SCOUR AROUND AN OFFSHORE WINDTURBINE

W.F. Louwersheimer[1], H.J. Verhagen[2] and J. Olthof[2]

During the construction of the first Dutch offshore wind farm prototype measurements were performed. These measurements were aimed to monitor the behaviour of the granular filter layer of the scour protection around the mono-piles upon which the wind turbines are founded. These measurements were compared to scale model test results and theoretical analysis. The measurements show an overall lowering of the filter bed surface during the period that the filter beds were exposed to hydraulic loading of waves and tidal flow.

INTRODUCTION

Off the coast of Egmond aan Zee in 2006 an offshore wind farm has been constructed. To answer the increasing demand for energy it is vital to look for other sources than fossil fuels. Wind energy is one of the most important options, to create a sustainable and renewable source for energy. Space however is limited in the Netherlands so attention goes from land to sea. This is a demonstration project for the Netherlands of 36 Wind Turbine Generators (WTG's).

Figure 1: Off the coast of Egmond aan Zee, visible on the horizon, the first Dutch offshore wind farm is constructed.

During the construction of the wind farm, prototype measurements were executed with the aim to monitor the behaviour of the filter layer, which is a part of the granular bed protection around the mono-pile foundations of the

[1] Delta Development, DHV B.V., P.O. Box 1132, 3800 BC Amersfoort, the Netherlands; www.dhv.com; wf.louwersheimer a gmail.com
[2] Section of Hydraulic Engineering, Faculty of Civil Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands

wind turbines. The bed protection consists of a filter layer of small sized rock and a top layer of a heavier rock grading. Interest goes to the scour process of the filter layer, under influence of the local environmental conditions. During the construction process of the wind farm this filter layer lays exposed to wave and currents for some time (see Figure 2). As the actual scour process, influenced by the interaction of waves and currents is not clearly understood, this was reason to carry out scale model tests at WL|Delft Hydraulics during the design phase. Prototype measurements may serve as a reference, verification and calibration of the scale model tests by comparing the obtained data with results of design formulas and physical model tests. For this purpose velocity measurements, wave characteristics and multi-beam depth soundings are gathered to give an overall impression of both the acting forces on as well as the strength of the filter bed.

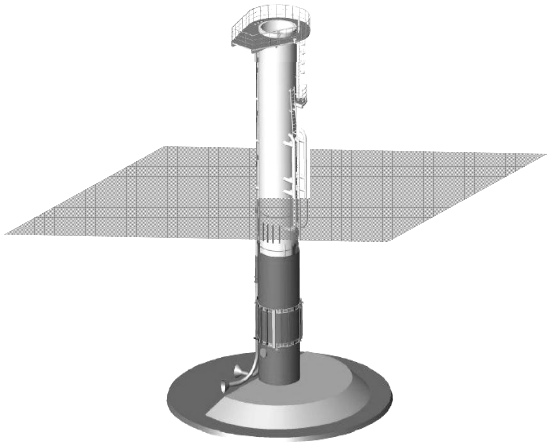

Figure 2: Scour protection around mono-pile; mono-pile driven trough the filter layer into the sea bed; the armour layer is visible on top of the filter layer

CONSTRUCTION OF THE WIND FARM

The wind farm consists of 36 wind turbines, founded on mono-piles, and one Meteo Mast, the latter is already present for three years. Each mono-pile has a scour protection with a diameter of 25 meter, while the Meteo Mast has none. The local depth ranges from 16 to 21 meter, pile lengths run up to 48 meter. The steel pile diameter is 4.6 meter. The pile was driven through the filter layer into the underlying sand bottom. The filter bed (with stone size D_{n50F} = 0.05 meter and with a layer thickness of 0.4 meter to 0.7 meter), lies directly on top of the sand of the sea bed (D_n = 250 μm).

MEASUREMENTS

Prototype measurements are performed to monitor the behaviour of the filter layer under exposure of currents and waves.

The **wave** conditions are registered using WaveRider buoys of Rijkswaterstaat at about 10 kilometres distance from the wind farm area.

The local current **velocities** are measured near one of the piles, WTG 09. Varying with the tide the measuring location lies in the wake of the flow or in full approaching flow. Measurements are done during a period of seven days around spring tide. Furthermore reference measurements at some distance from the pile are done to find the influence of the pile on the local (orbital and tidal) velocity.

The behaviour (deformation of) the **filter bed** material is registered using multi-beam survey data that were used by the contractor to demonstrate the as-built construction of the filter layer. Thus, information on the filter bed behaviour for a total of fifteen locations (thirteen filter layers) is gained, with different exposure times and characteristics.

The tidal currents recorded during the measurement campaign were in the order of 0.7 m/s and the significant wave heights were below 4.0 meter.

HYDRAULIC LOADING

The situation around the mono-pile can be described as an interaction process between waves, tidal currents and the structure. The hydraulic loading on the scour protection consists of a combination of tidal flow and the orbital wave action. An approximation for the average local tidal velocity ($u_{c\ av}$) is 0.7 m/s. The wind farm is located in a transitional depth with non-breaking waves. It could be concluded that linear wave theory is applicable with regard to the maximum orbital velocity near the bottom:

$$u_{w,\max} = \frac{\pi \mathrm{H}}{\mathrm{T}\sinh(\mathrm{kh})}$$

H= wave height [m]
T= wave period [s]
k= wave number ($k = 2\pi / L$)
L = wave length [m]
h= local water depth [m]

The structure interaction with the surrounding seawater is based on the interaction between flow and pile, waves and pile and combined wave/flow and pile. The Reynolds number (ratio between viscous and inertial forces) gives an indication of the type of flow regime around the monopole in the flow-only situation. The Reynolds number appears to be in the range 1.5*10e6 – 4*10e6, which indicates a situation of a completely turbulent boundary layer, on one side of the pile.

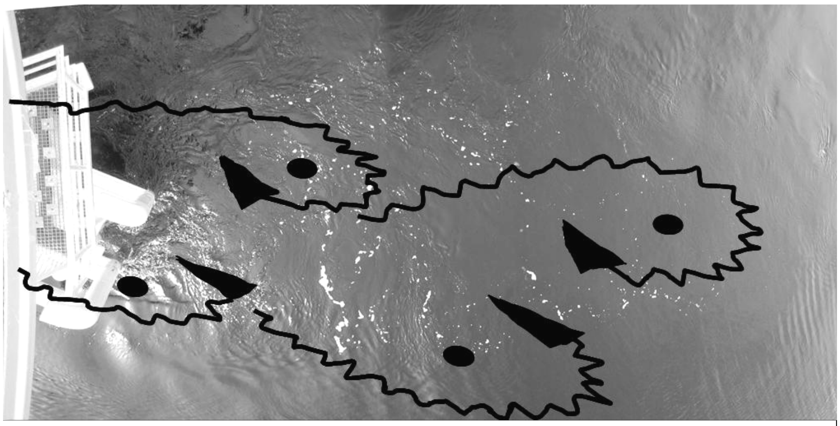

Figure 3: Lee-wake vortices behind mono-pile at sea in absence of waves

Vortices occur symmetrically on both sides of the pile due to the tidal flow (see Figure 3). The influence of the waves however prevents that vortex shedding can occur.

For the mono-pile in waves the diffraction parameter (D/L) and the Keulegan-Carpenter number show the relative pile size in relation to the wave characteristics. The diffraction parameter (D/L) shows the relative pile size in relation to the wave length. With values of D/L > 0.1 with it can be concluded that the mono-piles are in the diffraction regime during the measurement period. During storm conditions (Hs > 2.5 meter) the D/L ratio is below 0.1 which means that the piles are outside the diffraction regime.

An approach definition to rate the motion of water particles in relation to the width of the mono-pile is the Keulegan-Carpenter number, a dimensionless parameter. It has a value of KC = O(6) in design conditions.

$$KC = (u_{\max} T) / D = \frac{H\pi}{D \sinh(kh)}$$

with u_{max}= maximum orbital velocity near the bottom [m/s]

H= wave height [m]

T= wave period [s]

D= pile diameter [m]

k= wave number ($k = 2\pi / L$)

h= local water depth [m]

Table 1. KC-number definition[3]	
KC range	pile definition
KC < O(1)	large
O(1)< KC < 6	intermediate
KC >O(6)	slender

During the measurement period the wave heights H_s remained below 4.0 meter, so the piles are to be considered as large piles. This is because in these conditions KC < O(1) (see Table 1). The KC-number changes with a changing sea-state.

Hydraulic conditions

The mono-piles are slender piles in design conditions, while during the measurement period the piles are large to intermediate, which means:

- No horseshoe vortices occur, when KC < (O)6, nor will vortex shedding occur although lee-wake vortices can develop
- The steady streaming combined with phase resolved flow is the main actor in scour process for KC < (O)6.

Scour process

From the theoretical stability analysis the following can be concluded:

- Close to the pile, distance < 1.0 meter, the stones of the filter layer can be considered dynamically stable up to a wave height of H_s = 2.5 meter
- At greater distance (> 1.0 meter) from the influence of the pile the stones start to move when the waves exceed H_s > 3.5 meter.

Scour can occur around a pile in sand under the combined influence of current and waves. When vortex shedding takes place, a 'tornado' can sweep over the sea bed in the wake of the pile. Sediment particles are picked up, transported away from the pile and dropped again. However the vortex shedding will not occur for KC < (O)6. For the combination of waves and current in sand Haddorp (2005) shows that a scour hole can evolve with a depth of S < 0.3*D = 1.4 meter.

Scale model tests

The implication of the scaling parameters into the scale model tests to study the filter bed behaviour can be quite difficult and the results have to be regarded with some caution. The scale model tests show washing out of fine parts over the whole surface of the filter bed and no extra scour in the close vicinity of the mono-pile.

---

[3] Sumer and Fredsøe, 2002

Monitoring

The recorded **wave height** in the measurement period from March to September 2006 reached values up to $H_s = 3.6$ meter, $T_p = 8$ seconds. Especially a storm in May had high values. The resulting hydraulic loading on the filter construction is such that movement of filter stones can be expected. A filter bed level lowering is predicted applying formulas used for conceptual design of the scour protection.

With an Acoustic Doppler Current Profiler (ADCP) current **velocity** data are gathered. The average flow velocities are deduced from the results to investigate the influence of the presence of the pile. The average velocities are in phase with the water level fluctuation, which demonstrates that the data contain realistic trends. The average velocities are about the same as the approximated value of $u_c = 0.7$ m/s. According to the composed velocity/acceleration diagram the data contains reliable values because the values do not deviate too much from the gravitational acceleration or from the mean velocity[4]. Because it is reliable data, it can be used for calibration purposes. However due to difficulties with mounting the device on the monopole the data is only valid in a very specific location and direction. Further research on the velocity data is needed.
The **filter layer** of the scour protection of thirteen locations is monitored during construction. The locations were selected on the basis of availability and diversity of depth locations. The behaviour (deformation) of the filter layer is monitored by comparing two successive multi-beam depth surveys, showing the response on the hydraulic loading.

Results of filter bed monitoring

Sand ripples on the sea bottom around the scour protection move over a distance of 3 to 5 meter during a storm period with waves up to $H_s = 3.6$ meter. The sea bed does not show edge scour in the surroundings of the rock structure. Near the pile a lowering of the filter material is found of 0.4 meter ($0.1*D_{pile)}$ in a circle with a diameter of 8 meter (1.7 a 1.9 * D_{pile}).

Further analysis shows that the driving of the pile through the filter layer has a significant influence on this lowering (see Figure 4). For the surface of the filter layer an average lowering of about 0.07 meter was observed, mainly due to tidal currents and waves. Separate influences of waves, currents or local water depth could not be detected from the results.

---

[4] Goring and Nikora 2002

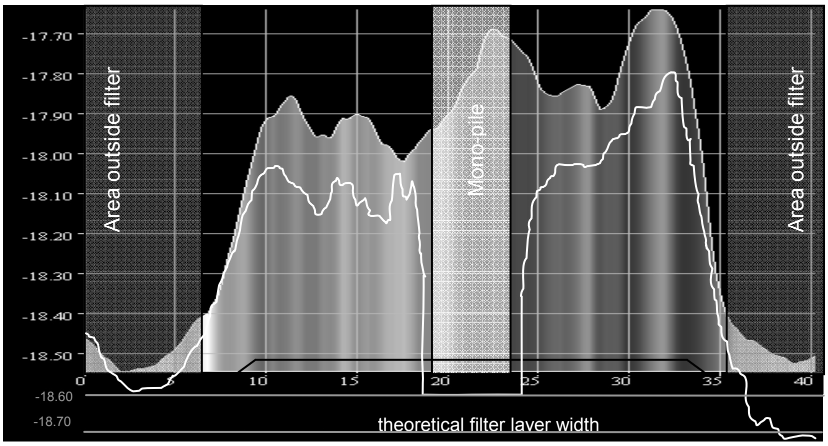

Figure 4: Lowering of the filter bed level (WTG 06 serving as example); clear lowering over the whole surface of the bed protection and lowering close to the pile.

The Meteo Mast, a mono-pile with D_{pile} = 2.9 meter was exposed for three years without bed protection. A snapshot of the dynamic scour process resulted in a depth of 2.3 m = 0.7*D_{pile} in 20 meter water depth, with a scour hole diameter of about 50 meter. In the scale model tests scour depths of 0.5*D_{pile} were measured.

In the wake of the mono-piles no extra scour becomes visible,. This indicates that the presence of mono-piles does not seem to have great influence on the scour protection. The direction of the tidal flow is visible in the orientation of the scour hole around the Meteo Mast.

DISCUSSION

The prototype measurements were aimed to monitor the behaviour of the filter layer of the scour protection around mono-pile founded wind turbines. The measurement results are shown in Table 2 below and can be compared to the scale model test results and theoretical analysis.

Table 2: Results of several Wind Turbine Generator locations: local depth, exposure time, number of storm events and average filter bed lowering.

	local depth [m]	exposure time [days]	number of storm events	storm conditions highest H_s [m]	average filter bed lowering [m]
WTG 03	17.5	114	5	3.6	0.11
WTG 04	17.0	41	3	3.6	0.08
WTG 05	17.1	104	5	3.6	0.07
WTG 06	18.3	63	3	3.6	0.09
WTG 11	17.6	71	3	3.6	0.10
WTG 12	17.7	82	5	3.6	0.02
WTG 17	16.5	43	No storms	2.3	0.06
WTG 19	18.6	38	No storms	2.3	0.08
WTG 21	17.8	37	No storms	2.3	0.05
WTG 23	19.0	40	No storms	2.3	0.08
WTG 25	20.0	42	No storms	2.3	0.03
WTG 26	16.0	38	No storms	2.3	0.04
WTG 31	17.5	13	No storms	1.7	0.07
Average filter bed lowering					0.07

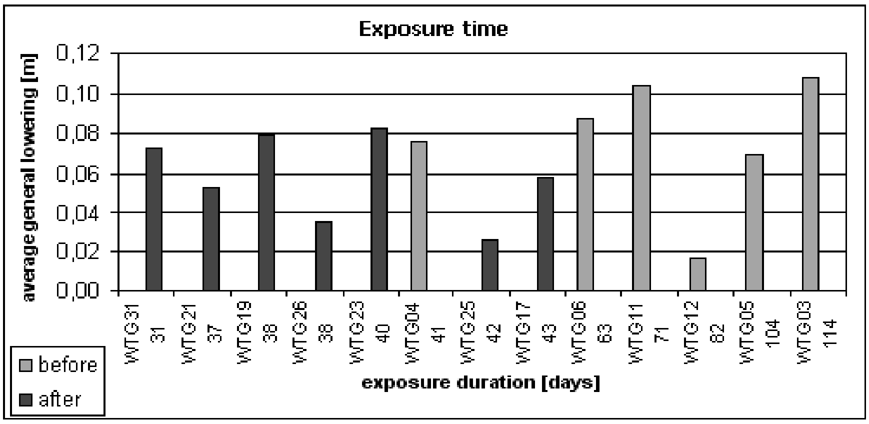

Figure 5: A longer exposure duration not necessarily results in more lowering; before and after the May storm. The average lowering of the filter bed levels is shown as a function of exposure time in days.

It is reasonable to expect a correlation between the average filter bed lowering and respectively the local depth, the exposure time (see Figure 5 on previous page) and storm intensity, since these variables represent or influence the acting forces on the scour protection. However, no correlation could be detected. The results are rather heterogenic, because all the locations have different characteristics.

Under the acting hydraulic conditions the design formulae, scale model tests and prototype measurements also all have their own results (see Figure 6).

- Formulae: stones are expected to move close to the mono-pile (< 1.0 meter) and for pile locations in shallower depths (h < 17.0 meter) the whole surface of the filter bed is expected to erode for waves H_s > 2.5 meter. For the other locations waves of H_s > 3.5 meter are needed to cause scour.
- Model Tests: washing out of fine parts over the whole surface of the filter bed, no extra scour in the vicinity of mono-pile; lowering of 0,1 meter.
- Prototype measurements: an average lowering of the whole surface of the filter bed level of about 0.07 meters. A lowering close to the mono-pile (< 1.5 meter) of about 0.4 meter is caused by the driving of the mono-pile trough the filter layer.

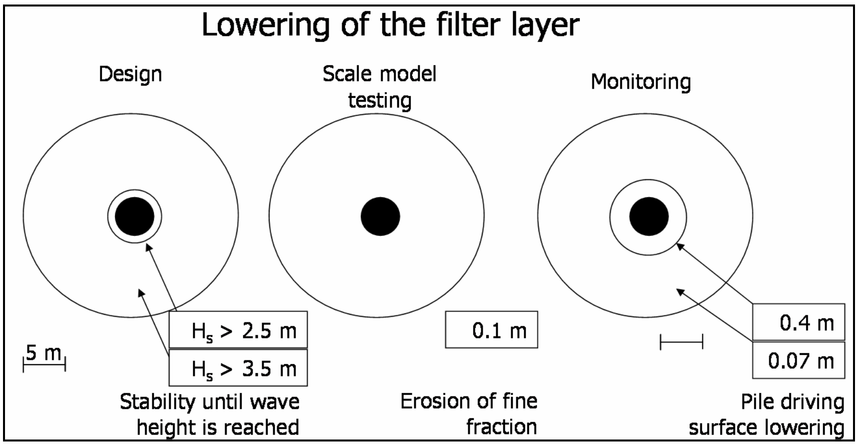

Figure 6: Lowering of the filter layer by design formulae, scale model test results and prototype measurements

The design formulas of the conceptual design show stone movement close to the pile (distance < 1.0 meter). The results of the measurements show a lowering close to the pile as well. However, it is reasoned that this is caused by the driving of the mono-pile through the filter layer. Part of it may be caused by the combination of currents and waves as well. It is however not possible to separate the results of both.

The presence of the Wind Turbine Generator mono-piles themselves does, under the acting conditions, not seem to have great influence on the scour protection, because only an overall lowering of the filter layer is visible and not a clear scour in the wake of the mono-pile. The applied filter layer of the scour protection is robust enough to cope with the hydraulic loading. The dynamic design method predicts an adequate flexibility of the filter bed.

RECOMMENDATIONS

- In the design of an offshore wind turbine the mono-pile diameter should be considered in the intermediate regime. Scour will then not be too large.
- For a scour protection an alternative design could be more feasible; a design that uses the formation of a scour hole in sand with equilibrium scour depth and subsequently fill this with small stones.
- The Acoustic Doppler Current Profiler seems to be effective in measuring the local velocities near the mono-pile, the mounting should however be done with caution.
- The multi-beam depth surveys can be well used to monitor the filter bed behaviour. Although the lowering of the filter layer has values of the same order as the accuracy of the survey system, the trend of overall lowering of the filter bed can be clearly detected with this method. The values of the lowering of the filter bed are small, but the overall trend is clear enough.
- A longer period to measure with higher waves (like in winter) is more interesting: more scour is expected. Performing the monitoring will be more challenging however.

ACKNOWLEDGMENTS

Without the contribution of the contractor Ballast-Nedam for giving the opportunity to perform proto-type measurements at sea during the construction of the offshore wind farm this research was not possible.
Also thanks goes to Delft University of Technology for publishing the full report on http://repository.tudelft.nl/file/537890/372445

REFERENCES

Goring, D.G. and Nikora, V.I. (2002): ' Despiking Acoustic Doppler Velocimeter Data ', Jrnl of Hydr. Eng., ASCE, vol 128, No 1, p117-126.
Haddorp, R. (2005): ' Predictability of Scour at Large Piles due to Waves and Currents ', Thesis study, Delft University of Technology, Delft. (available at http://www.hydraulicengineering.tudelft.nl/ -> Education -> MSc Theses)
Sumer, B.M. and Fredsoe, J. (2002): ' The Mechanics of Scour in the Marine Environment ', World Scientific Press, Singapore.

KEYWORDS – CSt07

Abstract acceptance number: 37
SCOUR AROUND AN OFFSHORE WIND TURBINE
1st Author: Louwersheimer, Willem Frederik
2nd Author: Verhagen, Henk Jan
3rd Author: Olthof, Jelle

Offshore wind turbines
Mono-pile
Scour protection
Filter layer
Stability
Rock grading
Monitoring
Erosion