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SCOUR AROUND MONOPILE FOUNDATIONS FOR OFF-SHORE WIND TURBINES

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Abstract

The present paper aims to describe the scour hole process around large piles through laboratory tests under waves, unidirectional and tidal currents in time. The process for unidirectional and tidal currents has been compared.
The tests have been carried out in a wave flume equipped with a two way recirculation pump at the Hydraulic Laboratory at Aalborg University. The mobile bed around the model was leveled with an automatic laser profiler and the results are graphically displayed as maximum scour depths and eroded volumes.

1. Introduction

Scour around monopile foundations for off-shore wind turbines is a problem growing together with the rise of offshore wind energy market in Northern Europe. Traditional design for foundations is based on the equilibrium scour depth and for the tower on fatigue that increases with increasing scour depths. It is very important, then, to evaluate correctly the maximum scour depth and give an esteem of the time development of the scour hole. Moreover scour protection might require the knowledge of time development and eroded volume that could be filled in with rocks before the hole is completely developed (dynamic scour protection).

The erosion process around piles has been exhaustively discussed in literature mainly concerning bridge scour (Breusers et al., 1977; Sumer and Fredsøe, 1997; Melville and Coleman, 2000; Richardson and Davis, 2001; den Boon et al., 2004): the presence of the pile in a flow is an obstacle that changes the flow pattern. The downflow ahead of the pier causes a horseshoe vortex at the base that lifts up the sediment that is carried away by the current. Downstream the erosion process is dominated by the wake vortices arisen from flow separation at the side of the pile. As a result of an asymmetrical process, an asymmetrical scour hole occurs. The equilibrium scour depth S occurs after a certain time T depending on different parameter as: the volume to be eroded V , the pile diameter D, the porosity n, the flow velocity U, the tide period T_m and the fluid's and sediment's characteristics.

The marine environment where wind parks are built, brings out new topics to be debated as the influence of tidal currents (Escarameia, 1999) and waves.

This article propose an evaluation of scour holes in tidal currents and a discussion of time development and scaling low.

2. The set-up

Tests have been carried out in the deep water wave flume at the Hydraulics and Coastal Engineering Laboratory at the Department of Civil Engineering at Aalborg University (DK).

The objectives of the experiments were:

- To describe the scour hole process around monopile foundations under unidirectional and tidal currents in time;
- to estimate the equilibrium scour hole for tidal currents and answer if it is or not deeper than in case of unidirectional currents.

2.1 The physical model

The flume used during the tests is 25 m long 1.2 m wide and 1.5 m deep (Fig. 1). The sloping bed was designed in order to provoke wave breaking. The bed was constructed of concrete with a 4 m long sand box filled with fine sand (grain size was 0.15 mm) where the model was fixed. Sand was spread out in a thin layer across the slope and all the tests were in live-bed conditions. A two way recirculation system allowed the simulation of steady and tidal currents. The scale of the model is 1:30.

Currents and waves were measured beside the model by an acoustic Doppler velocimeter and two wave gauges, one of them close to the wave generator in order to allow waves separation into incident and reflected waves.

The tests covered a wide range of velocities (0.3÷0.5 m/s) and water depth (0.1÷0.3 m) and two pile diameters (0.1 m and 0.2 m). Tide was simulated by reverting the current velocity every half an hour for two hours (2 tidal cycles).

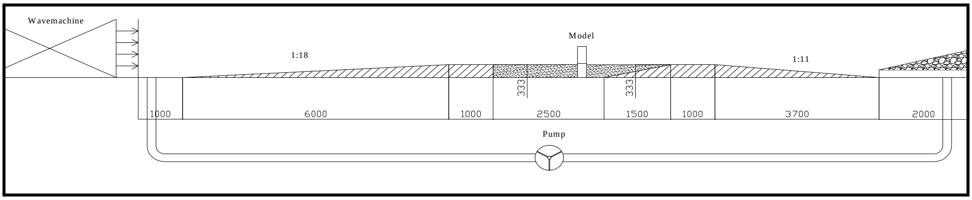

Figure 1. The tests flume equipped with wave generator, two ways recirculation pump, concrete slopes and sand box with model of the pile.

2.2 The profiler

The bed was levelled by an automatic profiler at the end of the steady current tests but in some cases the time evolution of the scour was monitored.

The profiler is working in a no contact manner using a laser for the measurements. Each axis is controlled by high precision step motors with a movement resolution of less then 1 mm. The main advantage consists on having accurate measurement without entering the tested area and without emptying the flume as the laser is able to work also under water level.

The measured grid was 1.5 m long by 0.93 m wide and the grid step was 1.5 cm. The time needed to take the measurement was 35 minutes. Before levelling the bed, the upper part of the model was dismounted in order to allow laser’s movements (Figure 2).

The profiler is controlled by the program EPro (Meinert 2004). This program enables multi-measurements of the defined target area and afterwards the profiled surface is visually presented and the results can be inspected in detail; the program also enable the damage calculation between two profiles as eroded volume.

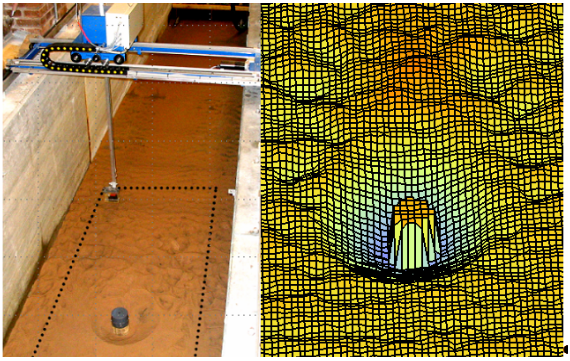

Figure 2. The profiler during a measurement of the tested area; the upper part of the pile was removed to allow laser passage. EPro graphic result.

2.3 Tests description

The tests are divided in tests with unidirectional currents (Table 1), tidal currents (Table 2), breaking waves and waves combined to unidirectional current (Table3). The red indicates tests of which the results are collected in Table 4.

Table1.

Test	For	Pile Diameter D (m)	Significant wave height H_s (m)	Peak period T_p (s)	Water depth at the pile h (m)	Current velocity (m/s)
4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9	Unidirectional currents	0.10	-	-	0.29 0.17 0.10	From 0.30 To 0.50
4.10 4.11 4.12 4.13 4.14 4.15 4.16 4.17 4.18		0.20	-	-	0.29 0.17 0.10	From 0.30 To 0.50

Table2.

Test	For	Pile Diameter D (m)	Significant wave height H_s (m)	Peak period T_p (s)	Water depth at the pile h (m)	Current velocity (m/s)
2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9	Tidal currents	0.10	-	60	0.29 0.17 0.10	From 0.30 To 0.50
2.10 2.11 2.12 2.13 2.14 2.15 2.16 2.17 2.18		0.20	-	60	0.29 0.17 0.10	From 0.30 To 0.50

Table3.

Test	For	Pile Diameter D (m)	Significant wave height H_s (m)	Peak period T_p (s)	Water depth at the pile h (m)	Current velocity (m/s)
1.1 1.2 1.3 1.4 1.5 1.6	Breaking waves and current	0.10	0.12 0.08 0.12	1.28 2.01 1.28 2.01 1.28 2.01	0.29 0.17 0.10	0.00 0.00 0.30

Tests in Table 1 and 3 lasted 30 minutes but the current was stopped also after 15 minutes to carry out the measurement of the scour hole. Only few tests lasted more (3 or 4 hours) than the decided duration in order to document time development.

Tests in Table 2 lasted 2 hours reverting the current every 30 minutes for 2 tidal cycles. The measurements were taken before reverting the current and for few tests that lasted longer (3 or 4 hours), every 5, 10, 15 minutes. The tidal current was simulated by adopting a steady current with velocity equal to the maximum half-period velocity. Tide period is then shorter then the oscillatory one.

As all tests were in live-bed conditions, small ripples and ripples have been observed: U^*/w= 0.68÷1.13. with w = falling velocity of the send = 1.5 cm/s e U^* bed shear velocity. $U^*\varepsilon/\nu$ (ε= roughness of the bed = 0.5÷1 cm) is higher than 50÷170 and therefore the bed is rough.

3. Results

Table 4. Significant result.

Test - duration before the measurement	Pile diameter	Max scour depth upstream	Max scour depth downstream	Front eroded volume	Back eroded volume	Lateral eroded volume	Total eroded volume
	cm	cm	cm	cm^3	cm^3	cm^3	V/D^3
			Tidal current				
2.1-2h	10	9.8	11.6	2200	1900	1800	8
2.2-30	10	9.4	13.0	1900	1900	2000	8
2.2-1h	10	12.6	14.4	4800	3500	2800	15
2.2-1h30	10	12.4	17.1	4500	3900	4100	16
2.2-2h	10	13.0	15.4	6000	4000	3400	17
2.3-2h	10	13.2	13.7	8100	4900	3500	21
2.5-2h	10	12.4	12.0	4300	3100	4500	15
2.6-2h	10	14.3	15.3	8500	4800	4400	22
2.7-2h	20	9.7	17.8	2600	1900	2300	1
2.8-2h	20	9.7	17.8	2600	1900	2300	1
2.9-2h	20	11.9	13.0	5200	3100	3500	2
2.10-2h	10	17.3	13.2	3100	4700	3400	16
2.13-2h	10	13.8	14.0	6200	6500	6000	25
2.16-2h	10	14.6	17.4	7100	5900	6700	26
			Unidirectional current				
4.1-5	10	3.2	3.3	300	500	200	1
4.1-10	10	3.7	3.8	400	600	400	2
4.1-15	10	4.4	4.6	500	700	500	2
4.1-30	10	7.1	6.3	600	900	900	3
4.1-1h	10	9.4	9.0	1400	1600	1700	6
4.2-15	10	6.7	9.2	1000	2000	1900	7
4.2-30	10	9.7	9.8	2100	3500	4600	14
4.3-15	10	14.4	15.0	4800	6300	8900	26
4.3-30	10	8.5	11.0	1900	2700	2200	9
4.5-15	10	8.3	8.2	1500	1300	1300	5
4.5-30	10	11.0	11.8	2100	2200	3300	10
4.6-30	10	10.6	11.9	2700	2600	2300	10
4.6b-30	10	11.8	11.8	3200	3200	3200	13
4.7-30	10	11.5	11.5	2700	2600	3400	11
4.9-30	10	12.5	17.6	3800	3400	4800	16

Significant results are presented in Table 4. The area around the pile was divide in a front, a rear and two laterals sub areas. For every one the eroded volume and the maximum scour depth were calculated.

In case of waves, for a given pile spacing D, the scour depth is mainly governed by the KC number = $U_m T/D$: the larger the KC number, the larger the scour depth. If $0 \leq KC \leq 4$ no scour hole occurs (Frigaard et al., 2005). In our case $1.7 \leq KC \leq 2.7$ and no local erosion was indeed measured (Figure 3) .

In case of waves superimposed to a current the dimensionless equilibrium scour hole is a function of the combined current and wave orbital velocity, the latter reducing the scour:

$$\frac{S}{D} = F(U_{cw}) \text{, where } U_{cw} = U_c /(U_c + U_m) \qquad [1]$$

and U_c= undisturbed current velocity, U_w=maximum value of the oscillatory flow velocity due to rms waves at the bottom. During tests with waves and currents, the global erosion was very high (≈ 0.025 m) and bigger for waves with higher T_p. Tests with stronger currents and waves were impossible to realize in our set-up. Although the estimate global erosion was not very precise, the result from the comparison with test 4.1 was unquestionable; according to it (Table 5) and to literature indications (Sumer and Fredsøe, 2002), waves do not increase scour depths when superimposed on a current.

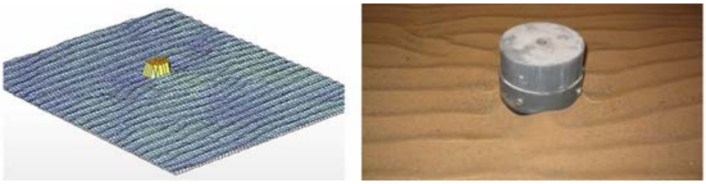

Figure 3 EPro graphic result and picture of no scour hole under wave attack. Small ripples.

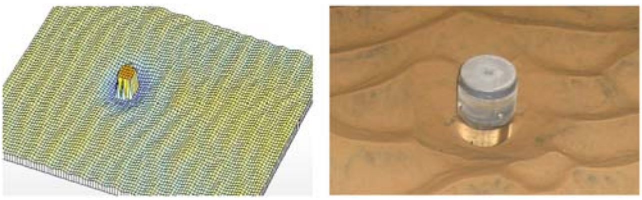

Figure 4. EPro graphic result and picture of scour hole under wave and current attack. Ripples and downstream damp outside the hole.

Table5. Results from tests with only waves and waves superimposed to current.

Test	T	U_c	U_w	KC waves and currents	U_{cw}	θ	Measured S/D (after 30 min)
4.1	-	0.3	0	-	0	0.074	≈ 0.65
1.5	1.28	0.3	0.21	4.7	0.41	0.138	≈ 0.65
1.6	2.01	0.3	0.13	6.6	0.31	0.078	≈ 0.45

For tidal currents the asymmetrical scour hole of the first half an hours becomes more symmetrical after a complete tidal cycle (Figure 5).

In case of only current the expected erosion at the equilibrium is estimate as:

$$\frac{S}{D} = 1.3 + \sigma_{S/D} \tag{2}$$

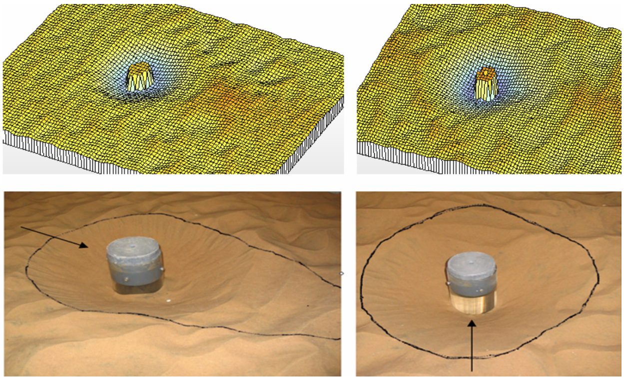

Figure 5. EPro graphic results and pictures of scour holes under unidirectional (left) and tidal current (right). The arrow shows the flow direction in the pictures.

3.1 Unidirectional currents

For unidirectional currents the scour hole increases till the equilibrium, maintaining the same asymmetrical shape (Figure 6): the slope is steeper in front of the pile than on the back where right after outside the hole there is a dam resulting from the deposition of the sand after a deceleration of the flow.

Upstream the angle of the slope is ≈ 40° (= φ = local response angle of the sand), according to the fact that the slope collapses in an avalanches adjacent to the front of the pile generated by the horseshoe vortex. Downstream the angle of the slope is always smaller than φ because the sand is swiped away by the wake vortices.

The maximum scour depth S at the time of the measurement has an exponential trend and the time development T is dependent on Shields parameter $\theta = U^{*2}/(\rho_s/\rho - 1)gD$: T decreases with increasing θ (Figure 7).

The results from three different tests have been interpolated with exponential curves like:

$$S(t) = S_{max}(1 - e^{-t/k}) \tag{3}$$

with k= equilibrium time; k = 13, 30, 35 minutes for θ=0.20, 0.8, 0.7.

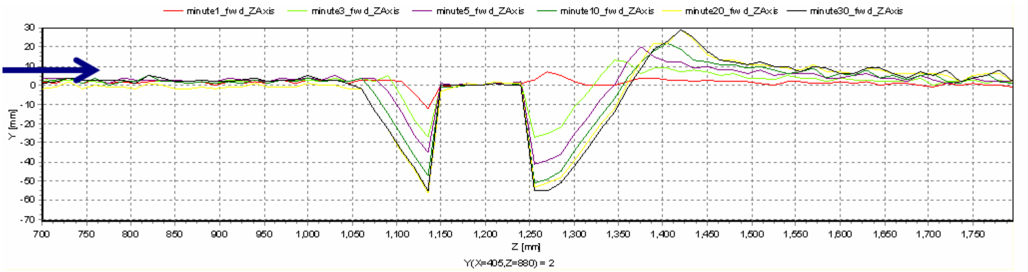

Figure 6. Evolution of the scour hole for unidirectional current: U=0.30 m/s. The scour hole increases asymmetrically in time. Graphical result from EPro; the arrow indicates flow direction.

After 30 minutes the development of the scour depth reaches the 99%,the 63% and the 58% in the three cases in Figure 7, meaning that a lot of the results obtained by the test program are not at the equilibrium. The same is for tests with 0.20 m diameter of the pile as the eroded volume is proportional to D^3 or to hD^3 for shallow water.

Using a simple scaling law based on Peter-Mayer formula and that considers the transport to be proportional to $(\theta- \theta_{cr})^{\alpha}$, the results from tests with low Shield parameter values and/or large diameters, were corrected to the equilibrium estimated value.

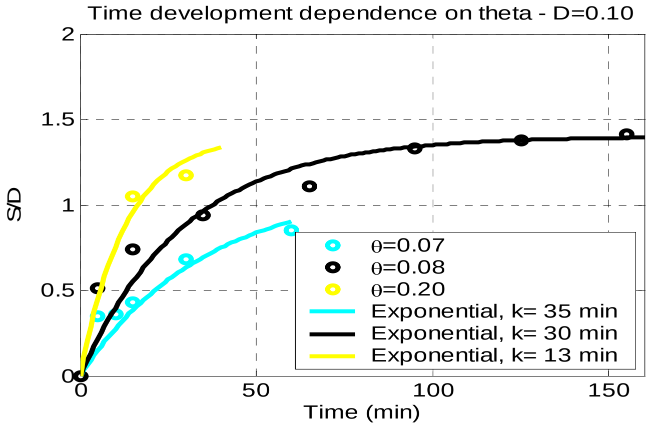

Figure 7. S/D dependence on Shield parameter. Interpolation of results with exponential curves. The lower curve is characterized by the lower time development k.

3.2 Tidal currents

The evolution of the scour hole for tidal currents is influenced by the inversion of the flow direction. The equilibrium time depends on Shield parameter and indicate the time for the equilibrium scour depth to occur.

In Figure 8 the evolution of the scour hole during two tidal cycles (reversing the current every half an hour, first direction: from the left side of the figure) for a current velocity U= 0.50 m/s and U/U_{cr}= 2.3 is presented. The equilibrium depth is reached already after 30 min and doesn't increase more. After that time the steeper slope (upstream first 30 minutes) is eroded when reverting the current, while on the back the slope become steeper. The slopes of the hole incur into erosion and deposition every half and hour tending to the same steepness and generating a symmetrical erosion. Such observed local deposition is not accompanied by a clear global accretion, i.e. in terms of volumes the deposition is weak or absent.

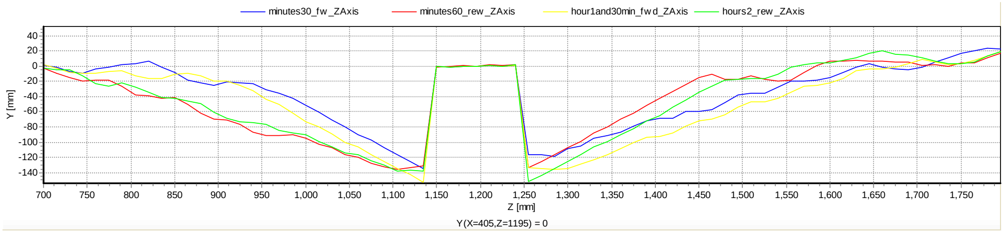

Figure 8. Evolution of the scour hole for tidal current: U=0.50 m/s. Graphical result from EPro; the first direction of the oscillatory velocity is left-right.

For a weaker tidal current the evolution in time is different (Figure 9 where U= 0.30 m/s and U/U_{cr}= 1.4) and deposition is not observed at all. While changing the flow direction S increases till the equilibrium after 1 hour and 30 min. After 3 hours the scour hole shape is quite symmetrical.

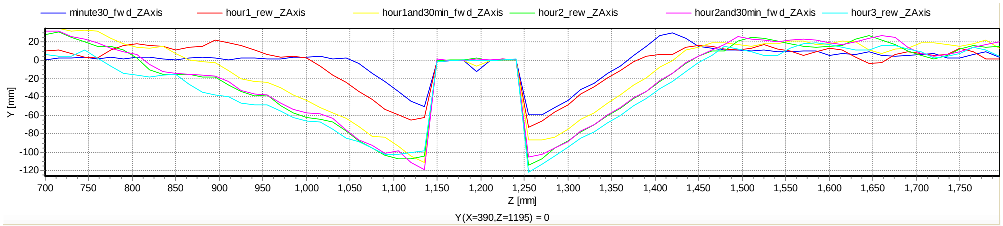

Figure 9. Evolution of the scour hole for tidal current: U=0.30 m/s. Graphical result from EPro; the first direction of the oscillatory velocity is left-right.

The comparison between the time development for unidirectional and tidal currents is plotted in Figure 10 for 2 different current velocities. The scour depth progress for tidal currents is influenced by the inversion of the flow following an "up and down" trend.

The two kind of currents generate the same scour depth at the equilibrium.

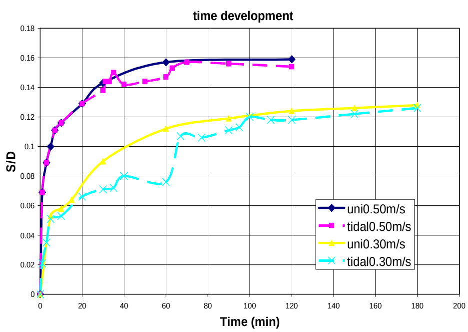

Figure 10. Plot of S/D from unidirectional and tidal tests.

3.3 Eroded volumes

It can be observed that the development of the scour is slower in presence of a tidal flow and that the hole becomes symmetrical.

The observed total eroded volume for tidal currents were close to equilibrium for cases with smaller pile diameter and greater mobility. In these cases $V/D^3 \approx 16$ is bigger than for unidirectional currents $V/D^3 \approx 13$ (Table 4); this is reasonable as the asymmetrical scour hole is enlarged in a symmetrical shape.

4. Conclusions

The significant test results have been presented in Tale 4.

1. The evolution of the scour depth for unidirectional currents follows an exponential trend in which the scaling time decreases with increasing θ and decreases with the volume to be eroded $\approx D^3$; for tidal currents S/D is the same as for unidirectional currents ≈1.3;
2. for unidirectional currents the eroded volume increases constantly maintaining a similar shape of the scour hole. For tidal currents the eroded volumes downstream and upstream increase intermittently depending on the direction of the last tidal flow; a slightly evident erosion and/or deposition may occur, while at the sides the erosion process is constant;
3. eroded volumes at the equilibrium are bigger for tidal currents than for unidirectional currents ($V/D^3 \approx 16$ for tidal case and ≈ 13 for steady current), due to the symmetry of tidal scour holes and to less steep slopes.

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