# Time-dependent scour development under combined current and waves conditions - laboratory experiments with online monitoring technique

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Since wind energy is becoming more important as a source of renewable energy, some offshore wind parks already have been built and even more wind parks are currently in the design phase. Scour around the foundation piles threatens the stability and the resonance frequency of the wind turbines. Therefore, accurate scour prediction tools are required. A laboratory test program was defined to investigate scour development with time under varying hydrodynamic conditions. These laboratory experiments gained insight in 1) equilibrium scour depths around relatively wide piles under time-varying combined current-and waves conditions, 2) time-scales of scour development and 3) backfilling behaviour and related timescales.

To obtain more insight into the time scale of scour development, a new monitoring technique was developed, which consisted of completely transparent cylindrical piles equipped with digital camera system inside the pile which recorded continuously the surrounding bed level. This technique provided images of scour development during test execution with great accuracy. After image processing, 360° water-seabed-interfaces became available, which provided valuable insight in scour development with time.

Based on existing scour formulae a scour prediction model was developed to compare the laboratory measurements with state-of-the-art knowledge. It appeared that existing scour prediction formulae were not very well applicable for the typical range of windfarm piles, which are often characterized by low KC-numbers and relatively wide dimensions relative to the water depth. Timescales according to existing formulae appeared to be much too short.

An extensive database of laboratory tests, both in-house and published in literature, was used to fit a new equilibrium scour depth formula for combined current-and-waves. This formula is applicable for low KC-numbers, pile heights smaller than the water depth, piles that are wide relative to the water depth and has a smooth transition towards current-only conditions. Also for the timescale a new conceptual formula was presented. Finally, when the scour prediction model was run with the improved scour formulae, the agreement between measurements and predictions improved significantly.

Key Words : scour, timescale, offshore wind park, cylindrical pile, combined current-and-waves

## **1. INTRODUCTION**

Since wind energy is becoming more important as a source of renewable energy, some offshore wind parks have already been built and even more wind parks are currently in the design phase. Scour around the foundation piles threatens the stability and the resonance frequency of the wind turbines. Therefore, accurate scour prediction tools and measures to reduce scour development are required. A laboratory test program was defined to investigate scour development with time under varying hydrodynamic conditions. These laboratory experiments gained insight in:

- 1. Equilibrium scour depths around circular piles (in relation to water depth) under time-varying combined current and wave conditions;
- 2. Time scales of scour development, both in current-dominated and wave-dominated conditions;

3. Backfilling behaviour and related time scales.

Previous studies regarding equilibrium scour depths mainly focused on current-induced scour around bridge piers<sup>1,2,3,4)</sup>. Far less research was executed on the topic of wave-induced scour<sup>5)</sup> or scour due to combined current and waves<sup>6,7,8,9)</sup>.

Applying already existing equilibrium scour depth formulations in typical wind park conditions often yields problems regarding I) the fact that most laboratory tests were based on unidirectional currents, whereas wind turbine piles are often located in tidal environments, II) the relatively wide pile dimensions relative to the water depth, III) the low Keulegan-Carpenter numbers (hereafter KC-number) of wind turbine piles, whereas most laboratory tests were executed for larger KC-numbers and finally IV) the fact that existing formulations predict negative or no scour depths in current-dominated conditions with low to moderate waves (low KC-numbers).

Less knowledge is available on timescales of scour development. Nakagawa and Suzuki<sup>3)</sup> based their formula for a characteristic time scale on laboratory tests and field measurements. Their formula predicts a continuous increase of scour depth without reaching equilibrium. According to the current-only formulations of Melville and Chiew<sup>10)</sup>, equilibrium is reached after a certain time, defined by a characteristic timescale. According to a more widely adopted approach<sup>2,9,11)</sup>, scour development in time can be described by an exponential function:

$$\frac{S(t)}{S_{eq}} = 1 - \exp\left(-\frac{t}{T_{char}}\right)$$
(1)

This formula implies that scour depth approaches an equilibrium scour depth without fully reaching it.

An approach for the conversion from theoretical consideration to practical implication in a wind park environment was presented by Nielsen and Hansen<sup>12</sup>. They presented predictions based on the scour formulae by Sumer and Freds¢e<sup>7,8,9</sup>. To the authors' opinion, the model is not always well applicable in the

typical range of conditions around wind turbine piles. This model was demonstratively applied at Horns Rev 1 Windfarm for the imaginary case, if no scour protection had been applied, and it was concluded that during periods with high loads on the foundation (i.e. during storms), the scour depths will be small. This statement resulted from small predicted equilibrium scour depths under wave-dominated conditions. The often used rule of thumb of S/D=1.3 was therefore considered to be too conservative. This conclusion, however, is strongly dependent on the existing formulations on timescales. Therefore, it was considered important to verify this statement.

In the present paper, the equilibrium scour depths and timescales in typical offshore wind park conditions are studied based on laboratory experiments (sections 2 and 3) and numerical predictions with a computer model (sections 4 to 5). Section 6 describes the conclusions.

# 2. SETUP OF LABORATORY EXPERIMENTS

When morphological modelling with fine sediments in basin experiments is executed, the water usually becomes more and more turbid during tests, making it impossible to monitor seabed changes near structures. Only after the basin is drained, the resulting bathymetry can be inspected. Since drainage may not cause any morphological and/or geotechnical changes to the bathymetry and the fine sandy sediment usually is poorly permeable, drainage takes a long time, thereby slowing down the test program.

Because no data on bed levels become available during these traditional tests, it is common practice either I) to continue until a presumed equilibrium scour depth is reached or II) to simulate a specific storm condition with certain duration. Of many type I-tests, it is uncertain whether equilibrium is indeed reached during the test. Type-II tests bring along the problem that timescales can not necessarily be scaled according to Froude scaling law and that no predictions can be made for different (especially longer) storm durations. Therefore, to be able to monitor scour development during tests, a camera monitoring system was developed that was placed inside a transparent cylindrical pile, see Fig. 1. Because the camera-lens-system required a minimum focal length, an inverted basic periscope was adopted.

The system consists of five components: I) a transparent cylindrical outer tube that is placed in the sandy bed and connected to the concrete floor underneath; II) an inner tube with a observation window, III) a downward looking digital camera, IV) a mirror under a 45° inclination and V) an automated stepper motor to rotate the inner tube inside the outer tube. The height of the inner tube was adjustable to adapt to different sediment layer thicknesses.

During the tests, the camera was monitoring the interface of sand and water via the mirror. Real time movement of bed forms and sediment plumes could be observed and recorded in digital video format at any requested radial position of the camera. Every five minutes, an automated rotating movement started to capture high-resolution camera images at steps of  $5.4^{\circ}$ . During a full cycle 70 images were captured, which were then combined to one panoramic picture, see **Fig. 2**.

With a newly developed software routine we were able to determine the sand-water interface based on colour gradients. Because the camera system was calibrated with a chessboard pattern on beforehand, the pixel coordinates of the sand-water interface could be translated to geometric coordinates (distance along pile perimeter and height level). From these coordinates, the maximum scour depth along the pile radius was determined. Also the mean, maximum, 10%-exceedance and 1%-exceedance scour depth along the pile perimeter were calculated with sub-mm accuracy.

With this system it was not only possible to observe whether equilibrium was reached, but also at which



Fig. 1 Design and prototype of camera pile; a) schematisation of complete pile; b) inner tube with 'inverted periscope' camera system; c) prototype in Schelde Basin after test execution.

location around the pile maximum scour depths occurred and at which rate scour developed. The camera system was also used to study the hydraulic stability and filter behaviour of scour protection material (not further elaborated in this paper).

Before test execution, four piles were installed in the Schelde Basin. Two of the four piles were equipped with the above described camera system (D=200mm and D=134mm); two 'traditional' piles (D=160mm and D=125mm) did not have any equipment. These pile diameters represent prototype scales of 1:20 to 1:36. The basin, which has a length of 30m and a width of 15m, see **Fig. 3**, 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 ( $d_{50}=130\mu$ m).

Two test series were executed. Test series 'M1' was a current-only test with step-wise increasing current velocity ( $u_c \approx 0.1/0.2/0.3$  m/s).

Test series 'M2' started with increasing waves-only 0.20/0.28/0.36/0.40), conditions  $(H_s/h_w \approx$ then proceeded with increasing combined current-and-waves conditions (uc  $\approx 0.1$  m/s & Hs/hw  $\approx$ 0.20;  $u_c \approx 0.2 \text{m/s} \& H_s/h_w \approx 0.28$ ;  $uc \approx 0.3 \text{m/s} \& H_s/h_w$  $\approx$  0.40). Subsequently, the scour depth was further increased during a current-only condition comparable to the last condition of test series 'M1' ( $u_c \approx 0.3 \text{ m/s}$ ) and finally the mildest combined current-and-waves condition ( $u_c \approx 0.1 \text{ m/s} \& H_s/h_w \approx 0.20$ ) was repeated to induce possible backfilling.

Five wave height meters and eight current velocity meters were installed in the test section of the basin for interpolation of the undisturbed hydrodynamic conditions to the structure locations. In the further analysis not the above described envisaged conditions, but the actual measured conditions, interpolated to the locations of the structures, are used.



Fig. 2 Panoramic picture of a) bed level just after start of test; b) bed level after test. Green line is calculated interface between water and sand (colour-gradient method).

# 3. RESULTS OF LABORATORY EXPERIMENTS

#### (1) Introduction

According to the above described approach, the scour development was calculated from the camera images for each of the two camera piles. **Fig. 4** shows the hydrodynamic conditions around the camera pile with a diameter of 200mm during test series 'M2'. The blue solid line (left vertical axis) represents the depth-averaged current velocity, while the red dashed line represents the significant wave height.

The water depth was held constant at  $h_w = 0.50m$ ; the wave period  $T_p$  was related to the significant wave height:  $T_p = 4.5\sqrt{H_s}$ . The middle graph presents two relevant hydrodynamic parameters: 1) relative mobility (MOB), which is the ratio between the actual mobility of the sediment and the critical mobility; 2) KC-number, which is a measure for the wave orbital motion at the seabed in relation to the structure width. Except for the current-only condition (roughly between 620 and 690 minutes), the relative mobility is well above the threshold of motion (MOB =1). Typical KC-numbers for mild to severe storm conditions are between 1 and 4.

The lower graph in Fig. 4 shows the maximum,10%-exceedance and mean scour depth along the pile perimeter, calculated from a Fig. 2-like picture. These lines illustrate that during waves-only and mild combined-current-and-waves conditions little bed level changes occur, while the mean scour depth 'Smean' remains even smaller. The scour depth rapidly increases when the wave heights and current velocities become more severe.



Fig. 3 Overview of Schelde Basin with wave generator at top left, current inflow boundary at top right, wave guidance walls and test section in the middle and outflow weirs at the lower left.

When, subsequently, the current velocity is almost kept constant and the wave generator is turned off, the scour depth further increases. During the final test condition (mild combined-current-and-waves), backfilling of the scour hole starts. It appears that the timescale of the backfilling process is much longer than the timescale of the scour process.

For further analysis on timescales and equilibrium scour depths, these parameters were extracted from the time series of measured scour depths.

#### (2) Scour depths

The equilibrium scour depths were calculated based on fitting the exponential function to the development in time of the measured scour depths along the pile perimeter. Table 1 shows some typical values. Largest scour depths occur in current-only conditions, but due to the relatively wide piles with respect to the water depth, the observed scour depth for typical tidal current velocities does not exceed 0.7-0.9 times the pile diameter. Waves-only conditions cause very little scour (up to 0.5m in prototype) and scour is clearly dependent on the relation between pile diameter and wave orbital motion. During combined-current-and-waves conditions the scour depth approaches (but does not exceed) the current-only scour depth as the conditions become more severe.

#### (3) Timescales

It is very likely that timescales in morphological models can not be scaled using Froude scaling.



Fig. 4 Panoramic picture of a) bed level just after start of test; b) bed level after test. Green line is calculated interface between water and sand (colour-gradient method).

Table 1: Typical equilibrium scour depths and timescales for various hydrodynamic conditions; values are valid for pile diameters from 2.7 to 4.0m and are based on scaling of laboratory test results according to Froude's Law (model scale 1:20)
\*) this current-only test was executed after several combined-current-and-waves tests. The increase of the maximum scour depth occurred approximately 3.5 times faster compared to the situation that only current action was present; also the equilibrium scour depth is not exactly the same.

	hydrodynamics				D/h <sub>w</sub> = 0.4		D/h <sub>w</sub> = 0.27		
type	u <sub>c</sub> [m/s]	h <sub>w</sub> [m]	H <sub>s</sub> [m]	T <sub>p</sub> [s]	S <sub>eq</sub>	S <sub>eq</sub> /D	$S_{eq}$	S <sub>eq</sub> /D	T <sub>char</sub> [hrs]
С	0.8	10	-	-	1.76	0.44	1.06	0.40	38.4
С	1.1	10	-	-	3.04	0.76	2.16	0.81	8.9
C*	1.1	10	-	-	2.86	0.72	2.46	0.92	2.5
W	-	10	2.0	6.3	0.20	0.05	0.28	0.10	2.5
W	-	10	2.6	7.6	0.46	0.12	0.36	0.13	2.2
W	-	10	3.4	8.5	0.48	0.12	0.44	0.16	1.1
W	-	10	4.0	8.9	0.50	0.13	0.48	0.18	1.0
CW	0.5	10	2.0	6.3	0.52	0.13	0.32	0.12	3.0
CW	0.8	10	2.8	7.6	0.84	0.21	1.50	0.56	2.6
CW	1.1	10	4.0	8.5	1.84	0.46	1.90	0.71	1.9

Timescales might be smaller, because due to sediment scaling in physical models, the mobility of the sand in prototype scale is often larger than in model scale. On the other hand, side slopes are generally gentler and scour holes are generally wider in prototype scale. This means that scoured volumes are larger, which takes more time.

Another complex issue is the effect of tidal currents on scour development. To the writers' knowledge, there is no general agreement on whether tidal currents will increase or decrease scour depths and whether this effect will be similar for all current velocities and all pile diameter/water depth ratios.

From the scour tests some typical values for characteristic timescales were deduced and summarized in the last column of Table 1. It can be concluded that in general more severe conditions are characterized by shorter timescales. However, it seems that the timescale is also dependent on the already present scour hole (shape and depth). The second and third line in Table 1 represent comparable current velocities, but due to initial differences in the seabed around the pile, not only the equilibrium scour depths are different, but also the timescales vary with a factor of about 3 to 4. Because in prototype situations some kind of scour-induced shape will be present in the vicinity of a structure, it is probably not feasible to determine the timescale very accurately. It is more important to get the right order of magnitude of the timescale (in the order of minutes, hours or days?).

Whitehouse et al performed current-only and combined current and waves scour tests around wind turbine piles and found time scales (prototype) in the order of 144 minutes (current-only) and 88-230 minutes for combined current and waves, which are of the same order of magnitude of the present tests.

### (4) Side slopes

The observed side slopes were in the order of  $30-35^{\circ}$  and are in accordance with Whitehouse et  $al^{13}$ , who found side slopes of  $30-32^{\circ}$ , close to the angle of repose, for both current-only and combined current and waves tests. In prototype situations, the side slopes are in general gentler (see also Rudolph et  $al^{14}$ ).

# 4. SETUP AND VALIDATION OF SCOUR PREDICTION MODEL

Together with the laboratory experiments, a mathematical scour prediction model was set up, based on the exponential function, describing scour development. If this formula is discretized for a time interval dt, the following relation describes the increase (or decrease) in scour depth:

$$S_{n+1} = S_{eq,n+1} + (S_n - S_{eq,n+1}) \exp\left(-\frac{dt}{T_{char}}\right)$$
 (2)

Various formulae for the equilibrium depth ' $S_{eq}$ ' and the characteristic timescale ' $T_{char}$ ' were tested. The purpose of this model was twofold:

- 1. to verify which scour formulae perform well in the typical offshore wind turbine pile conditions, i.e. combined current and waves and low KC-numbers;
- 2. to determine when most critical load combinations are to be expected, based on the idea that wind and wave loads on wind turbines are generally most severe during storm conditions, but that it is often assumed that current-only conditions induce most severe scour.

In this paper, the performance of this model is validated against the laboratory experiments, while in Rudolph et al<sup>14)</sup> prototype measurements from the Dutch Offshore Wind Park 'Q7' are used in the analysis.

When the Scour Prediction Model is used to calculate scour development in time for the

laboratory tests, the results can be compared to the actual measurements, see **Fig. 5**. The upper graph is for the pile with a diameter of 200mm; the lower graph for the pile with a diameter of 134mm. The black line represents the measured 10%-exceedance scour depth, whereas the red line represents the calculated prediction of the Scour Prediction Model. The hydrodynamic conditions during this test were equal to the upper graph of **Fig. 4**. The calculations are based on the following formulations:

- Sumer&Freds¢e-formula for equilibrium scour in wave-dominated conditions<sup>9</sup>; for current-dominated situations (*or* very long waves) this formula reduces to  $S_{eq} = 1.3D$ ;
- timescale for erosion in waves according to Sumer and Freds¢e<sup>9</sup>;
- timescale for erosion in current according to Sumer and Freds¢e<sup>9</sup>;

When the model predictions are compared to the measurements, the following remarks can be made:

1. The equilibrium scour depth for currents is clearly dependent on the current velocity, whereas the relation  $S_{eq}$ =1.3D does not show this dependency.



Fig. 5: Scour measurements and predictions, based on existing and new scour formulae for pile with: upper graph) D = 200 mm (D/hw = 0.4) and lower graph) D = 134 mm (D/hw = 0.27)

- 2. The equilibrium scour depth in current and waves is reasonably predicted by the Sumer&Freds¢e-formula, but whereas this formula predicts no scour for waves-only conditions, characterized by small KC-numbers, the laboratory tests show that some scour occurs.
- 3. The predicted timescales are much too fast for all laboratory test conditions.

The performance of the scour prediction model can only be increased if the formulae for both the equilibrium scour depth and the timescale are adjusted.

### 5. IMPROVEMENT OF SCOUR PREDICTION MODEL

To improve the existing equilibrium scour depth formulae, a database, containing both in-house test results and test results published in literature, was constructed. This database consisted of 192 tests with waves-only and combined current-and-waves tests. Because multiple sources were used and tests were executed at quite different scales, a significant scatter was present in the measurements.

Most important requirements of the new formula for the equilibrium scour depth were that it should:

- 1. be applicable for all wave-dominated and combined current-and-waves conditions;
- 2. be applicable for all ratios of pile diameter and water depth;
- 3. incorporate the effect of pile heights smaller than the water depth;
- 4. have a smooth transition towards current-only conditions;
- 5. yield better predictions especially in the range of low KC-numbers;
- 6. be in accordance with earlier gained knowledge, incorporated in formulae of Breusers<sup>1)</sup>, Sumer and Freds¢e<sup>7,8)</sup> and Rudolph and Bos<sup>6)</sup>

The following formula looks like the Breusers-formula, equipped with two additional correction factors:

$$S_{eq} = 1.5D \cdot \tanh\left(\frac{h_w}{D}\right) \cdot K_w \cdot K_h \qquad (3a)$$

in which  $K_h$  is a correction factor for the pile height to account for piles that do not extend over the entire water column:

$$K_h = \left(\frac{h_p}{h_w}\right)^{0.67} \tag{3b}$$

and  $K_{\rm w}$  is a correction factor accounting for the wave action:

$$K_w = 1 - \exp(-A) \tag{3c}$$

in which A is dependent on the relative velocity and the KC-number:

$$A = 0.012KC + 0.57KC^{1.77}U_{rel}^{3.76} \qquad (3d)$$

Around piles that extend over the entire water column ( $h_p = h_w \rightarrow K_h \uparrow 1$ ) this formula reduces to the Breusers-formula for current-dominated scour ( $U_{rel}\uparrow 1$ ) or for very long waves ( $KC \rightarrow \infty$ ), since  $K_w$ approaches 1. For very shallow water depths ( $h_w < D$ ), the equilibrium scour depth further reduces to:  $S_{eq} = 1.5h_w$ . According to this formula there is no threshold of wave-dominated scour that is dependent on the KC-number, although predicted scour depths for very mild wave conditions are still very small. For waves-only scour A reduces to 0.012KC.

The performance of this formula for all 192 test results is shown in **Fig. 6**. The scatter between measured and predicted equilibrium scour depths is better than for existing formulae but still relatively large and probably related to the wide range of boundary conditions, experimental set-ups and durations of the tests.

The relation between KC-number and relative velocity (Urel) is illustrated in the lower graph of **Fig. 6**. The typical S-shaped dependency on the relative velocity is nicely predicted by this formula.

Together with a new formula for the equilibrium scour depth, new conceptual formulations for timescales of scour development were developed on the basis of the present laboratory tests and engineering judgement<sup>14</sup>:

for current-dominated scour:

$$T_{char;c} = \frac{1000 \cdot D^2}{u_c^3} K_{mob}$$
(4a)

and for wave-dominated scour:

$$T_{char;w} = \frac{1000 \cdot D^2}{\hat{U}_w^3} K_{mob}$$
(4b)

in which  $K_{mob}$  is a multiplication factor, which reduces to 1 for high sediment mobility:

$$K_{mob} = 1 + \frac{10}{MOB^2} \tag{4c}$$

Although these timescale formulae are only conceptual and are fitted on quite a limited amount of data, it was shown in Rudolph et al<sup>14)</sup> that the orders of magnitude of the timescale predictions were in accordance to field observations. An example of the predicted scour development in time, on the basis of the improved formulations of equilibrium scour depth and time scales, is plotted in Figure 5 (blue line). Besides formulae 3) and 4), the

formula of Sheppard et al<sup>4)</sup> for current-dominated scour was used.

Although the predictions still do not perfectly match the scour measurements, the basic trends are reasonably well captured by the scour prediction model. The most important improvements that can be observed are that:

- scour development for waves-only conditions with low KC-numbers is well predicted by the model;
- 2. the effect of superimposing a current on waves severely increases scour depths, dependent on the relative velocity;



Fig. 6 Predictions with new formula for equilibrium scour depth in combined current and waves against: upper left) actual measurements; upper right) dimensionless scour depths; lower graph) relation between equilibrium scour depth and relative velocity for various KC-numbers.

- 3. the equilibrium scour depth in combined-current-and-waves seems to be rather sensitive to the exact combination of KC-number and relative velocity  $U_{rel}$ ;
- 4. current-only conditions yield largest scour depths around cylindrical piles;
- 5. backfilling behaviour is measured during the test as well as predicted by the model;
- 6. timescales of backfilling are easily about a factor ten larger than scouring timescales.

Because it was observed that the exact scour depth is dependent on the shape and dimensions of the already existing scour hole, a scour prediction model can only predict scour development within a certain accuracy range. In addition, the timescale is most likely dependent on the already present scour hole. However, for practical purposes it is usually sufficient to know at least the order of magnitude of the timescale and the equilibrium scour depth within a certain range.

### 6. CONCLUSIONS

Because during test execution of morphological tests in model basins no information on scour development becomes available, a new camera technique was developed to study the bed level changes. This camera monitoring technique proved to deliver very accurate bed level measurements as well as valuable insight in the governing processes regarding sediment movement around offshore structures. At present, this technique is extended to more complex structure shapes, applied in offshore oil&gas drilling.

This monitoring technique was applied for two pile diameters in two test series, consisting of multiple, successive hydrodynamic test conditions, varying from mild current-dominated conditions to severe wave-dominated storm conditions. During these test series accurate time series of scour depths along the pile perimeter were obtained.

Simultaneously, a Scour Prediction Model was developed, which, at first, was based on existing formulae for both equilibrium scour depths and time scales of scour development. Comparison between laboratory measurements of scour depth and model predictions revealed that existing formulations for the equilibrium scour depth in wave-dominated conditions are not applicable for relatively wide piles. Timescales of scour development, deduced for more slender piles, are much too short, compared to the laboratory measurements. Therefore, a new formula for the equilibrium scour depth in wave-dominated conditions was developed, that is applicable for all pile dimensions and shows a reliable relation to the KC-number and relative velocity. Also new formulations for the current-dominated and wave-dominated timescales were implemented in the scour prediction model. The improved scour prediction model performed much better in capturing the scour processes.

# APPENDIX A LIST OF SYMBOLS

- D = diameter of cylindrical pile [m]
- $H_s =$  significant wave height [m]
- $h_p = pile height [m]$
- $h_w =$  water depth [m]
- KC = Keulegan-Carpenter [-]
- $MOB = relative mobility; \theta/\theta_{cr} [-], calculated acc. to Soulsby^{15)}$
- S = scour depth of scour hole [m]
- $S_{eq} =$  equilibrium scour depth [m]
- $T_p = peak wave period [s]$
- u<sub>c</sub> = depth-averaged current-velocity
- $U_{rel} =$  relative velocity,  $U_{rel} = u_c / (u_c + U_w)$
- U<sub>w</sub> = amplitude of orbital velocity above seabed
- $\theta =$  mobility of sediment according to Soulsby
- $\theta_{cr} = critical mobility of sediment (= threshold of motion)$

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