational costs of both rigs, costs of delays etc. Since these considerations are often site-, time- and company-specific, they are left out of this example.

8. CONCLUSION AND DISCUSSION

In this paper a brief overview of scour-related laboratory research in recent years at WL | Delft Hydraulics was presented. These experiments focused on scour and scour protections around various offshore structures subjected to extreme storm conditions. After analysis of the measurements, a new design formula for scour protections consisting of small size rock (e.g. gravel and cobbles) was deduced, which accounts for structure shape and dimensions, penetration depth, hydrodynamic load, time effect and size and volume of the applied scour protection material. Because the test database was most comprehensive for triangular structures, fitting coefficients of the new formula were only presented for triangular structures.

To illustrate the applicability of the new design approach for scour management during different stages of the drilling operation, an imaginary field case was discussed. Although this paper focused on triangular submerged structures, the same procedure can be followed for any structure shape that is used in offshore practice. Once the fitting coefficients of a certain structure are determined, the formula can be applied in various circumstances (like different seasons, locations, durations, available protection material etc.).

References

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Figures

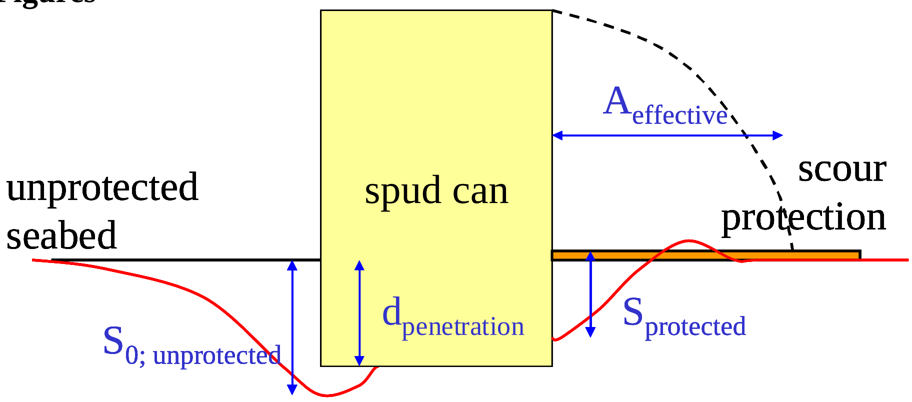

Figure 1: Purpose of applying dynamically stable scour protection; (left) without scour protection the scour hole extends underneath the spud can; (right) with scour protection scour can sufficiently be reduced

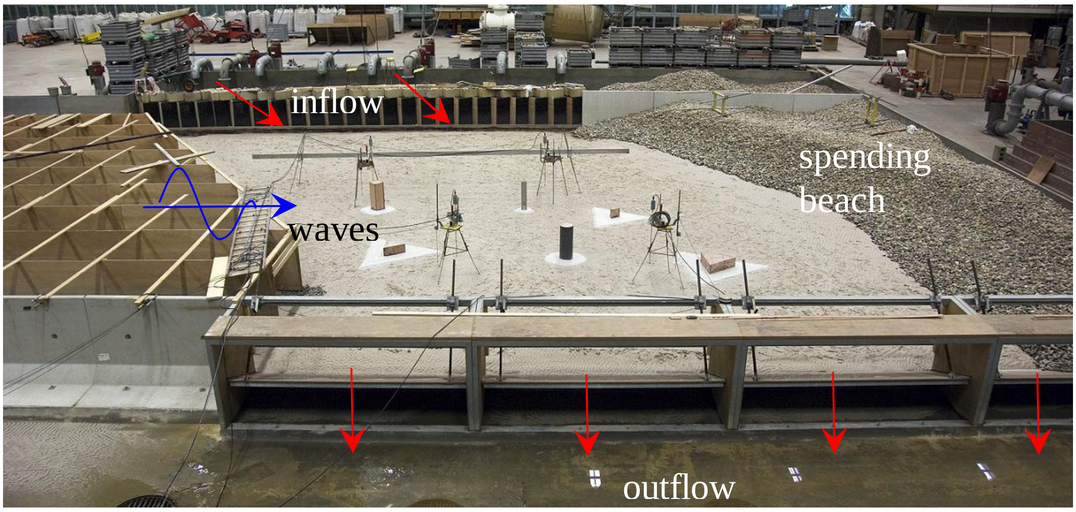

Figure 2: Overview of test facility 'Schelde Basin' before test execution. Wave guidance walls at the left, inflow boundary at the top, wave spending beach at the left, adjustable discharge weirs at the bottom and 6 structures provided with scour protection at the sandy bed in the middle.

Figure 3: (left) top view of spud can with scour protection before test execution; (right) spud can with redistributed scour protection. The side slopes of the two scour holes at corners B and C are completely covered by protection material.

Figure 4: (left) top view of spud can before test execution with scour protection applied at some distance from the spud can; (right) spud can with redistributed scour protection. Due to the redistribution the initial gravel ridges are re-shaped.

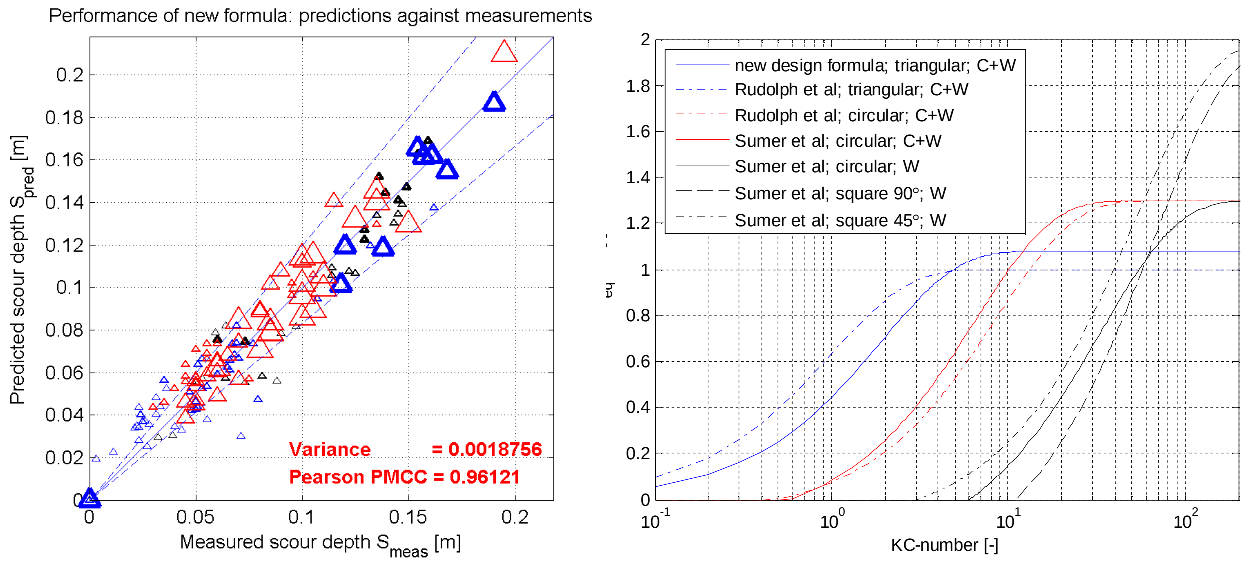

Figure 5: (left) Predicted scour depth by formula (4) against measured scour depth during laboratory tests. The marker size is a measure for the structure size, the marker line width is a measure for the structure height, the colours represent different years; (right) Comparison of different scour prediction formulae for structures without scour protection

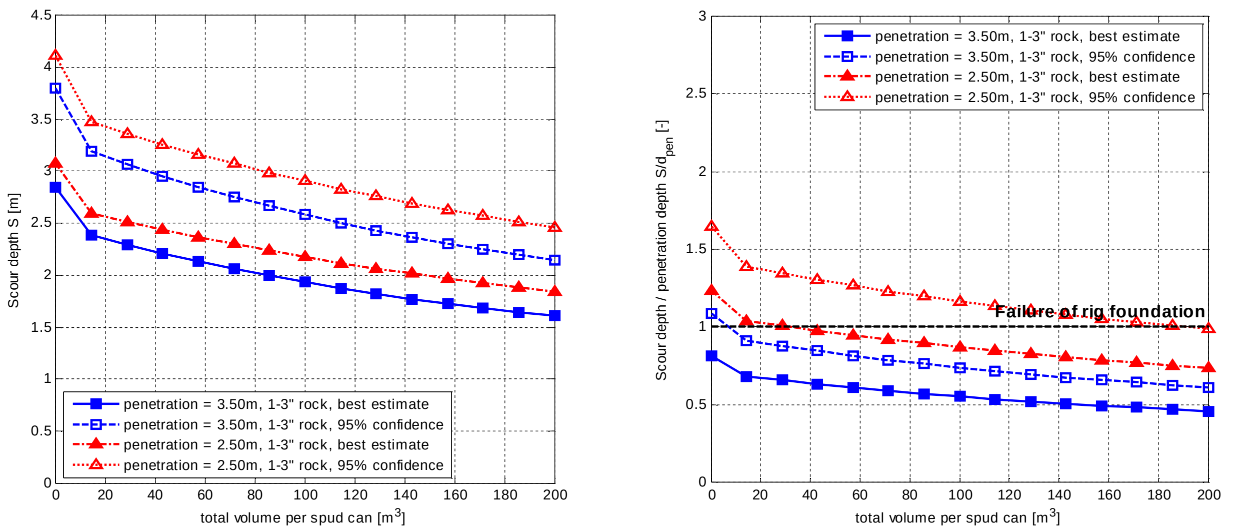

Figure 6: Scour prediction for two penetration depths after 1/20 year storm in summer season for 1-3" gravel; best-estimates and 95%-confidence values

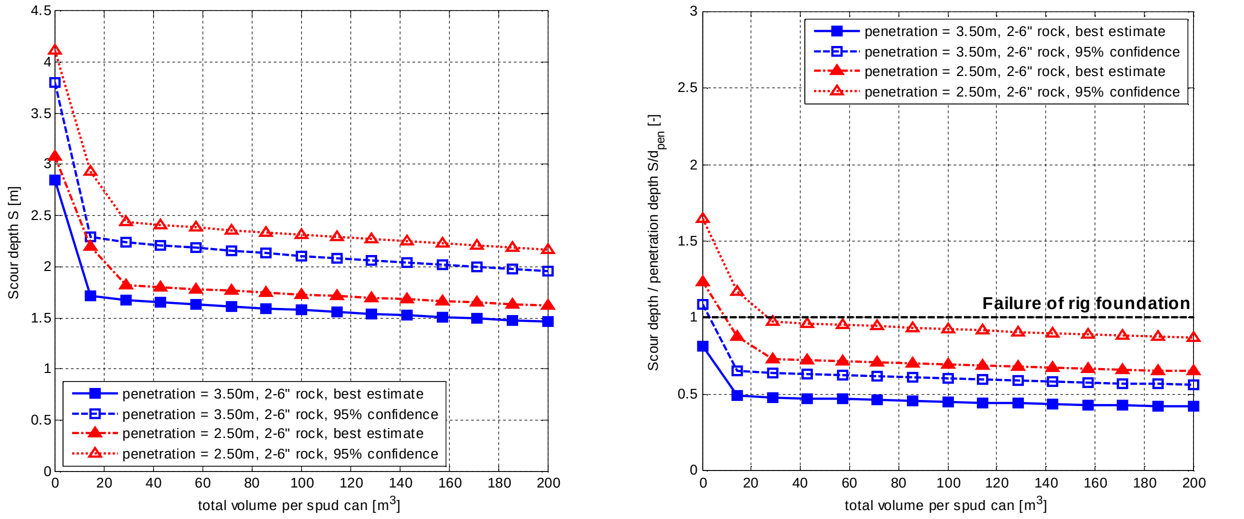

Figure 7: Scour prediction for two penetration depths after 1/20 year storm in summer season for 2-6" cobbles; best-estimates and 95%-confidence values

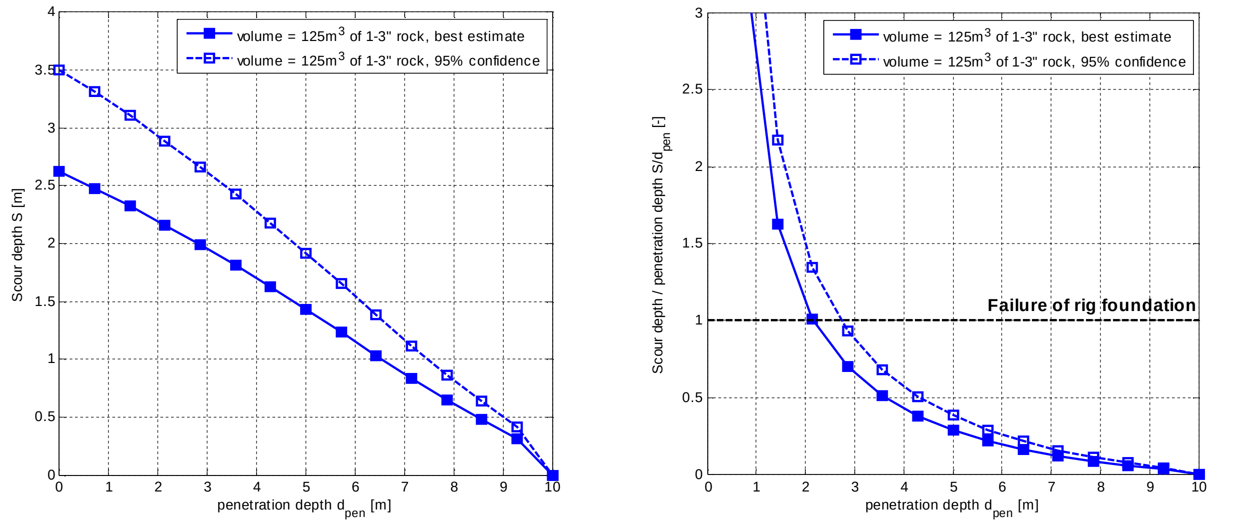

Figure 8: Scour prediction against penetration depth, given the fact that 125m^3 1-3" gravel is dumped within the effective area of each leg

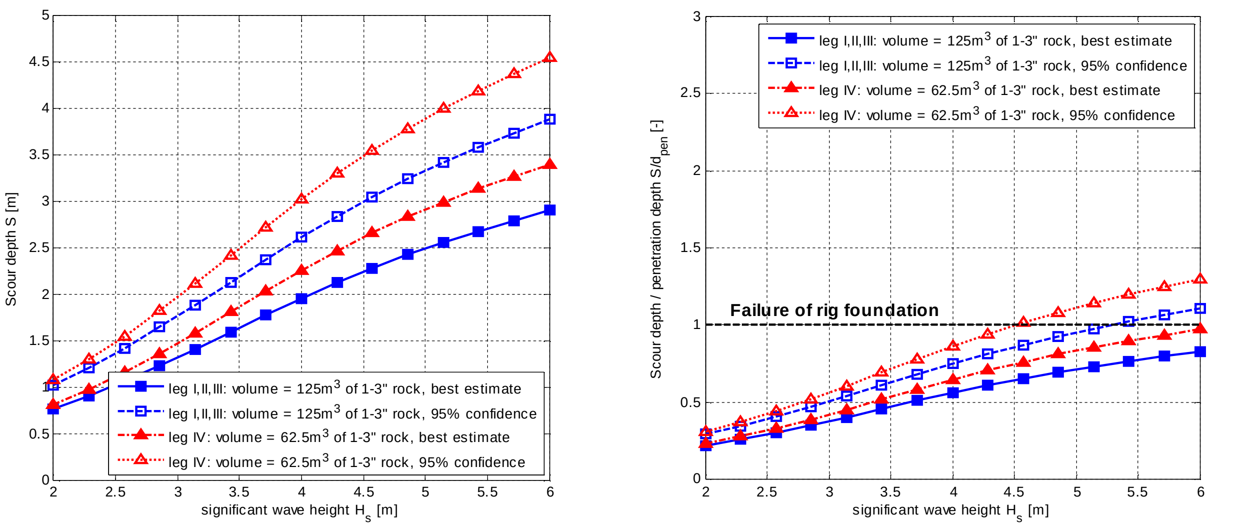

Figure 9: Scour prediction against significant wave height for two amounts of dumped 1-3" gravel