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# TIME-DEPENDENT SCOUR DEVELOPMENT UNDER COMBINED CURRENT AND WAVE CONDITIONS – HINDCAST OF FIELD MEASUREMENTS

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This paper contains a comparison between empirical scour formulae based on experimental data and field measurements around offshore monopiles.

The field measurements were taken in the offshore windpark Q7 which is located 20 kilometres off the Dutch coast. The water depths were between 20 and 25 metres. The monopiles (diameter of 4.0 metres) were exposed to waves and currents for several months without scour protection. The measured maximum scour depths were between 1.5 to 4.3m, the scour hole extents (radii of longest axes) were in the order of 20 to 30 metres.

These field measurements indicated that equilibrium scour depths (in the order of the commonly applied rule of thumb $S=1.5*D_{pile}$) were not reached within a period of several months. The measured scour depths can only be explained if backfilling is taken into account. In wave-dominated conditions, the time rate of scour development was orders of magnitudes slower than expected on the basis of available prediction formulae. New formulae for the time rate are presented which provide an estimate of the order of magnitude of the speed of scouring and backfilling. These formulae are mainly based on recently conducted laboratory experiments and the scour depth hindcasts show reasonable agreement with the Q7 field data presented in this paper.

***Key Words:*** *scour prediction, monopile, offshore windpark, field measurements*

## 1. INTRODUCTION

In connection with the development, installation and maintenance of offshore windparks, scour around monopiles under combined current and wave conditions has become an important topic for project developers, contractors and engineers.

For design, optimisation of pile length and installation accurate scour prediction is needed. However, the presently published knowledge on the time rate of scour development is based on a limited number of small-scale laboratory experiments for the situations “waves only” and “current only” (but not for combined wave and current action) and lacks prototype validation.

In order to improve the understanding on scour development as a function of time and to verify formulae derived from small-scale model tests, a large set of field measurements was analysed and measured scour depths were hindcasted. Furthermore, available and new scour formulae were evaluated.

This paper contains selected field measurements, results of the analyses and new scour formulae.

## 2. AVAILABLE FIELD MEASUREMENTS: Q7 WINDPARK

### (1) Scour surveys

After several months leaving the windpark monopiles unprotected, multibeam echo soundings were conducted. From these bathymetric surveys scour depths were derived. The accuracy of the scour depths was estimated at 0.2 to 0.3m which is mainly related to uncertainties in the definition of the surrounding undisturbed seabed. For the definition of the extent of the scour hole we chose a bed slope criterion: The scour hole ends if the bed slope is 1:100 or more gentle.

From the available raw survey data, 29 data sets were selected and incorporated in the analysis. The selection was made on the basis of reliability of measurements and completeness of seabed coverage around the piles.

### (2) Monopile foundations

The outer pile diameter is 4.0 metres.

### (3) Seabed material

The seabed material in the windpark area generally consists of fine to medium non-cohesive sand ($d_{50} \approx$ 0.1 to 0.3 mm).

### (4) Hydrodynamic conditions

Time series of wave measurements were mainly obtained from the nearby measurement stations "IJmuiden Munitiestortplaats". Because of the proximity to the Q7 windpark and the comparable water depth (21 metres rel. MSL), the measurements were judged to be representative for the Q7 windpark. Data gaps in the measurements were filled by correlating wave measurements at IJgeul-5, platform K13-A and the meteomast of the Egmond windpark.

Time series of tidal water levels and current velocities were derived on the basis of inhouse available tidal predictions. The main direction of the tidal current is SSW-NNE. The maximum tidal current during a spring tide is about 1.0 m/s (depth-averaged).

From the combined time series, the probabilities of exceedance curves of the characteristic parameters Keulegan-Carpenter number (KC) and relative velocity ($U_{rel}$) were computed, see Figure 1. It can be seen that during most of the time (exceeded by 10% of the time), the KC number was below 1, only during three events within one year the KC-value exceeded a value of 3. The probability of wave-dominated conditions (here $U_{rel}<0.5$) was about 15%. This means scour development at the Q7 site can be characterised as predominantly current-dominated.

### (5) Processed scour depths and scour hole extents

A typical scour pattern 10 months after pile installation is shown in Figure 2. This scour pattern is representative for the monopiles in the Q7 windpark. The following was generally observed:

- The maximum scour depths were in the range between 1.5m and 4.3m. Although the hydrodynamic conditions were mainly current-dominated and the exposure time of the piles was several months to one year, scour depths of more than 1.1 pile diameter were not found.

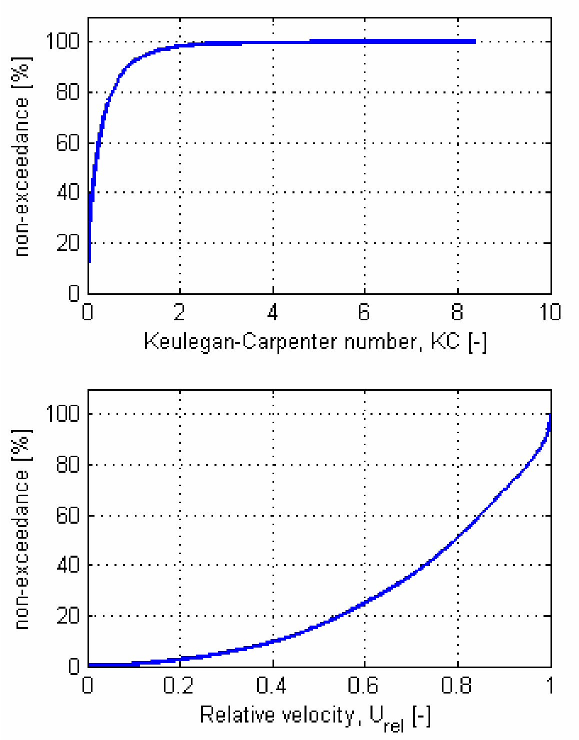

**Fig. 1** Probability of exceedance of KC (upper) and $U_{rel}$ (lower) in the Q7 windpark area based on a time series between 23/12/2006 and 17/11/2007

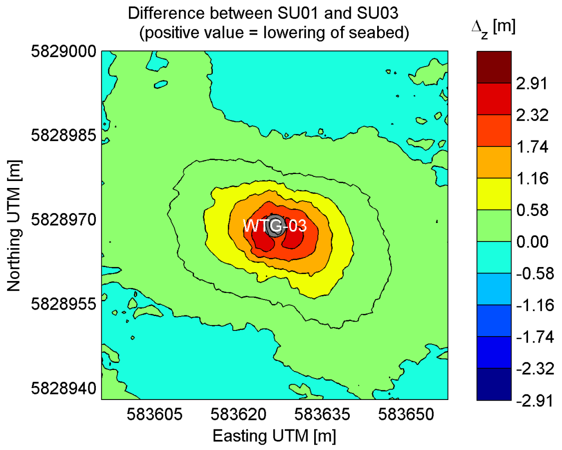

**Fig. 2** Typical example for scour pattern around monopile, 10 months after installation (scour depths obtained from the difference between 2 surveys)

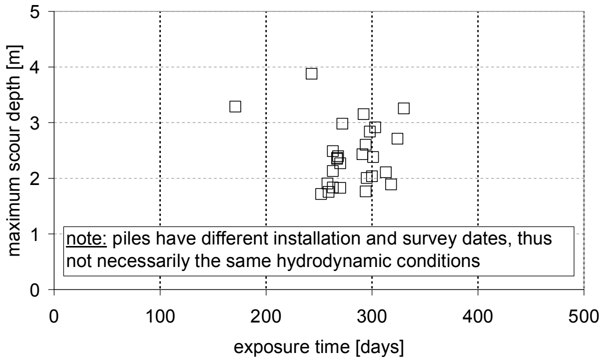

**Fig. 3** Maximum measured scour depths versus exposure time

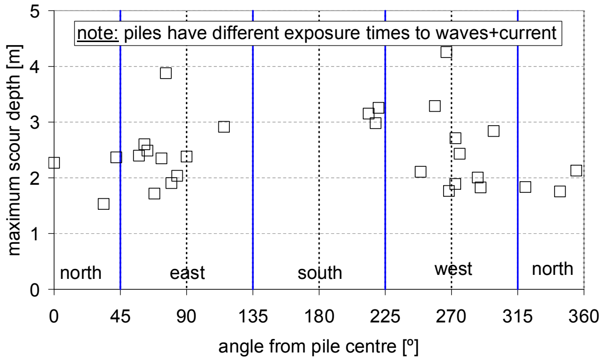

**Fig. 4** Maximum measured scour depths versus angle from pile centre where max. occurred

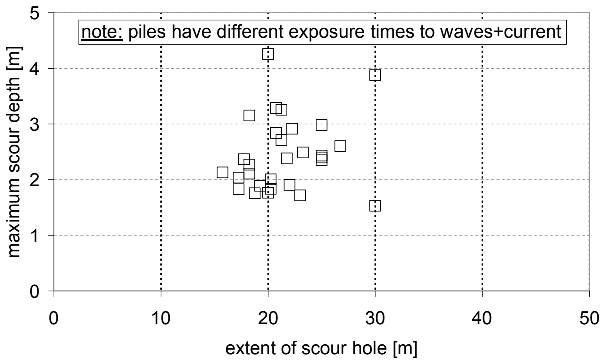

**Fig. 5** Maximum measured scour depths versus extent of scour holes

- The difference between the maximum measured scour depths and the average around the pile was about 15%.
- There was no clear trend between the exposure time and the maximum scour depth (see Figure 3). However, the hydrodynamic conditions were not exactly the same among the piles because of different pile installation and survey dates. The effect of the actual hydrodynamic conditions on scour development is addressed in Section 4 of this paper as part of the hindcast analysis.
- The maximum scour depth occurred predominantly at the western side (10 of 29 data sets) and at the eastern side of the piles (10/29), see Figure 4.
- There was no clear correlation between the maximum scour depth and the extent of the scour hole, see Figure 5. The average ratio between extent and maximum scour depth was 9.3, the standard deviation was 2.8. The slopes of the scour holes were typically around 1:4 to 1:5 very close to the pile which is roughly a factor 2 steeper than the average slope.
- The maximum extent occurred at the western and the eastern side, which is perpendicular to the axis of the tidal current. This is not in line with physical modelling which usually indicates a scour hole orientation along the direction of the current.
- The shape of the scour hole was oval with a length ratio of 1.8 between the main axis (averaged radius 27m) and the short axis (average radius 15m).
- The absolute values of the scour depths are further elaborated in Section 4 in connection with presentation of the time-dependent analytical hindcast model.

### (6) Comparison with experimental data

The distribution of scour depths along the perimeter, the side slopes and the scour hole extents have not yet been addressed extensively by researchers. From data found in the literature on current-only situations and available inhouse data the following can be concluded:

- Differences around the pile depend on the dominant hydraulic conditions. For current only, laboratory experiments indicated depth variations around the pile of about 20% (valid for $h_w/D_{pile}>4$). This is in agreement with the range found in field measurements. For wave-dominated scour inhouse data indicated a ratio $S_{max}/S_{mean}$ of about 50%.
- The side slopes in laboratory experiments are

often reported to be about 1:1.5 to 1:3[1),3)]. The slopes found in the Q7 field data were much gentler (order of magnitude 1:10). Consequently, also the extents of the scour holes are shorter in laboratory experiments than measured in reality. We see two possible reasons for this discrepancy:

- There is a “Reynolds effect”. The vortices in small scale laboratory experiments are less turbulent than in reality and the boundary layer separation is laminar. This means that pile-induced turbulence at the downstream side is shorter in the model than in reality.
- The seabed mobility and the ratio of suspended sediment are higher in reality than in experimental studies. At model scale, sediment moved away from the pile settles faster than at prototype scale because the (turbulent) motion of the water cannot carry the full sediment load which is moved away from the structure.

The Reynolds effect rather plays a role in small scale experiments with low flow velocities. The second effect (seabed mobility) is inherent for morphological modelling and is probably the main reason for the differences in scour hole extents between model and prototype.

In the Q7 windpark, the orientation of the scour hole is probably affected by the presence of sand waves which have crest orientations west – east (perpendicular on the tidal flow). This aspect was, however, not further addressed in this study.

## 3. BRIEF REVIEW OF SCOUR PREDICTION FORMULAE

For the hindcast of the measured scour depths as a function of hydrodynamic conditions scour prediction formulae are required. These formulae were taken from literature and supplemented by assumptions and engineering judgement.

### (1) Short literature review

The scour development under combined waves and current conditions has only been addressed by a few researchers[1),2),3),4)]. Two publications[1),4)] led to prediction formulae for the equilibrium scour depth under combined waves and currents. However, typical prototype conditions (windpark piles in moderate current and waves) are outside the validated range of these formulae. Recently a large set of experimental data was re-analysed and a new formula for the equilibrium scour depth in wave-dominated conditions was proposed[5)]. This formula is also applicable in the typical range for wind turbine piles (characterized by low KC-numbers and relatively wide pile diameters). Due to a better fit, the performance of the new formula was also improved.

Regarding the time rate of scour, available formulae for current only and waves are based on small scale laboratory experiments[6)]. The application of the formula for waves outside the validated range indicates some unexpected trends for prototype situations. We compared the basic parameters and trends with inhouse data[5)] and found the following:

- The scour rate follows an exponential law which is confirmed by recent experiments[5)].
- Situations with relatively low KC numbers and high mobility often occur in reality but the time scale according to presently available formulae appears to be orders of magnitude too fast.
- The bed orbital velocity is important for the time rate. The time rate decreases more than linearly with an increase of the bed orbital velocity. This is already incorporated in the presently available formulae.
- We expect that the time rate increases with the pile diameter because the scour hole becomes larger and more bed material has to be moved. The presently available formulae for wave-dominated conditions indicate that the time rate decreases with pile diameter. This would mean that a scour hole develops faster at a large pile than at a small pile. In view of the applied scale of small scale experiments[6)] we assume that scale and model effects might have played a role in the relation between pile diameter and time rate.
- The seabed mobility is expected to influence the time rate. However, above a certain mobility we assume that the influence of the mobility negligible.

### (2) New formulae

In a re-analysis of the time rate of scour in waves we used inhouse data (pile diameters 0.1-0.2m) and previously published data[6)]. A new order of magnitude estimate was derived for the time rate of scour in waves only.

The scour development follows an exponential law:

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

The new estimate for the characteristic time reads:

$$T_{char,waves} \approx 10^3 \cdot D_{pile}{}^2 \cdot U_{bed}{}^{-3} \cdot K_{mob} \qquad (2)$$

$$T_{char,current} \approx 10^3 \cdot D_{pile}{}^2 \cdot u_c{}^{-3} \cdot K_{mob} \qquad (3)$$

For the mobility factor $K_{mob}$ we applied $K_{mob}=1+10(\theta_{cr}/\theta)^2$ which is also an order of magnitude approach. The mobility can be computed with standard formulae for bed shear stress.

It should be noted that these formulae are based on a combination of data fitting and engineering judgement. The formulae are simple engineering tools to get an idea on the order of magnitude of the time rate. The verification of the presented equation is given further below on the basis of available field measurements. Additional experimental and field data would be useful for further validation.

## 4. HINDCAST OF SCOUR DEPTHS AS FUNCTION OF HYDRODYNAMIC CONDITIONS

### (1) Approach

For each time step of the time series of waves, currents and water depths the equilibrium scour depth, the characteristic time and the incremental increase/decrease in scour depth are computed. The chosen approach[7)] contains four basic steps, see also Fig. 6.

1. Time series of hydrodynamic conditions follow from measurements (waves) and predictions (tidal current). The upper graph shows exemplarily an extract of a current. Similar graphs were used for significant wave height, peak period and water depth.
2. Time series of characteristic times were computed on the basis of available formulae and engineering judgement. The characteristic time is a measure for the required time to reach a certain percentage of the equilibrium scour depth. A short characteristic time means that the equilibrium is reached quickly.
3. Time series of equilibrium scour depths were computed on the basis of available formulae and engineering judgement. The equilibrium scour depth depends on the hydrodynamic condition, the water depth and the pile diameter.
4. Time series of scour depth development with time were derived on the basis of hydrodynamic conditions, the equilibrium scour depth and the characteristic time.

A similar approach was also applied by other researchers[8)] but did not have experimental and field data available for a critical evaluation of available formulae for the time rate.

For each time step of the time series of waves, currents and water depths (see Figure 7) the Keulegan-Carpenter number (based on $H_s$ and $T_p$), the relative velocity, the relative mobility, the equilibrium scour depth, the characteristic time and the incremental increase/decrease in scour depth were computed. The uncertainties of various assumptions were considered in sensitivity analyses.

It should be noted that this hindcast does not provide full evidence that the scour prediction formulae work perfectly because the available measurements are only instantaneous measurements (instead of continuous) after several months of exposure to waves and current.

The applied formulae are so far only validated for continuous laboratory data. The field data provide a valuable indication on whether the orders of magnitude of the scour development can be predicted in reality and not only at model scale.

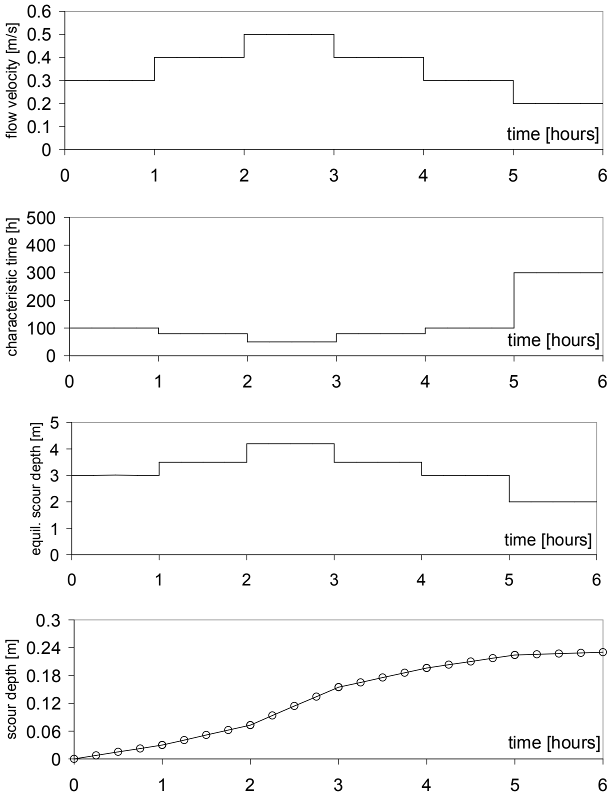

**Fig. 6** Principle approach for scour depth prediction in varying conditions

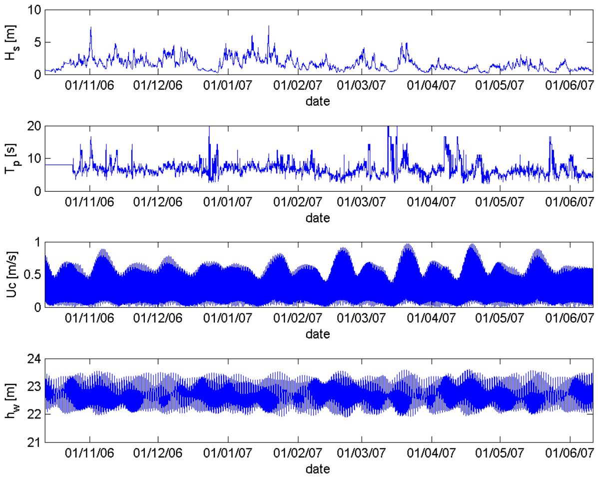

**Fig. 7** Time series of hydrodynamic conditions in the Q7 windpark between pile installation and scour survey

### (2) Hindcast model calibration and sensitivity analysis

In the calibration of the scour hindcasts and the sensitivity analyses we differentiated between two aspects:

- Uncertainties in the description of the processes (parameter settings of available formulae). This is related to the quality of the available formulae on time scale and equilibrium scour depth. Since there are no formulae available to describe backfilling, the backfilling rate was assumed to be proportional to the scour rate. Furthermore, there are e.g. uncertainties in the transition between current-dominated and wave-dominated time rates.
- Uncertainties in the input. This is related to uncertainties between predicted, measured and actual wave and current conditions. Furthermore, the seabed material (mean grain size, cohesive/non-cohesive) is not known accurately. Also, bed forms (ripples) influence the bed roughness and therefore also the bed mobility.

From the sensitivity analysis regarding the uncertainties in the process description we found the following:

- The measured scour depths can only be explained if backfilling is taken into account. The backfilling rate appears to be in the order of 10 to 100 times the scour rate. The best estimate is a factor of 20. (This, however, must also be seen in combination with other parameter settings).
- The time rate formulae suggested above for current-dominated scour (Equation 3) and the Sumer formula6) perform well.
- The time rate formula suggested above for wave-dominated (Equation 2) performs well. The time rate formula for waves suggested by Sumer et al.6) predicts too fast scour development and consequently also too fast backfilling (because backfilling is directly linked to scour in our approach).
- The time rate formulae suggested above (Equation 2 and 3) are also robust with respect to the choice of the transition between wave-dominated and current-dominated scour. This transition is described in terms of the relative velocity $U_{rel}=u_c/(u_c+U_w)$. A sensible criterion for $U_{rel}$ appears to be in the range between 0.5 and 0.7. In our best fit hindcast we applied $U_{rel}=0.5$.
- The choice of the equilibrium scour depth formulae for wave-dominated conditions does not have a strong influence on the scour hindcast. This is because the situation "wave-induced scour" hardly occurred in this area. However, for consistency reasons, especially for low KC numbers, which are typical for the North Sea, we used a recently published formula5) as input for the hindcasts.
- For current-dominated scour, the Sheppard formula9) performs best. The application of the Breusers formula10) leads to a clear overestimate of the scour depth. This overestimate cannot be compensated by choosing other reasonable parameter settings. The difference between the Sheppard formula and the Breusers formula is that Sheppard et al. took into account current velocity while Breusers rule of thumb suggests $S_{max}$ being independent from current velocity.

From the sensitivity analyses regarding the uncertainties in the process description we found the following:

- The effect of uncertainties in the bed material was found to be limited. There is little difference between scour hindcasts for mean grain sizes of 0.1mm to 0.3mm. Similarly, the assumption for the bed roughness was of low influence on the hindcast.
- A clear influence was found regarding the current velocity. An overestimation of the current velocity would lead to an over prediction of the scour depths. (This is of course not surprising because the current-dependent scour formula was found to match data very well.)
- Uncertainties in the wave conditions (variation of 10%) had little effect on the scour depth hindcast because the situation "wave-induced scouring" hardly occurred (<<1% of the time).

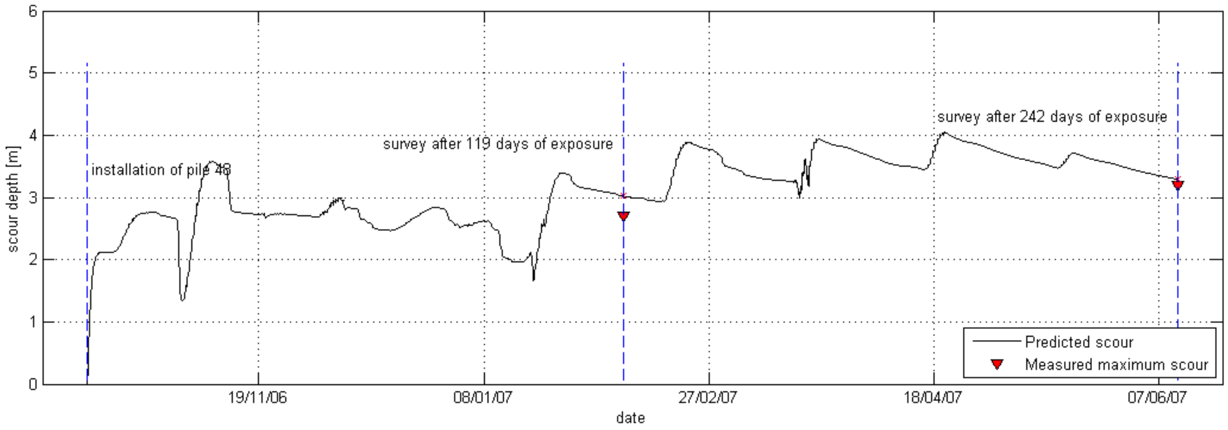

**Fig. 8** Time series of scour depth as function of time for pile 48

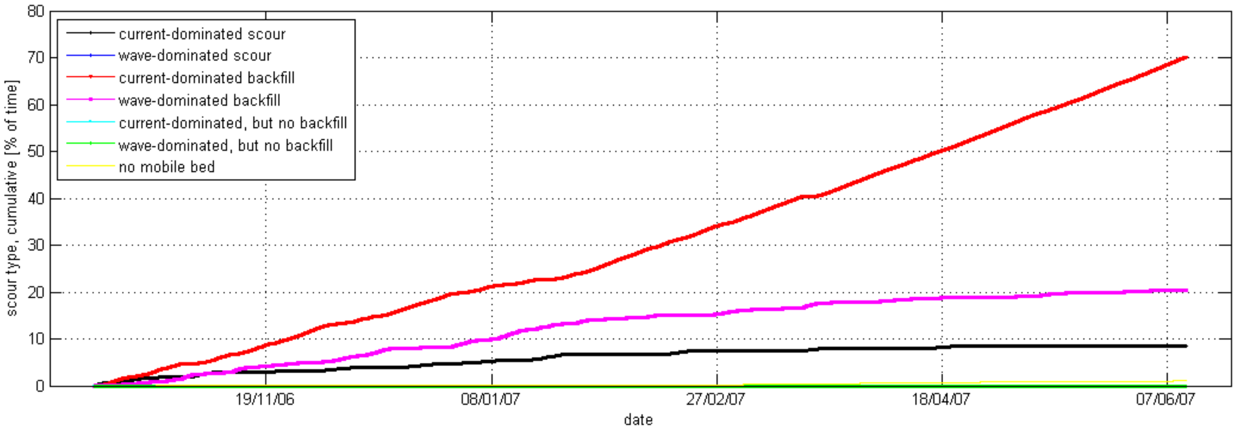

**Fig. 9** Computed time series of relevant processes for scour development

**(3) Results**

Figure 8 shows exemplarily the computed time series of expected scour depth development with time, which corresponds to the history of hydrodynamic conditions between pile installation and survey date (see Figure 7). In this example, the measured and the predicted scour depth match well because the survey data were used for calibration of parameter settings. Hindcasts were made for the other available data sets accordingly.

…Figure 9 gives an indication on the dominant processes. It can be seen that during less than 10% of the time scour increased. About 90% of the time backfilling of the scour hole was the dominating process (70% current-dominated, 20% wave-dominated). A realistic scour prediction cannot be made without backfilling prediction.

Figure 10 contains the comparison between measured maximum scour depths and hindcasted scour depths for all available data sets. The predictions are around the ideal line with some scatter. The standard deviation of the ratio prediction/measurement is about 30%. This is comparable with the quality of fit of equilibrium scour depths found by Raaijmakers et al.$^{5)}$.

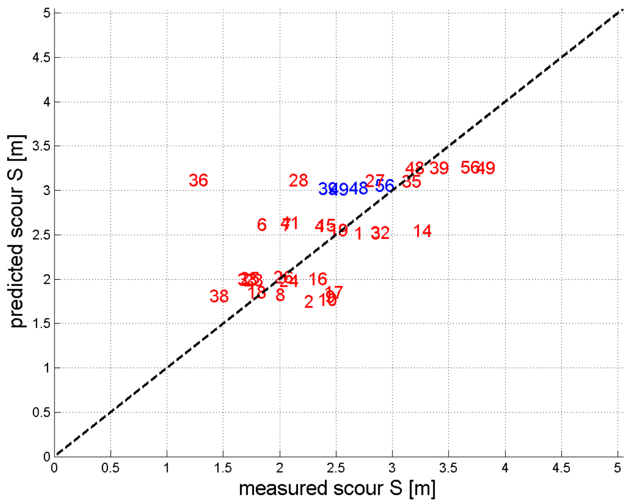

**Fig. 10** Comparison between measured maximum scour depths and hindcasted scour depths. For four piles two data sets were available (blue data points).

## 5. CONCLUSIONS

A large data set of field measurements was analysed in order to evaluate scour prediction formulae which are based on small-scale model tests. The data originated from the unprotected monopile foundations of the offshore windpark Q7 off the Dutch coast.

After several months of exposure to waves and currents, the scour depths (1.5m-4.3m) appeared to be clearly below the well-known rule of thumb, which assumes that the maximum scour depth $S_{max}=1.5D_{pile}$.

The extents of the scour holes were in the order of 20 to 30 metres (radius) which is in the order of 9.3 times the pile diameter. This is significantly larger than often found in laboratory experiments.

A new order of magnitude estimate for the time rate of the scour development was proposed which is based on experimental data and engineering judgement. New formulae for the time rate were used to calibrate the prediction model and to hindcast the scour depths measured in the Q7 windpark.

On the basis of limited experimental data and the field data of the Q7 windpark we conclude that the time scale of backfilling is in the order of magnitude of 10 to 100 times the time rate of scouring. Our best estimate for backfilling is about 20 times the scour rate given in Equation 2 and 3 of this paper.

For the Q7 windpark data it was concluded that during 10% of the time scour development took place and during about 90% of the time backfilling. This means that both processes scouring and backfilling are equally important in a scour assessment. Future scour research should therefore also focus on the backfilling rate.

**ACKNOWLEDGMENT:** This research project was co-financed by the Dutch Ministry of Economic Affairs. The authors are thankful to Van Oord for the provided field measurements.

## APPENDIX A LIST OF SYMBOLS

$D$ = diameter of cylindrical pile [m]
$E$ = horizontal extent of scour hole [m]
$H_s$ = significant wave height [m]
$h_w$ = water depth [m]
$KC$ = Keulegan-Carpenter [-]
$S$ = scour depth of scour hole [m]
$S_{eq}$ = equilibrium scour depth [m]
$T_p$ = peak wave period [s]
$u_c$ = depth-averaged current-velocity
$U_{rel}$ = relative velocity, $U_{rel} = u_c/(u_c+U_w)$
$U_w$ = amplitude of orbital velocity above seabed
$\theta$ = mobility of sediment
$\theta_{cr}$ = critical mobility of sediment

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