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Scour Development Around Truncated Cylinders: A Modified Approach

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ABSTRACT

This paper is focused, primarily, on investigating the effect of cylinder height on scour depth. Other parameters such as structure geometry and flow intensity have also been shown to influence the scour depth, but these have not been explored in detail in the present study. The paper explores a modification to the expression proposed by Sumer and Fredsøe to determine the effect of pile height on scour depth. A number of datasets obtained from previously published studies have been used in the analysis. The preliminary results of the re-analysis suggest that the modified expression may provide a better estimation of scour depth for piles of finite height. However, the analysis also highlights an inconsistency between what parameters are plotted and whether the reduction in scour depth is as large as either the original or modified expressions would indicate.

INTRODUCTION

In the offshore environment the design of subsea and bottom mounted structures can require a composite assessment of scour, for example the scour development associated with jacket structures or subsea protection structures. Scour associated with truncated piles can provide a simple analogue or form part of the solution of determining the scour magnitude related to these more complex structure configurations and yet comparatively few studies have been undertaken looking at the development of scour around truncated piles. The use of standard empirical equations for surface piercing piles results in overly conservative estimates of scour depth as they ignore the reduction in blockage effect. Therefore, having an approach that incorporates this reduction is important for engineering design. However, existing methods for calculating scour at these truncated structures may be unconservative, and this may lead to unsafe designs.

DHI/Snamprogetti (1992) undertook a joint venture to investigate seabed instability around seabed mounted structures. The principal aim of the study was to provide an understanding and description of the scour processes around "small" 3-dimensional structures sitting on the seabed exposed to waves and currents. A total of 12 idealised structures were tested, none of which were surface piercing, but most of which continued into the sand test bed, although some were pile mounted. The median grain size of the sediment was 0.165 mm and two vertical cylinder sizes were used, with ratios of h/D of 1 and 3 (h is the water depth in the test section and D is the cylinder diameter).

Sumer and Fredsøe (2002) summarized the DHI/Snamprogetti results for the two cylinders, albeit the data was very limited. On the basis of these results they presented an expression to correct the scour depth for a finite height vertical cylinder (Eqn. 1), where S_e is the equilibrium scour depth associated with the truncated pile; $S_{e,inf}$ is the equilibrium scour depth for a surface piercing (infinitely tall) pile; h_c is the truncated pile height and D is the pile diameter. β is a parameter based on the experimental data, which Sumer and Fredsøe determined as $\beta = 0.55$, although this was determined from only two experimental data points. From the figure presented in Sumer and Fredsøe (2002 – Figure 3.28; redrawn in Figure 1 below) they suggested that beyond about $h_c/D \geq 5$ the effect of the height of the finite pile can be neglected.

$$\frac{S_e}{S_{e,inf}} = 1 - exp\left(-\beta \frac{h_c}{D}\right) \tag{1}$$

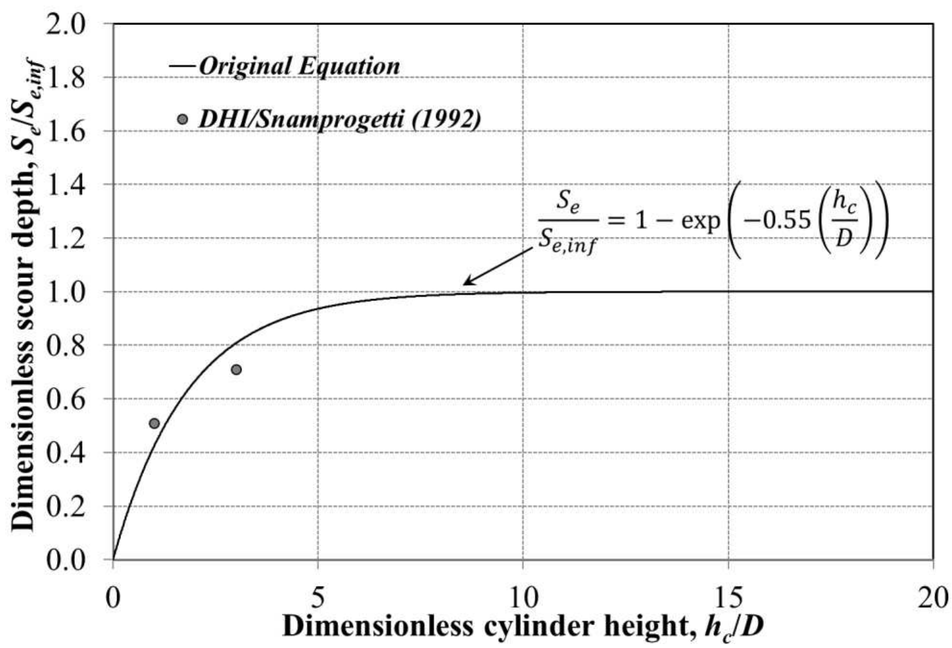

Figure 1: Effect of pile height on scour depth (*After Sumer and Fredsøe, 2002).*

Simons *et al*. (2007) undertook experiments using two submerged circular cylinders as well as including a test at an “infinitely high” (surface piercing) cylinder in steady current conditions. The experiments investigated the effect of skirt length on a truncated cylinder, albeit without the ability of the structure to tilt or slide. The experiments include tests with a reversing current to simulate tidal conditions. Their results, when compared with the DHI/Snamprogetti data reported by Sumer and Fredsøe (2002), suggested that the expression proposed by Sumer and Fredsøe (2002) overpredicts the reduction that occurs due to the reduced cylinder height.

Dey *et al*. (2008) presented results from an experimental study on clearwater scour at submerged circular cylindrical obstacles in an uniform sediment bed under steady flow conditions. Dey *et al*. noted that from their experiments the scour depth at the submerged cylinders decreased with increasing submergence ratio, S_r, defined as $(h - l)/h$, where h is the flow depth upstream of the cylinder and l is the length of the cylinder above the original bed level. An acoustic Doppler velocimeter (ADV) was used to take measurements of velocity along the vertical plane of symmetry and these data were used to determine the corresponding vorticity contours. From these measurements Dey *et al*. observed that the horseshoe vortex circulations also decreased with increasing submergence ratio.

Euler and Herget (2011) proposed an analytical methodology to determine local scour at obstacles in a fluvial environment. As part of these studies they conducted small flume experiments using a coarse quartz sand with a median grain size (d_{50}) of 0.75 mm, but with different geometric standard deviations of particle size (σ_g) of 1.3 and 1.55. Circular brass cylinders with diameters between 0.011 m to 0.03 m were used in the experiments, attached to the bed of the flume about 2.7 m downstream of the inlet. The experiments were conducted under clearwater conditions, although for runs 1 and 2 some fine particles began to move upstream of the cylinder due to slightly lower flow depths in the inlet section of the flume. In their tests, Euler and Herget noted that the shape of the scour hole varied from elliptical to crescent-shaped. Also, for the larger geometric standard deviation (σ_g = 1.55), the larger sediment particles formed a slight armour layer in the base of the scour hole. They also found that in six tests the scour at the front of the cylinder did not fully form due to reattachment of the flow behind the cylinder.

Zhao *et al*. (2010) investigated local scour at a submerged vertical circular cylinder in steady currents both experimentally and numerically. Zhao *et al*. (2010) found that the decrease in the height of the submerged cylinder led to a reduced scour depth at the front of the cylinder and a weakened vortex shedding structure behind the cylinder. From their investigation they found values of the parameter β in the range 1.88 to 2.10 based on their tests under live-bed conditions (Zhao *et al*., 2012).

More recently Yao *et al*. (2018) reported on experiments carried out on submerged circular and square piles. The experiments considered a wide range of cylinder height to diameter ratios (h_c/D in the range 0.1 to 8) under flow conditions ranging from clearwater to sheet flow. In this paper only the results for the circular cylinders are considered. Yao *et al*. found that the amount of reduction in scour depth with aspect ratio for short piles is dependent on the flow intensity and that the effects of aspect ratio and flow intensity on scour depth cannot be separated.

Figure 2 represents the flow intensity in terms of the depth-averaged velocity normalized by the critical threshold velocity of the sediment for the various studies summarized above. It can be seen in the plotted data that flow intensity influences the scour depth at the submerged cylinders. This aspect is discussed in more detail in Yao *et al*. (2018).

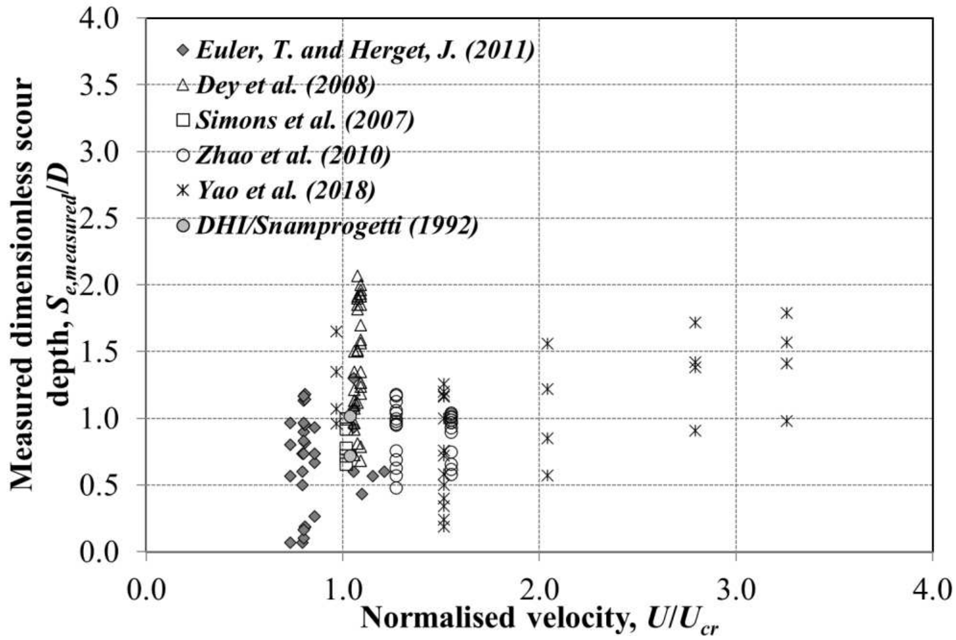

Figure 2: Range of flow intensity and effect on scour depth for the different data sets.

For surface piercing cylinders the local flow structures reflected in the scour process include the horseshoe vortex, driven by the downflow pressure at the front face of the cylinder and the wake vortices driven by the flow separation off the sides of the cylinder. Therefore, considering that both finite depth and finite pile height should reduce the pressure gradient down the front face of the cylinder it is interesting to compare these cases with work undertaken for surface piercing cylinders, in this instance cylindrical bridge piers. It is to be expected that the corrections to scour depth for cylinders with finite height and finite water depth will look similar.

Johnson and Ayyub (1996) undertook a study investigating the modelling uncertainty in the prediction of bridge scour using fuzzy regression techniques. Taking data from a number of sources they proposed Eqn. (2) for scour depth based on a power regression. The equation considered live-bed conditions only and, therefore, neglected velocity.

$$\frac{S_e}{h} = 1.06\left(\frac{D}{h}\right)^{0.667} \tag{2}$$

In Eqn. (2) h is the water depth, S_e is the equilibrium scour depth and D is the pile/pier diameter. If the water depth, h is replaced by the height of the cylinder, h_c, then Eqn. (2) should also provide a reasonable fit to the truncated cylinder data. The results are shown in Figure 3.

In general the fit of the truncated cylinder data to Eqn. (2) is reasonable. For larger ratios of D/h_c the experimental data shows more scatter, but this is to be expected as the scour development induced by the horseshoe and wake vortices will start to be affected by other flow processes such as the flow separation over the top of the cylinder. However, in general, when $D/h_c \leq 1$ the fit is acceptable.

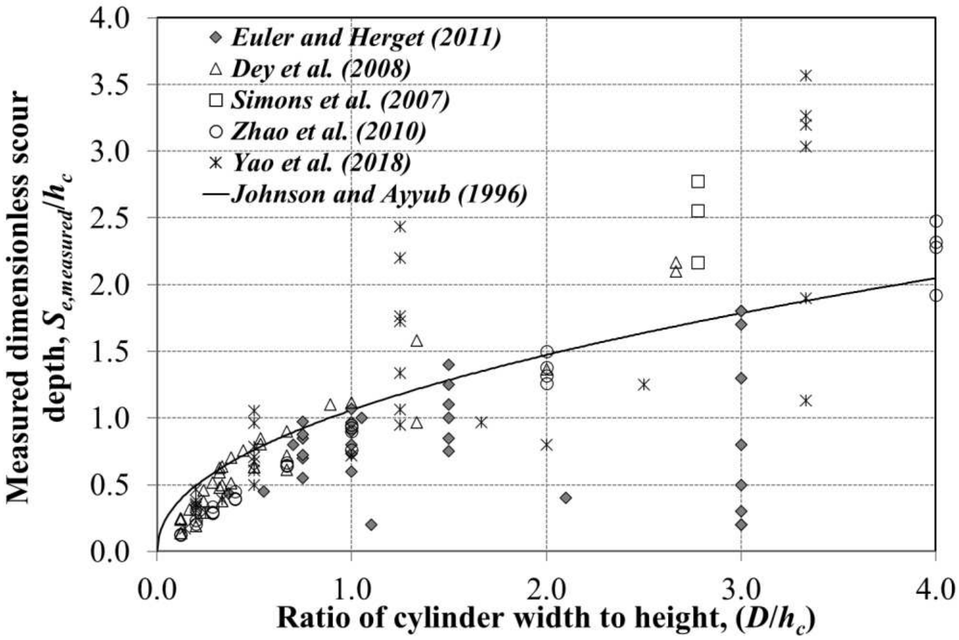

Figure 3: Plot of the ratio of cylinder width to height against relative scour depth.

METHODOLOGY

The expression proposed by Sumer and Fredsøe (2002) for correcting the scour depth associated with piles of finite height, noted earlier, has been found to over predict the reduction that occurs due to the reduced cylinder height (e.g. Simons et al., 2007; Zhao *et al*., 2010; Yao *et al*., 2018). Through the introduction of an exponent term, n, in Eqn (1) it is possible to adjust the expression's rate of growth or decay. In addition, the introduction of an additional multiplier, β, in the expression serves as a simple scaling factor, moving the values of h_c/D up or down. Therefore, on this basis it is proposed to modify Eqn. (1) to the form given in Eqn. (3):

$$\frac{S_e}{S_{e,inf}} = 1 - exp\left(-\beta\frac{h_c}{D}\right)^n \tag{3}$$

The values of β and n are considered unknowns at this point and will be assessed within the analysis. A summary of the analysis is given below.

RESULTS

A number of experimental data sets for truncated cylinders in steady flows have been used in the assessment of the modified equation: Euler and Herget (2011), Dey *et al*. (2008), Simons *et al*. (2007), Zhao *et al*. (2010), Yao *et al*. (2018) and experimental data for complex truncated structures undertaken as part of studies performed by researchers at the University Western Australia (Yao, *Pers. Comm.*). These latter data have been collectively grouped as "UWA – complex cylinders".

Figure 4 shows a comparison of measured dimensionless cylinder height (h_c/D) against dimensionless scour depth ($S_e/S_{e,inf}$), where $S_{e,inf}$ is the equilibrium scour depth for an "infinite height" cylinder of identical diameter (reported within the studies themselves). In Figure 4 only those data for circular cylinders where a measured equilibrium scour depth is quoted are plotted. After regression analysis Eqn. (4) was fitted through the data with $\beta = 1.2$ and n = 0.7 and this is shown on the figure. Also shown on the plot is the original equation proposed by Sumer and Fredsøe (Eqn. (4) with $\beta = 0.55$ and n = 1.0). From the figure it can be observed that the revised equation provides a better overall fit to the experimental data sets used in the analysis (R^2 values of 0.41 and -0.21, respectively). This implies that the reduction in scour depth due to reduced cylinder height is less than that obtained using the expression proposed by Sumer and Fredsøe. This is in line with other studies such as Simons *et al*. (2007) and Zhao *et al*. (2010) where similar conclusions were reached.

Therefore, to further investigate the equilibrium scour depth, $S_{e,inf}$ has been calculated using the method of Sheppard *et al*. (2011) and then corrected using the modified expression (Eqn. 4) with $\beta = 1.2$ and $n = 0.7$. These predicted values have then been normalized using cylinder diameter and compared with the measured normalized scour depth, giving Figure 5. The method of Sheppard *et al*. (2011) has been used because for a large number of studies undertaken at HR Wallingford the method of Sheppard *et al*. has been found to give good agreement with both field and laboratory scale data. However, other approaches could be applied and the results from these different empirical models would potentially lead to changes in the outcomes obtained and reported in this paper.

Figure 5 shows the revised equation with $\beta = 1.2$ and n = 0.7 to be generally conservative, implying that the parameter fitting based on dimensionless cylinder height (h_c/D) against dimensionless scour depth ($S_e/S_{e,inf}$) is giving smaller reductions in scour depth than generally observed in the experimental data. This raises an interesting question with regards to the revised equation, as depending on how the data is analysed and what parameters are selected to undertake the regression analysis it would be possible to obtain a different outcome.

In Figure 5 it can be observed that for some of the UWA complex cylinder data some tests were conducted with the cylinder level with the sediment bed (i.e. no stick-up height). The experiments showed scouring to occur, whilst from theory if the cylinder is flush with the bed there is no exposure height and thus no scour. The observed scour is considered to be a result of the change in roughness and due to imperfections in the bed level, which are not possible to remove generally. Combined, these resulted in observations of finite scour depth in clearwater conditions. Therefore, these results imply that Eqn. (1) is invalid when $h_c/D = 0$ in clearwater conditions. Fredsøe *et al*. (1993) noted that the amplification in the shear stress caused by a step change in the roughness ranges from 1 to 2.5, the maximum amplification is around 2.5, no matter whether the flow is a steady current or an oscillatory flow.

Returning to the difference in fit between Figure 4 and Figure 5, one possible issue is related to using the equilibrium scour depth to normalize the observed scour depth for the truncated structures. It is possible that the reported values of the measured equilibrium scour depths for the surface piercing cylinders do not actually represent equilibrium conditions. Determining the "true" equilibrium scour depth may require much more time than allowed within the experiments even though the scour development has evolved to the point where changes in scour depth are not observable within several hours.

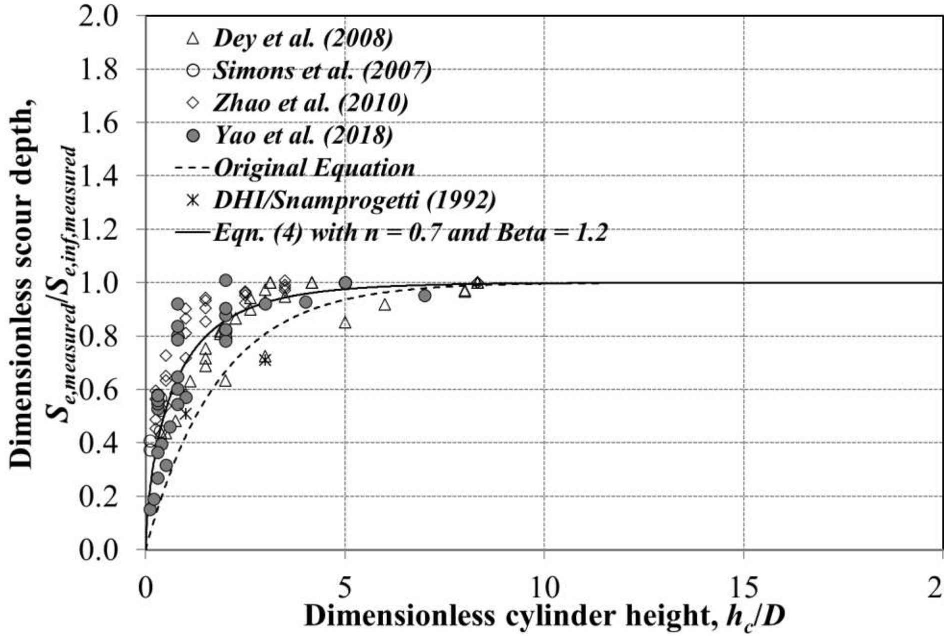

Figure 4: Dimensionless cylinder height against dimensionless scour depth. The solid line represents Eqn. 4 with β = 1.2 and n = 0.7 and the dashed line represents the original equation with β = 0.55 and n = 1.0.

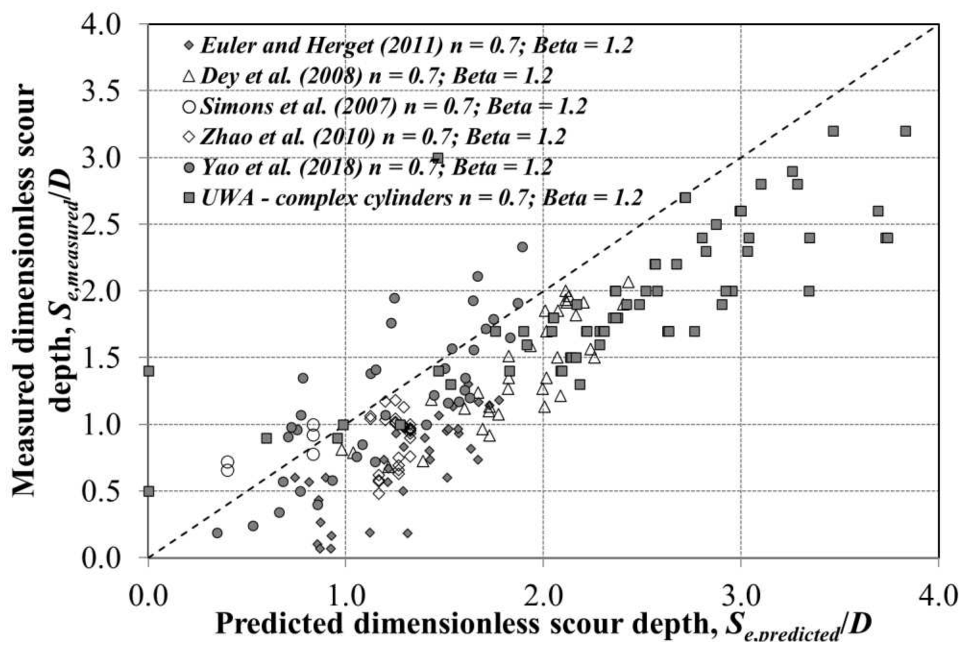

Figure 5: Predicted dimensionless scour depth against measured dimensionless scour depth determined using Eqn. 4 with β = 1.2 and n = 0.7.

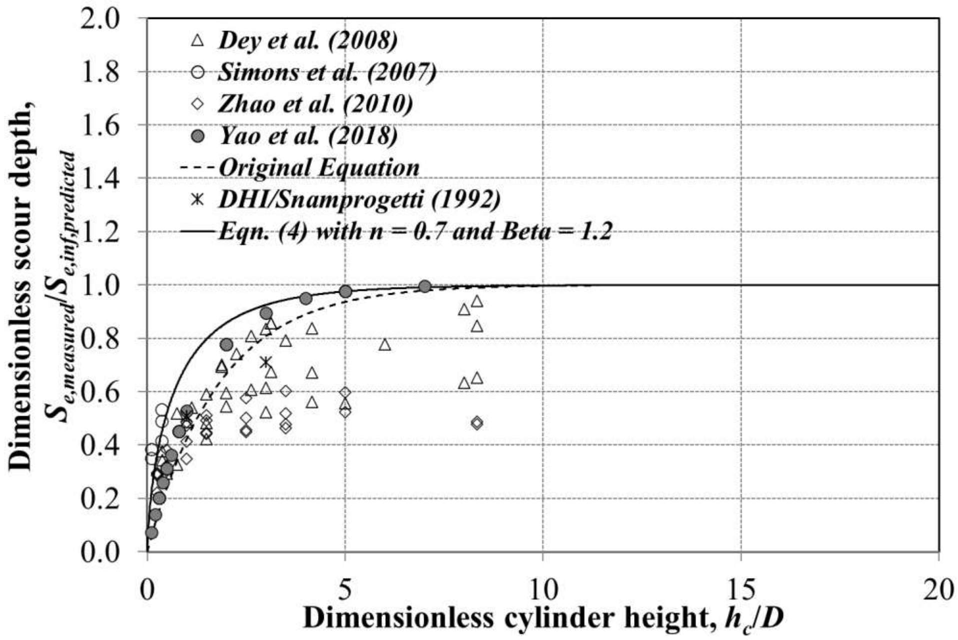

Figure 6: Dimensionless cylinder height against dimensionless scour depth. The solid line represents Eqn. 4 with β = 1.2 and n = 0.7 and the dashed line represents the original equation with β = 0.55 and n = 1.0. In this figure $S_{e,inf}$ is the predicted value.

Replotting Figure 4 using the predicted values of $S_{e,inf}$ obtained using the empirical approach of Sheppard *et al*. (2011) to derive the equilibrium scour depth gives Figure 6. Figure 6 demonstrates that an under-prediction in the value of $S_{e,inf}$ can result in a very different outcome. However, by using predicted values of $S_{e,inf}$ this has introduced another source of uncertainty, although it clearly demonstrates the possible change in outcome if the measured values are under-predicted.

Therefore, an alternative approach would be to fit the data for the measured scour depth against the predicted scour depth, and tune the parameters n and β. At the current time a detailed regression analysis has not been done using this approach although from some initial calculations an example of the fit to the data using a values of n = 0.5 and β = 0.75 is shown in Figure 7. The agreement between the data is generally better than that shown in Figure 5 (R^2 value of 0.58 compared with 0.07), but the values only represent an initial reassessment.

CONCLUSION

This paper has undertaken a re-analysis of published and unpublished data of scour development at submerged circular cylinders. Whilst the current paper is focused on investigating the primary dependence on cylinder height, it is important to note that other parameters such as flow intensity have been shown to influence the relative scour depth for cylinders of finite height. The principal aim of the study was to provide an improved empirical formula for the prediction of scour at truncated cylinders. A modification to the expression proposed by Sumer and Fredsøe (2002) has been suggested to improve the fit based on available laboratory data.

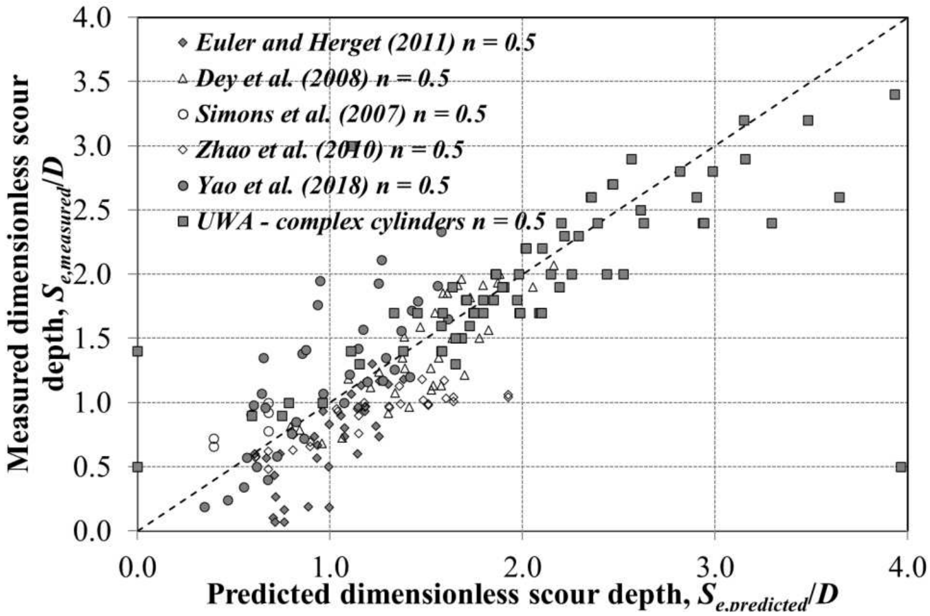

Figure 7: Predicted dimensionless scour depth against measured dimensionless scour depth determined using Eqn. 4 with β = 0.75 and n = 0.5.

Based on a comparison of experimental data from a number of sources the dimensionless cylinder height (h_c/D) and measured dimensionless scour depth ($S_e/S_{e,inf}$) were used in a regression analysis to determine Eqn. (4) with $\beta = 1.2$ and n = 0.7

$$\frac{S_e}{S_{e,inf}} = 1 - exp\left(-\beta\frac{h_c}{D}\right)^n$$

Applying this modified equation to compare the measured normalized scour depth against the predicted normalized scour depth (normalized on cylinder diameter) led to typically conservative results, implying that the parameter fitting based on dimensionless cylinder height (h_c/D) against dimensionless scour depth ($S_e/S_{e,inf}$) is giving smaller reductions in scour depth than generally observed in the experimental data. This raises an interesting question with regards to the revised equation, as depending on how the data is analysed and what parameters are selected to undertake the regression analysis it would be possible to obtain a different outcome.

One possible issue in the analysis is related to using the equilibrium scour depth to normalize the observed scour depth for the truncated structures, as it is possible that the reported values of the measured equilibrium scour depths for the "infinitely high" cylinders do not actually represent equilibrium conditions. Determining the "true" equilibrium scour depth may require much more time than allowed within the experiments even though the scour development has evolved to the point where changes in scour depth are not observable within several hours.

To demonstrate this effect the predicted values of $S_{e,inf}$ were used to demonstrate that an underprediction in the value of $S_{e,inf}$ can result in a very different outcome. However, the use of the predicted values of $S_{e,inf}$ introduces another source of uncertainty.

Some initial analysis on using the measured normalized scour depth against the predicted normalized scour depth to determine values for n and β has been undertaken, but only at a preliminary level at this time. Ultimately there is a requirement to develop a new equation that is capable of incorporating the different drivers to the scour process at these submerged cylinders including parameters such as flow intensity and structure geometry as well as pile height.

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