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Scour around a monopile under combined wave-current conditions and low KC-numbers

DANIEL RUDOLPH[1], KLAAS JAN BOS[2]
[1] *WL | Delft Hydraulics, P.O. Box 177, 2600MH Delft, The Netherlands; daniel.rudolph@wldelft.nl*
[2] *WL | Delft Hydraulics, P.O. Box 177, 2600MH Delft, The Netherlands; klaasjan.bos@wldelft.nl*

Abstract
This paper describes selected results of scale model tests on scour around an unprotected monopile under combined wave and current conditions with oblique direction. Physical modelling experiments were carried out using structures with two different diameters and variable hydraulic conditions. The choice of the model scale was guided by typical situations of offshore monopiles in the southern North Sea (monopile diameter 3-6m, water depth up to 30m). The results were compared with published data. An improved formula is presented for the prediction of scour around monopiles in non-cohesive material (sand) which is valid for wave and current dominated situations.

1 Introduction

Recently numerous monopile foundations have been planned and installed in connection with the development of offshore wind energy. The assessment of the scour potential and the design of scour protection has become subject to discussion. The present knowledge on the development of scour has been mainly based on rules of thumb derived from model scale tests under flow only conditions. Little research has been carried out on scour in waves (e.g. Sumer & Fredsøe, 1992) and scour under combined current and wave conditions (e.g. Sumer & Fredsøe, 2001). However, these works do not necessarily cover the typical range of situations for which the potential of scour needs to be estimated in practice. The range of results for the maximum scour depth based on the currently available formulae and rules of thumb indicate a range of $S_{max}=0.1...2.5*D_{pile}$. Such a wide range is unsatisfactory for both researchers and designers.

Therefore, a research project was set up in order to improve the understanding and to clarify on scour prediction for monopiles in an offshore environment.

The choice of the model set-up and the test conditions was guided by the typical range of prototype conditions to be studied:

- Normal conditions, i.e. tidal current and low to moderate waves: The hydraulic conditions are characterised by flow-only situations or flow domination.
- Extreme conditions, i.e. high waves in combination with wind-driven and tidal currents. The hydraulic condition can be characterised by “wave-domination”. The situation “waves only” hardly occurs in prototype.

Typical prototype conditions are summarised in Table 1. These ranges were used to guide the choice of the model set-up and the test programme.

parameter	symbol [unit]	minimum value	maximum value
water depth	h_w [m]	10	30
significant wave height	H_s [m]	0	9
spectral peak wave period	T_p [s]	0	13
depth-averaged current velocity	u_c [m/s]	0.5	1.2
pile diameter	D_{pile} [m]	3	6
seabed material	d_{50} [mm]	(fine sand)	(coarse sand)
Keulegan-Carpenter number	KC [-]	0	10

Table 1 Basis for model-set-up: Typical prototype conditions for offshore monopiles

This paper includes a short literature review on scour around a monopile in combined waves and current (Chapter 2) and it describes recently conducted scale model tests (Chapter 3). In Chapter 4 the results are presented. An interpretation of available data together with a new scour formula is given in Chapter 5. Finally, conclusions are presented (Chapter 6).

2 Published experimental results

A recent summary on research on scour around monopiles is given in Sumer & Fredsøe (2002). Among the published experiments on scour around a slender pile we mainly found the results presented by Sumer & Fredsøe (2001) conclusive and sufficiently described to use them in a re-analysis and to compare those with the results obtained from our own experiments.

Sumer & Fredsøe (2002) presented the following scour depth prediction formula for the experimental data presented in Sumer & Fredsøe (2001):

$$\frac{S}{D_{pile}} = \frac{S_c}{D_{pile}} \cdot \left[1 - \exp\left\{-A \cdot \left(KC - B\right)\right\}\right] \qquad KC \geq B \quad (1)$$

$$A = 0.03 + 0.75 \cdot U_{cw}^{\;2.6} \qquad (2)$$

$$B = 6 \cdot \exp\left(-4.7 \cdot U_{cw}\right) \quad (3)$$

$$U_{cw} = \frac{u_c(z = 0.5 \cdot D_{pile})}{u_c(z = 0.5 \cdot D_{pile}) + U_w} \quad (4)$$

$$KC = \frac{U_w \cdot T_p}{D_{pile}} \quad (5)$$

with

S … scour depth [m]

D … pile diameter [m]

S_c … scour depth due to current only situation, average $S_c/D=1.3$

KC … Keulegan Carpenter number

U_{cw} … relative velocity [-]

u_c … current-induced velocity at a height $z=0.5D_{pile}$ above the bed

U_w … maximum bed orbital velocity

A … empirical coefficient representing the effect of the relative velocity U_{cw}

B … empirical coefficient representing the KC-threshold when scour starts to develop

This formula is valid for single slender piles. The criteria for a slender pile are

- the wave length is large relative to the pile diameter ($L_{wave}/D_{pile}>5...10$)
- the water depth is large relative to the pile diameter ($h_w/D_{pile}>4$)

We have identified a few aspects to be considered in further research:

- The typical range of offshore monopile foundations is $0<KC<10$. Only very little scale model test data are available for this range of KC values. Therefore, scale model tests were conducted to obtain additional data for the practically important range of $KC<10$.
- The formula presented by Sumer & Fredsøe (2002) leads to unexpected results in flow-dominated conditions. In case of relatively low waves on a moderate current (e.g. h_w=20m, u_c=0.6m/s, H_s=2m, T_p=6s, D_{pile}=5m) the formula predicts negligible scour (KC=0.2, U_{cw}=0.7; S/D_{pile}=0.01) whereas the expected scour is significant because situation is flow dominated, therefore similar to "current only".
- A comparison of measurements (Sumer & Fredsøe, 2001) and hindcast (equation 1) indicated that the data fit is not optimal. The formula generally overpredicts the maximum scour depth measured in the laboratory by on average 50% (see Figure 4 at the end of this paper).

These points were addressed in the model set-up and in the analysis of data.

3 Scale model set-up and test conditions

All tests were carried out in Delft Hydraulics' Scheldt basin (see Figure 1). The angle between waves and current was between 60° (D_{pile}=0.08m) and 90° (D_{pile}=0.12m). The pile surface was very smooth (material: PVC). The bed of the facility was covered with a 20cm non-cohesive sand layer (d_{50}=0.13mm). 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. Velocity and wave height measurements were performed at various positions in the test section. 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 pile and the surrounding undisturbed bed level.

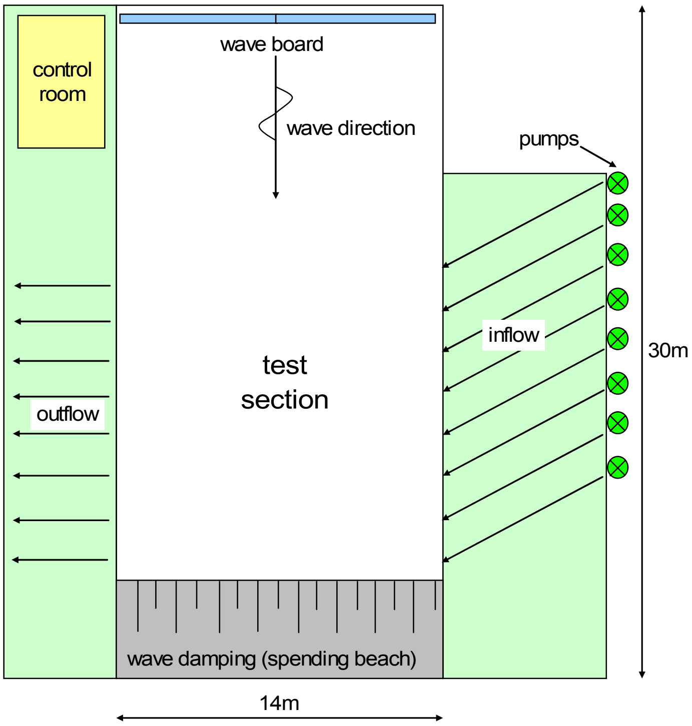

Figure 1 Schematisation of the test facility layout

The hydraulic conditions and scour measurements are summarised in Table 2.

4 Interpretation of model test results

Figure 2a and 2b give impressions on scour which occurred under current dominated conditions (left side) and wave-dominated conditions (right side). In case of the flow dominated situation, the edges of the scour hole could be clearly distinguished from the surrounding undisturbed seabed. The upstream extent of the scour hole was about 1-1.5*D_{pile} (slope about 30-40°), the downstream extent was about 2*D_{pile} (slope 25-30°). This is in agreement with typical values found in literature. In case of wave dominated situations, the scour hole became much more shallow. The transition between the local scour hole and the surrounding bed was rather continuous. The side slopes were in the order 1:5 to 1:10. Sand ripples also occurred in the scour hole. The ripple texture was locally slightly affected around the pile.

Figure 2 Photo taken after execution

Left side: pile 1 (D_{pile}=120mm; KC=1.5, U_{cw}=0.7; S_{max}=6.5cm)
Right side: pile 2 (D_{pile}=80mm; KC=10.2; U_{cw}=0.3; S_{max}=5.4cm)

The accuracy of the scour depth measurements was estimated at about 5mm which is in the order of 5% of the pile diameter. The scour depths given in Table 2 refer to the maximum scour depth and the time equilibrium found at the piles. Two test runs were repeated in order to obtain an impression on the scatter of the maximum scour depths. It was found that scour depth differences among comparable test runs were in the order of 1-1.5cm. This might be explained by a model effect: The migration of sand ripples (which have a height of about 1cm) leads to depth variations of the (relatively shallow) scour holes, especially in the case of wave dominated situations. This leads to a time dependent variation of the maximum scour depths of about 0.1…0.2*D_{pile}. This is taken into account in the interpretation and analysis of the data summarised in Table 2.

5 Data analysis

Key parameters

The following definitions were applied:

- Pile Reynolds number (constant flow)
- Keulegan-Carpenter number according to Equation (5)
- Mobility parameter
- Relative flow velocity

The flow regime around a cylindrical pile in constant flow is commonly expressed in terms of the Reynolds number. According to Sumer & Fredsøe (1997), vortex shedding starts for Re>40 and the wake is turbulent for Re>300. Typical prototype Reynolds numbers are in the order of 10^6 to 10^7. The pile-Reynolds numbers (constant flow) in the scale models were generally between $0.5*10^4$ and $3*10^4$. In our analysis we have assumed that the Reynolds number beyond Re=300 has little influence on the equilibrium scour depth. Since all test were carried out with Re>$0.5*10^{\wedge 3}$, the scour depth was not expressed in terms of the Reynolds number. However, the parameters affecting the flow regime (pile diameter, flow velocity) were taken into account in the analysis.

Under the presence of waves, the hydrodynamic regime is typically described in terms of the Keulegan Carpenter number KC. In the considered range (KC<10), the flow regime changes from „no separation“ (KC<1) to „vortex shedding“ (KC>7). Therefore, the parameter KC was considered as one of the key parameters in the analysis.

The mobility of the bed material was assessed by using the bed shear stress concept as presented by Soulsby (1997). The computed mobility parameters were above 0.2, while the critical mobility parameter of sand was about 0.068. It was concluded that the bed material was mobile during all tests („live-bed“).

Current profiles were constructed from velocity measurements at different height levels. It was found that the current profile followed a typical logarithmic-relation with a seabed roughness of k_s=0.01m and z_0=k_s/30. The current velocity was taken at z=D_{pile}/2 with an upper limit of z=0.5δ (δ…thickness of bed boundary layer). The relative flow velocity U_{cw} was defined as in Equation 4.

Based on these parameters, a new formula for the estimation of the maximum scour depth at a single circular pile under combined waves and currents was derived.

Data applied in the analysis

The following data were applied:

- Test results as presented in Table 2.
- Data as presented by Sumer & Fredsoe (2001).

Sumer & Fredsoe (2001) concluded that the effect of the angle between flow and waves on the maximum scour depth around a slender circular pile appears to be very low. Based on our experience and engineering judgement we agree with this conclusion. Therefore, we have taken into account available data with codirectional waves and currents and oblique direction.

Physical boundaries

The following criteria were introduced to satisfy physical boundaries:

- no waves, no flow: Scour does not occur (S/D=0)
- waves, no flow: Scour is a function of KC, the relation fits to data published by Sumer & Fredsøe (1992): S/D=f(KC)
- no waves, flow: In case of current only, it is assumed that S_c/D=constant
- waves, flow: scour depends on KC and U_{cw}

Improved data base and scour prediction formula

The main parameters determining the non-dimensional scour depth S/D_{pile} were assumed to be the Keulegan-Carpenter number (KC) and the relative nearbed velocity (U_{rel}). This is in agreement with the parameterisation chosen by Sumer & Fredsøe (2002).

The analysis of the chosen data led to the following *best-fit* expression

$$\frac{S}{D_{pile}} = 1.3 \cdot \left[1 - \exp\left\{-A \cdot \left(KC - B\right)\right\} \cdot \left\{1 - U_{cw}\right\}^{C}\right] = 1.3 \cdot K_{wave} \qquad KC \geq B \tag{6}$$

$$A = 0.03 + 1.5 \cdot U_{rel}{}^{4} \tag{7}$$

$$B = 6 \cdot \exp\left(-5 \cdot U_{rel}\right) \tag{8}$$

$$C = 0.1 \tag{9}$$

The definitions of KC and U_{cw} were given in Equation 4 and 5. This formula is valid for a single circular pile, live-bed situation and narrow-graded bed material. It is based on a best fit and does not include safety factors. An indication on the dependency of the non-dimensional scour depth from the relative flow velocity and the KC-number is shown in Figure 3. The black symbols represent the measurements including the estimated accuracy range.

Quality of data fit

Equation 6 represents a best fit of the available data. The quality of the data fit was assessed by comparing non-dimensional scour depth measurements and hindcasts (see Figure 4b). The variation from the "perfect fit" was analysed in terms of the standard deviation. The standard deviation of the ratio measurement/hindcast was about 50%.

The data fits were also compared with respect to the Keulegan Carpenter number (Figure 5) and the relative velocity (Figure 6). The differences between hindcast and measurement are more or less normally distributed and do neither depend on KC nor U_{rel}.

In order to obtain significant scour in flow-dominated situations (and very low KC numbers), an additional factor $(1-U_{cw})^C$ was introduced. However, no data were available to check the accuracy of this assumption for KC<1.

Interpretation for design purposes

For design purposes a safety factor and additional correction factors should be applied to account for the effect of a limited water depth ($h_w<4D_{pile}$). The design formula then reads:

$$\frac{S}{D_{pile}} = \gamma \cdot 1.3 \cdot K_{wave} \cdot K_{h_w} \tag{10}$$

with

γ	safety factor, depending on design process and acceptable risk, typically γ=1.5
K_{wave}	wave reduction factor, relation see Equation 6
K_{hw}	correction factor for limted water depth, according to Breusers et al. (1977) $K_{hw}=\tanh(h_w/D_{pile})$

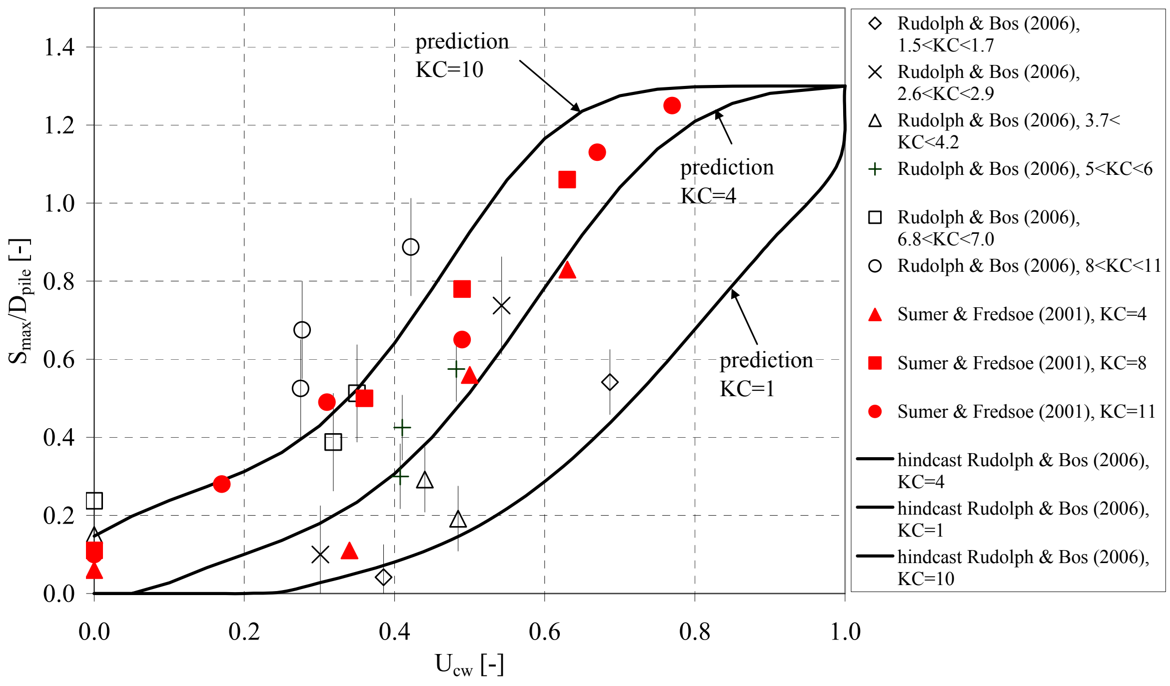

Figure 3 Comparison of measurements with predictions, data based on Table 2 and Sumer & Fredsoe (2001)

The principal set-up of Equation (10) is well known and has been published earlier, e.g. Melville & Sutherland (1988). The innovation of this formula is the improved correction factor for the effect of waves, especially for low Keulegan Carpenter numbers. K_{wave} satisfies the demands of physical boundaries: little scour in case of wave-dominated conditions, maximum scour in case of flow-dominated situations.

We suggest not to apply equation (10) including the K_{wave}-factor for structures with a different shape. Local hydrodynamic conditions (vortex shedding) and the onset of scour differ from circular piles, especially in wave-dominated situations. In wave-dominated situations and low KC numbers, scour will be significant at angular structures while scour is generally low in case of monopiles.

Additional remarks on the use for design purposes

Practically, it is of interest how scour develops with time and under a sequence of hydraulic conditions. This aspect was not considered in this study. All test results refer to the equilibrium scour depth under a given combination of hydraulic conditions.

Care must be taken in connection with the use for design purposes. Although it is believed that the data and formulae presented in this paper give a good indication on expected scour in prototype situations, several scale effects might be present. Without further study (scale model tests) or relevant field measurements it is proposed to apply a safety factor. The choice of the safety factor should depend on the specific situation. Suggestions by various authors are summarised for example by Breusers et al. (1977), Melville & Sutherland (1988), Hoffmans & Verheij (1997) and Whitehouse (1998).

6 Conclusions

Scale model tests were carried out to study the scour development around monopile structures in combined wave and current situations. It was focussed on the range 1<KC<10. Although this range is typically found in shallow-water offshore projects (say up to 30m water depth), little research has been published so far.

The test results generally confirmed the trends published by Sumer & Fredsøe (2002). The analysis of the new test data and data published in literature led to a new scour prediction formula for a single pile in a live-bed situation. It was found that the relative velocity (describing wave or flow domination) and the KC-number are the predominating factors for the prediction of the scour depth.

Compared with existing formulae the improved formula contains the following improvements:

- In case of flow dominated situations with moderate waves, scour depth predictions orientate at the current-only situation.
- The scour prediction is based on an extended data set which covers the typical range of applications of shallow water offshore projects, such as offshore windparks (1<KC<10)

In case of a design study, the scour depth prediction should take into account an appropriate safety factor and project-specific correction factors (sediment gradation, structure shape, limited water depth etc.).

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The improved formula represents a best fit and reads:

$$\frac{S}{D_{pile}} = 1.3 \cdot K_{wave} = 1.3 \cdot \left[1 - \exp\left\{-A \cdot \left(KC - B\right)\right\} \cdot \left\{1 - U_{rel}\right\}^{C}\right] \qquad KC \geq B$$

Figures

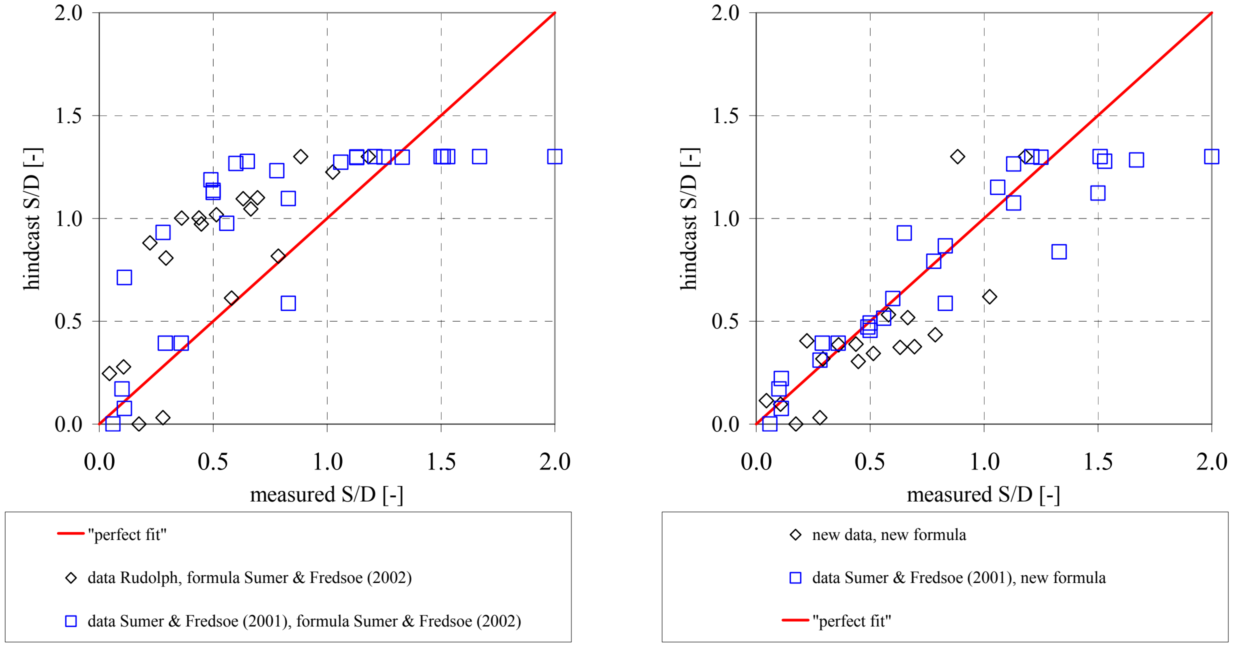

Figure 4 **Comparison of measured and predicted scour depths, left: formula Sumer & Fredsoe (2002), right: Rudolph & Bos (2006)**

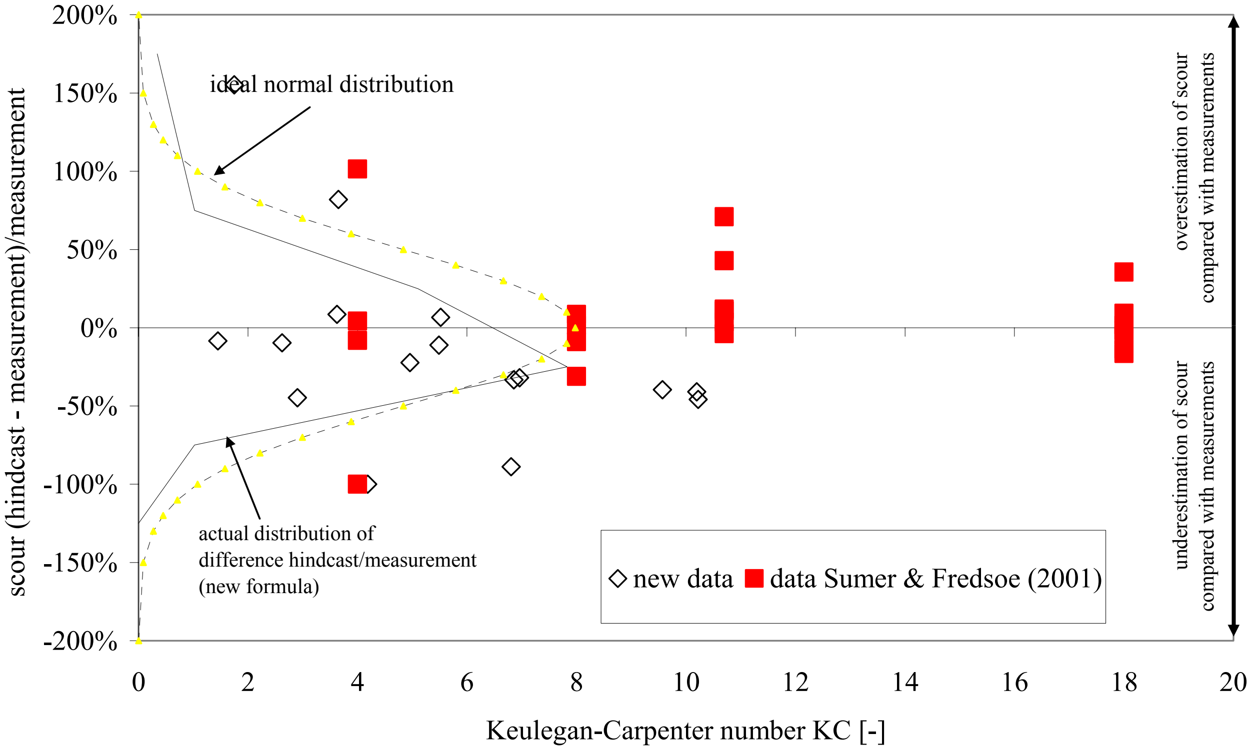

Figure 5 **Comparison of measured and predicted scour depths, depending on Keulegan-Carpenter number**

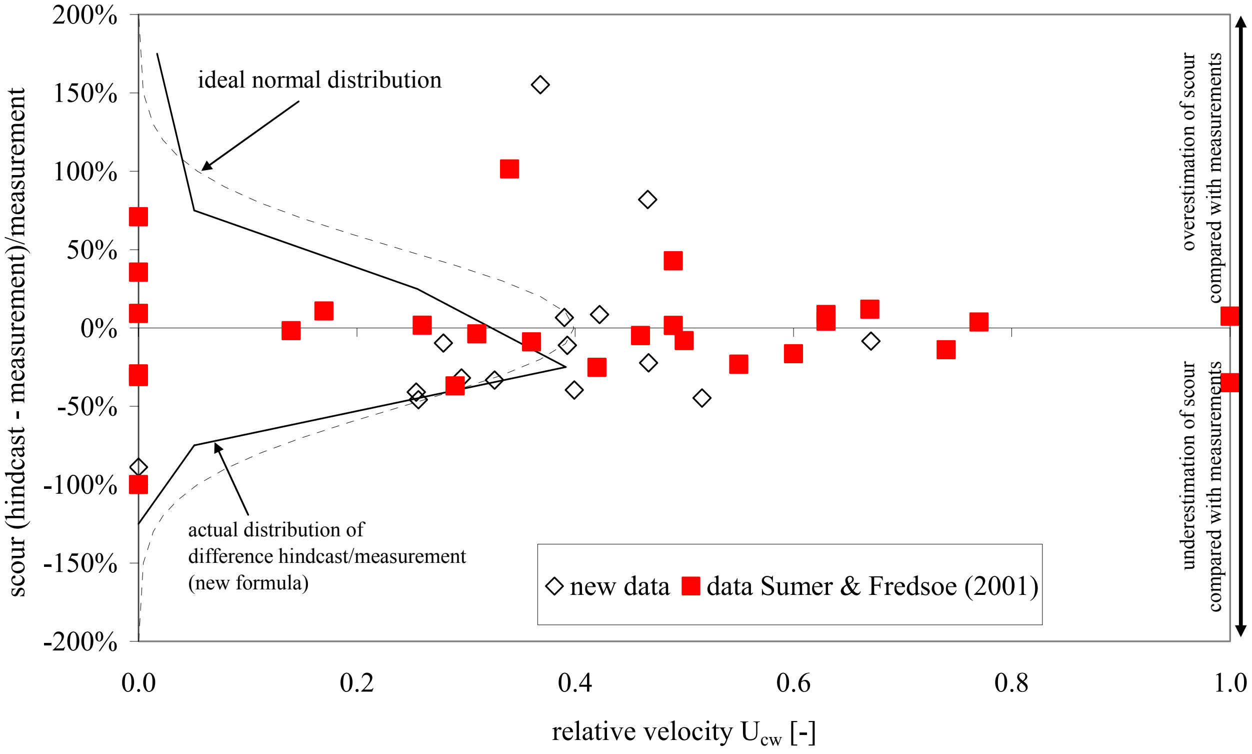

Figure 6 **Comparison of measured and predicted scour depths, depending on relative flow velocity**

Tables

test id	***D_{pile} [m]***	***h_w [m]***	***H_s [m]***	***T_p [s]***	***U_{bed} [m/s]***	***u_c [m/s]***	***u(z=D/2) [m/s]***	***KC [-]***	***Θ [-]***	***U_{rel} [-]***	***Re_D [-]***	***S/D_{pile} [-]***
1-3	0.120	0.50	0.150	1.82	0.28	-	-	4.2	5.3	0.00	-	0.17
1-1	0.120	0.50	0.135	1.82	0.24	0.26	0.23	3.7	5.0	0.48	$2.4*10^4$	0.22
1-2	0.120	0.50	0.135	1.81	0.24	0.21	0.19	3.6	5.0	0.44	$2.0*10^4$	0.29
1-6	0.120	0.50	0.096	1.33	0.13	0.32	0.29	1.5	4.4	0.69	$3.0*10^4$	0.58
1-7	0.120	0.50	0.115	1.34	0.16	0.11	0.10	1.7	4.7	0.39	$1.0*10^4$	0.04
1-9	0.120	0.50	0.166	2.03	0.33	0.34	0.31	5.0	5.9	0.48	$3.2*10^4$	0.66
1-10	0.120	0.50	0.165	2.03	0.33	0.26	0.23	5.5	5.4	0.41	$2.4*10^4$	0.36
1-11	0.120	0.40	0.152	1.80	0.33	0.34	0.23	5.5	5.4	0.41	$2.4*10^4$	0.44
1-4	0.120	0.40	-	-	-	0.29	0.26	-	0.2	1.00	$2.8*10^4$	0.88
2-3	0.080	0.50	0.153	1.89	0.29	-	-	6.8	5.3	0.00	-	0.28
2-1	0.080	0.50	0.171	1.80	0.31	0.17	0.15	7.0	5.7	0.32	$1.0*10^4$	0.45
2-2	0.080	0.50	0.169	1.79	0.31	0.20	0.17	6.9	5.7	0.35	$1.2*10^4$	0.51
2-6	0.080	0.50	0.138	1.29	0.18	0.25	0.21	2.9	5.3	0.54	$1.5*10^4$	0.79
2-7	0.080	0.50	0.121	1.31	0.16	0.08	0.07	2.6	4.8	0.30	$0.5*10^4$	0.11
2-9	0.080	0.50	0.205	1.79	0.43	0.36	0.31	9.6	6.8	0.42	$2.2*10^4$	1.03
2-10	0.080	0.50	0.209	2.02	0.40	0.18	0.15	10.2	6.1	0.28	$1.1*10^4$	0.63
2-11	0.080	0.40	0.209	2.02	0.40	0.18	0.15	10.2	6.1	0.28	$1.1*10^4$	0.69
2-4	0.080	0.40	-	-	-	0.38	0.33	-	0.3	1.00	$2.3*10^4$	1.18

Table 2 Overview on hydraulic conditions and scour measurements