Scour in a marine environment characterized by currents and waves

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Preface

This project reviews selected parts of accessible knowledge on the topic of scour in relation to the engineering issues of this phenomenon. A series of scale model tests have been conducted, for the purpose of comparison, and to achieve information on the effect of especially wave activity with regard to the back filling of scour holes, as well as the characteristics of scour in tidal currents. These subjects have not been addressed to the same degree as other topics regarding scour, in literature. Furthermore, no agreement on the effect of tidal conditions as well as the consequence of wave activity on scour development has been found, indicating that these topics are not addressed sufficiently.

The project reports on the effect of tidal current conditions, in relation to scour depth, scour configuration and time scale, as well as the effect of waves in a scouring environment. A simple set of equations for the prediction of scour dynamics in combined current-wave conditions is presented. Based on environmental data measured at Horns Rev wind farm, the effective range of back filling in a current-wave environment is estimated.

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Acknowledgement

This project relies heavily on scale model test results, obtained at the Hydraulic Laboratory in Aalborg, and from the Hydraulic Laboratory at Gent University, Belgium. I wish to acknowledge Gent University for providing laboratory access. The tests conducted at Gent University were possible due to the assistance and goodwill of especially Leen DeVos, who provided valuable assistance and comments, during the tests and data analysis.

Contents

1. Motivation

Scour around offshore structures located on erodible seabeds is a well-known problem for structures situated in waters characterized by currents and waves, such as bridge piers and offshore structures. Commonly scour protection is achieved by dumping large rocks or concrete blocks around the base of the structure. Offshore wind turbines are commonly situated in coastal regions in shallow waters, as this location is a compromise between wind intensity and water depth. Offshore wind farms are potentially subjected to astronomical tides, breaking and non-breaking waves and wind induced currents among other conditions that can cause erosions.

Offshore wind turbines are typically erected on gravitational footings or circular steel cylinders, (mono piles), driven 20-30 m into the seabed. Scour is of concern for both foundation types, but generally, the circular piles are referred to in this project.

When constructing offshore wind farms, it is estimated that as much as 25 % of the total costs of the substructures are related to scour protection, and consequently there is a potential benefit of being able to predict the scour depth if no scour protection is used. In the case of no scour protection, the footing or pile will have to be modified to maintain the stability. (For example a gravitational footing would be designed with a larger base area, and a pile would have to be driven deeper into the sea bed). If the additional cost of increasing the dimensions of the footing/pile is less than the cost of the scour protection, this would be an attractive solution.

The available knowledge regarding the time variation of scour in a marine environment, characterized by currents and waves, is limited. Sumer et al. (2002), among others, have addressed the issue of steady state values for scour depths in currents and/or linear waves, but a method to predict the variation of scour in a current-wave environment has not been found in the literature. The subject of back filling of current developed scour holes, due to wave activity, has been observed in natural environments, but no predictive methods to quantify this phenomenon has been found in the literature. Whitehouse, (1998), refers to experiments conducted by Di Natale (1991) on the scour development during the passage of a storm;

> "The results from the experiments showed that the peak of the scour development was out of phase with the peak of the storm and that the maximum scour depth recorded during the storm was considerably different (4 to 7 times greater) than was observable at the end of the storm, i.e. back filling had taken place after the storm had passed."
>
> Whitehouse, (1998), p. 117

This observation indicates that the wave activity is an important factor in regard to the development of a scour hole. It also indicates that the mean scour depth could be reduced by including the wave climate in predictive equations. Whitehouse, (1998), refers to the work of Bijker and de Bruyn, (1988) on scour in wave-current flow;

> "Bijker and de Bruyn, (1988) found that the wave plus current shear stress was increased more in the upstream of the pile than in the vicinity of the pile and that the enhanced transport of sediment towards the pile led to a reduction in the scour depth."
>
> Whitehouse, (1998), p. 116

This work suggests that the back filling is linked to the increase in stirred up sediments due to wave activity. Other investigators found that wave action superposed on the current, increases the scour depth as much as 10%. Chow and Herbich, (1978). Generally, it can be concluded that there is no general agreement on the effect of waves in relation to the scour depth.

The aim of this project is to quantify the effect of wave activity in regard to back filling, and to develop a method for estimating the scour depth in a current-wave climate. This work relies heavily on results from scale modelling.

2. Summary and Conclusion

In the following, a summary of the most important results and findings from the physical scale model tests on scour/back filling, resulting from current and wave activity and also the results from the work conducted on a case study regarding scour at an unprotected mono pile located at Horns Rev wind farm are outlined.

2.1. Equilibrium scour depth

2.1.1. Scour depth in currents

The effect of a tidal currents with regard to scour depth and time scale of the process has been investigated, and compared to experiments conducted with unidirectional currents. The question with regard to tidal scour, was if the tidal current would create larger and/or deeper scour holes than unidirectional currents, and whether or not the time scale of the scour process would be affected by the tidal current. Both issues were addressed in this study. From experiments conducted in the Hydraulic Laboratory at Aalborg University, it was possible to establish the equilibrium scour depth for different current conditions, and it was found that there was no apparent effect on the equilibrium scour depth, when simulating a tidal current. In figure 2.1 the development of scour in a tidal current condition is shown.

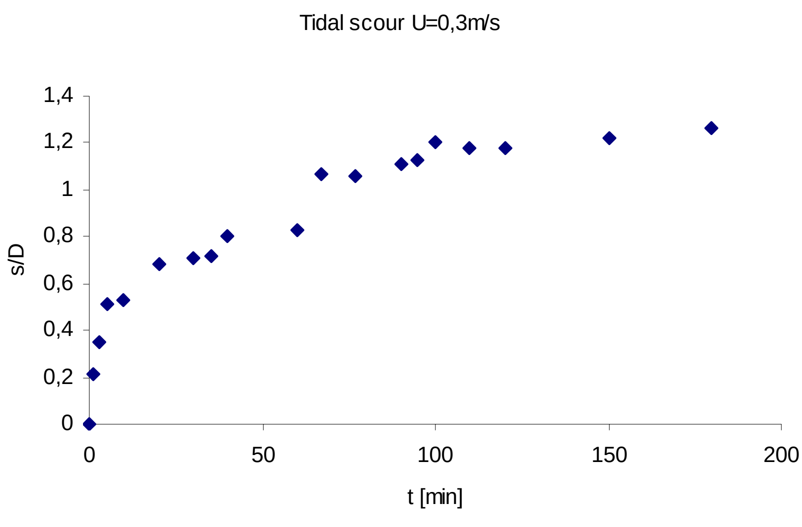
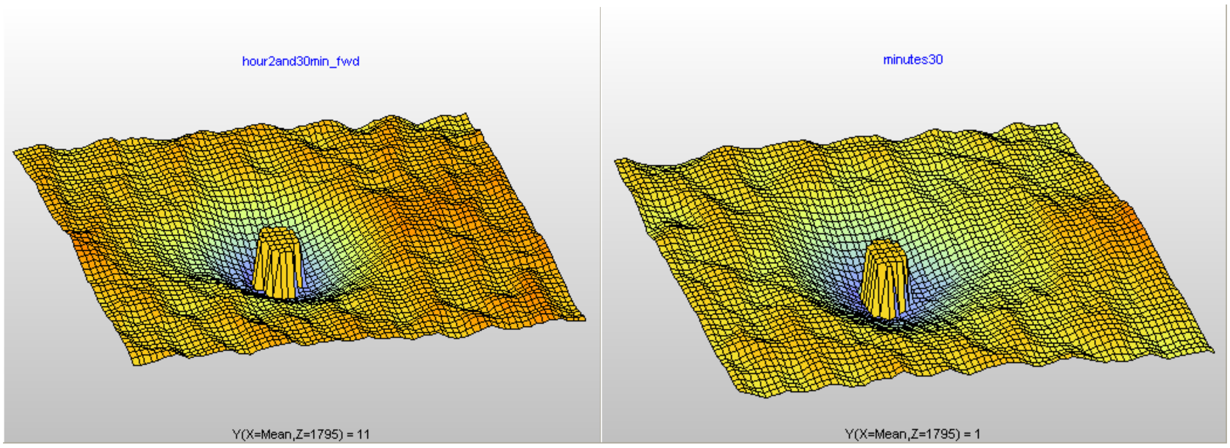


Figure 2.1 Laboratory results, scour development in simulated tidal current, U=0,3 m/s

From the result of the tidal current test, it was found that the scour depth, s/D, was approximately 1,3. This equilibrium scour depth is in general agreement with the equilibrium scour depth found for unidirectional currents. Based on this result it is suggested that existing equations developed for unidirectional currents are valid also for tidal currents. In conclusion, the scour depth, s/D, in live bed-, tidal- and clear water current conditions, is well represented by following equation presented by Sumer et al. (2002)

$$\frac{S}{D} = 1.3 \text{ with } \sigma_{s/D} = 0.7$$

With regard to the physical shape and volume of the scour hole, it was found that a tidal current condition had limited effect on the shape of the scour cavity. The most significant effect of the tidal current was the development of the sediment hump on the leeside of the pile, which is characteristic for unidirectional current scour. Figure 2.2 shows a comparison between the physical shape of a scour hole developed in uni- and co-directional current.



Co-directional current **Unidirectional current**

Figure 2.2 Characteristics of scour cavities developed in co-, and uni-directional currents

In the figure, it is seen that a sediment hump typically develops both up- and downstream of the pile in a co-directional current opposed to leeside in a unidirectional current. Apparently, this scour topography has no effect on the engineering questions dealt with in this study. (Equilibrium scour depth and time scale of the process). In conclusion it has been found that the scour characteristics are not influenced by a tidal current, suggesting that the existing equations established for unidirectional currents are valid for tidal currents also.

2.1.2. Scour in irregular waves

Experiments were conducted with irregular wave series, to estimate the wave induced equilibrium scour depth, s_{ew}/D, (upper limit of back filling). It was found that the equilibrium scour depth in irregular waves can be estimated from

$$\frac{S_{ew}}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot KC\right)\right)$$

This equation is a modified version of an equation proposed by Sumer et al. (2002). KC is calculated as

$$KC = \frac{U_m \cdot T_p}{D}$$

where U_m is calculated as

$$U_m = \sqrt{2} \cdot \sigma_U$$

$$\sigma_U^2 = \int_0^\infty S(f)\,df$$

where *s(f)* is the power spectrum of U_w, and *f* is the frequency. Based on the tests conducted for this purpose it was found that existing equations (developed for regular waves) proposed by [Sumer et al. (2002) underestimate the scour depth in irregular waves. The tests showed that irregular wave series with KC=3,2 generate scour depths in the range of s/D=0,1-0,2. The existing equation predicts that no scour develops when KC<6.

2.1.3. Scour, current-wave conditions

As it was not known if back filling from waves would take place in a combined wave-current climate, laboratory experiments were conducted with waves superposed on a current. The results showed that back filling toke place, and the equilibrium scour depth was reduced by more than 50%. The test results are shown in figure 2.3.

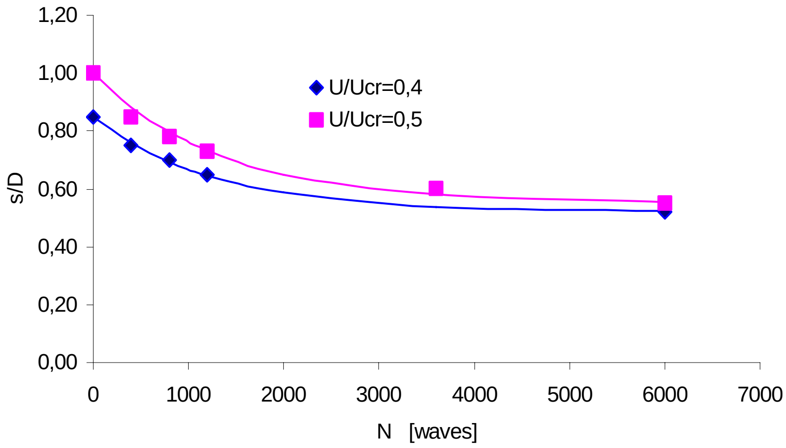


Figure 2.3 Laboratory results, combined current-wave environment

From the results, it is clear that back filling takes place in a marine environment, also when currents are present. The test shows that there is a potential for a significant reduction in the expected scour depth, when the effect of wave back filling is taken into account. The results of the current-wave equilibrium scour test compared well to predictions made by Sumer et al. (2002).

$$\frac{s}{D} = 1.3 \cdot \left(1 - \exp\left(-A \cdot (KC - B)\right)\right) \text{ for } KC \geq \{3\text{-}4\}$$

The coefficients A and B are functions of the combined effect of the current velocity, U, and the orbital velocity under the wave at the sea bed, U_w or U_m.

$$A = 0.03 + 0.75 \cdot U_{cw}^{2.6}$$
$$B = 6 \cdot \exp\left(-4.7 \cdot U_{cw}\right)$$

where U_{cw} is calculated as

$$U_{cw} = \frac{U_c}{U_c + U_w} \quad \text{for regular waves}$$
$$U_{cw} = \frac{U_c}{U_c + U_m} \quad \text{for irregular waves}$$

2.2. Time scale of scour/back filling

2.2.1. Time scale of scour in currents

With regard to the time scale of the scour process, it has been concluded from experiments that the time scale is mainly a function of the flow-depth-to-pile diameter ratio, δ/D, and the shields parameter, θ. It is also concluded that the tidal current condition apparently has no effect on the time scale, again implying that the existing equations developed for unidirectional currents are valid for the tidal current regime. Tests conducted with δ/D=3, and various current conditions, (live bed-, tidal- and clear water-current), showed no effect of the current classification, indicating that the time scale of the scour process in a natural environment is governed by δ/D and shields parameter, θ only. In figure 2.4 the result of the work involving the time scale of the scour process is shown along with the results of others.

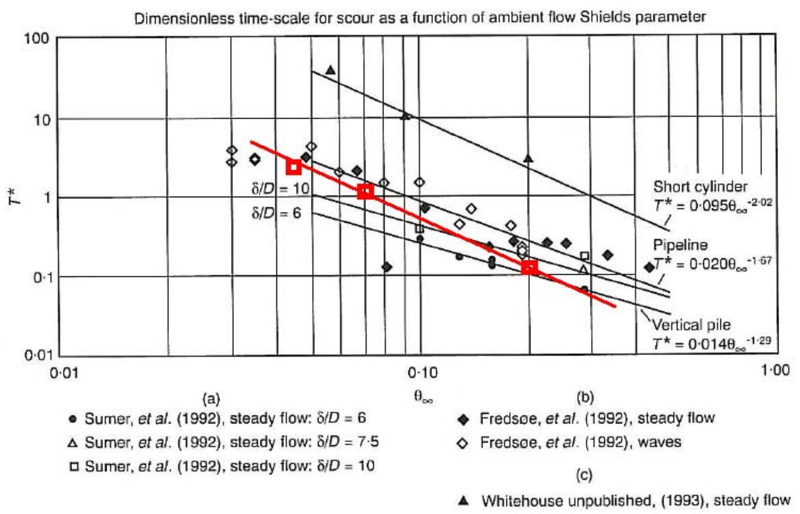


Figure 2.4 Result of scale model tests on the non dimensional time scale T for δ/D=3 (marked in red) along with the results of others.*

The following function for the non dimensional time scale T* was obtained from the laboratory results shown in figure 2.4

$$T*\left(\frac{\delta}{D}=3\right)=0.0022\cdot\theta^{-2,43}$$

where θ is the shields parameter. The equation is very similar to the equation by Sumer et al, (2002) for unidirectional currents. Consequently there has been found no effect of a tidal current in relation to the time scale of the scour process and it is found that the development of a scour hole in a live bed-, tidal or clear water current condition can be predicted by following equations, developed by Sumer et al. (2002), for unidirectional currents,

$$\frac{s(t)}{D}=\frac{s_e}{D}\cdot\left(1-\exp\left(-\frac{t}{T}\right)\right)$$

where *s*(*t*) is the scour depth at time t, s_e is the equilibrium scour depth, estimated as 1,3D from the the scour experiments. The timescale of the scour process is reasonably described by

$$T=\frac{D^2}{(g\cdot(s-1)\cdot d_{50}^3)^{1/2}}\cdot T*$$

where the non dimensional timescale T* is estimated as

$$T^*=\frac{1}{2000}\cdot\frac{\delta}{D}\cdot\theta^{-2.2}$$

This representation for T* is preferred here because it contains an adjustment for the flow depth to pile diameter, δ/D, and it fits relatively well to the results from scour tests conducted during this project.

2.2.2. Back filling in waves

No agreement on the effect of waves in relation to scour has been found in the literature. Some researchers have found that waves reduce scour and some report that waves increase the scour depth. Therefore, a substantial amount of the time invested in this study has been directed towards this topic. The tests conducted in this project show that a significant reduction of the scour depth can be expected when waves are present. Back filling tests, performed on actual scour holes developed in currents, show that the waves back fill the cavity, and that the time scale of this process is similar to the time scale of the scour process. In figure 2.5 the result of the back filling experiments conducted in the Hydraulic Laboratory at Aalborg and Gent University are shown.

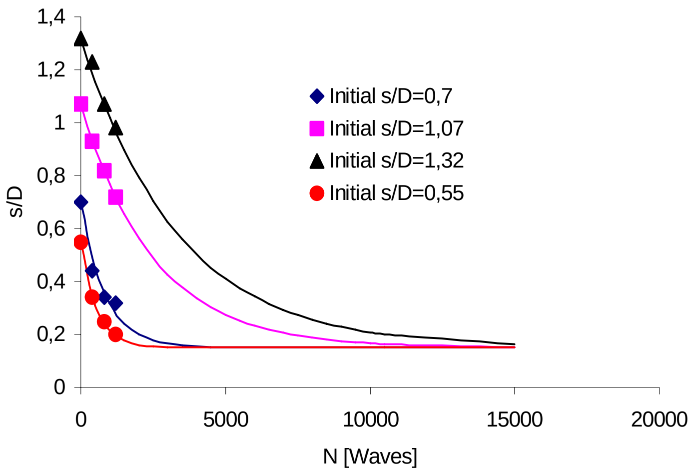


Figure 2.5 Test results on the back filling of current induced scour holes

The laboratory experiments show that a scour hole exposed to wave activity will be back filled, and that the effect of back filling is of major significance with regard to the scour depth. The back filling experiments revealed the following expression for the decree of s/D as a function of the number of waves applied to the scour hole

$$\frac{s}{D}(N) = \left(\frac{s_i - s_{ew}}{D}\right) \cdot \exp(a \cdot N) + \left(\frac{s_{ew}}{D}\right)$$

where s_i and s_{ew} are the initial and wave induced equilibrium scour depths and a is a parameter dependent on the initial scour depth. The coefficient a was found to be represented by following expression

$$a\left(\frac{s}{D}\right) = -0.0026 \cdot \left(\frac{s}{D} - 1.3\right)^2 - 0.00031$$

where the value 1,3 represents the dimensionless maximum (equilibrium) scour depth. Based on the results of the back filling experiments it is concluded that wave activity greatly reduces the scour depth, and that the time scale of back filling is comparable to the time scale of scouring. This result shows that wave activity potentially reduces the scour depth.

2.2.3. Time scale, combined current-wave environment

The results from the combined current-wave scour tests, showed that the effect of scour and back filling could be treated separately and superposed. This result is important for two reasons. First of all this result indicates that back filling and scouring are driven by different parameters, secondly it shows that the scour variation as a function of the environment (current and waves) can be modeled as a scour-part and a back filling-part and then superposed. The scour model resulting from this study is based on the superposition principle and was tested against the data from the wave-current scour test. In figure 2.6 the laboratory results are shown along with model results.

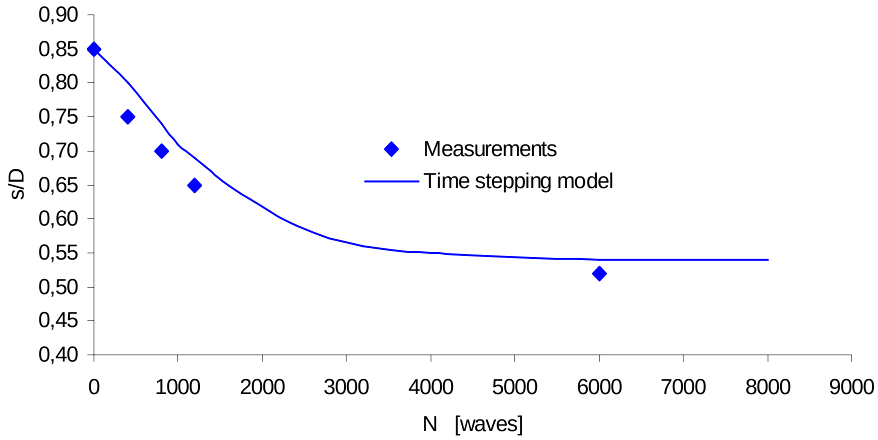


Figure 2.6 Comparison between measured and modeled current-wave scour development

In the figure, it is seen that the model reproduces the decree of the scour hole relatively well, and it is concluded that scour and back filling can be modeled satisfactorily by superposing the scour and back filling processes for a given environment. This is considered an important result as it indicates that scour in a marine environment can be simulated relatively easy with reasonable accuracy. The result of this work is following equation that updates the scour depth in time, with current velocity and wave activity as input.

$$\frac{s(t+\Delta t)}{D} = \underbrace{\left(\frac{s(t)}{D}\right) + \left(\frac{s_e - s(t)}{D}\right) \cdot T^{-1} \cdot \Delta t}_{\text{Scour}} - \underbrace{\left(\left(\frac{s(t) - s_{ew}}{D}\right) \cdot \left(1 - \exp\left(a \cdot N(\Delta t)\right)\right)\right)}_{\text{Back filling}}$$

In conclusion, it has been shown that scour development can be estimated in the time domain by separating the processes of current scour and wave back filling.

2.3. Case study, Horns Rev

Prior to the installation of the Horns Rev wind farm, environmental data was logged on site to gain information on wind velocity, wave activity, currents and water depth, as well as the scour development. From this survey, it was observed that the environment was adequate for scour to develop due to a mean current velocity in the range of 0,3-0,4m/s. However, it was observed that the scour around the unprotected measuring platform built to gather the environmental data was significantly less than expected. Seven scour depth measurements were carried out during the survey period. These measurements showed that the scour depth was less than one third of the equilibrium scour depth for unidirectional current at most inspections. Since the current velocity on site was adequate for scour to develop, it is believed that back filling had taken place due to the wave activity on site.

2.3.1. Case study, results

The developed scour model was used to investigate if the observed absence of scour can be related to the wave activity at the site. Figure 2.7 shows the result of the model calculation, driven by the environmental data measured on site.

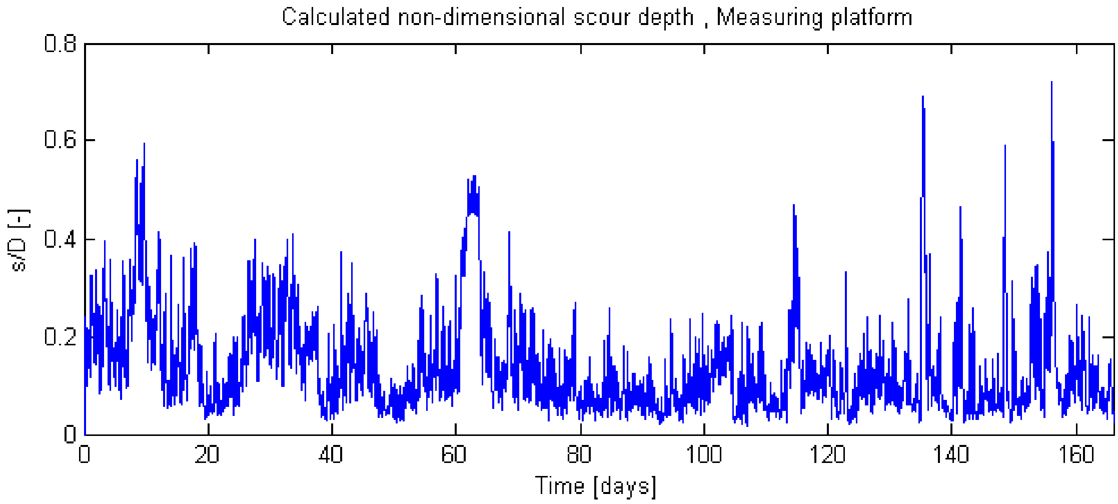


Figure 2.7 Modeled scour variation, Horns Rev measuring platform

The modeling indicates that the absence of scour can in effect be explained by the wave activity on site, and that the scour environment was dominated by the wave activity. Due to the limited amount of environmental data (170 days of measurements), it is unclear to what degree the environment on the site is characterized by the available data. Assuming the data is representative for the location, the model predicted following significant scour depth

$$\left(\frac{S}{D}\right)_{1/3} \approx \underline{0.28}$$

when fitting a two parameter Weibull distribution to the modeled results. This result shows that the scour depth for the environment at Horns Rev is reduced by 75% when back filling due to waves is taken into account. It is noted that this result is supported by the measurements conducted during the survey period, illustrating the importance of including back filling when predicting the scour depth.

Since no laboratory tests were conducted on the relationship between wave activity and the ability to cause back filling, a conservative relation was used to scale the back filling effect. As it is believed that back filling is correlated with the ability of the waves to stir up sediments, the back filling was scaled according to the wave-shields-parameter θ_{wave} . The relation between the wave characteristics and the back filling rate needs further investigation.

2.3.2. Effective range of back filling

By manipulating the environmental data from Horns Rev it was found that the current velocity, generally governs the scour depth in a wave-current environment, suggesting that back filling is only expected to be of significance for environments with relatively low current velocities. From the result of this work a general description of the scour characteristics as a function of the current velocity was established.

$$\overline{U}_{current} = \begin{cases} > 0.7 & \text{Current dominated environment} \\ (0.6 - 0.7) & \text{Transition} \\ < 0.6 & \text{Wave dominated environment} \end{cases}$$

Based on this condition, it is concluded that environments with mean currents below 0,6 m/s are candidate for unprotected offshore structures, as the wave activity greatly reduces the mean scour depth. However, peak scour depths in the range of 1,3D must be considered in design.

3. Introduction to scour

The purpose of the section is to introduce the general principles of scour, and to introduce the most important factors controlling scour in a marine environment. The section is largely based on chapters 1 and 3 in Sumer et al. (2002). All figures in this section are also taken from Sumer et al. (2002).

3.1. General concept of scour

Scour is a term used for erosion of the seabed caused by the presence of a structure. In this context, it will be used to describe the erosion around a circular pile. Scour around piles is generated by the obstruction of the flow past the structure. When the flow is obstructed by the pile, a build up of water is created on the upstream surface causing down flow as a result of the deceleration. Upstream to the surface of the pile the boundary layer separates. The separated boundary layer rolls up and forms a spiral vortex around the structure that trails of downstream. This vortex is called a horseshoe vortex and is caused by the rotation of the separated boundary layer. As the water passes the pile, there is a contraction of the flow, and thereby increased velocities near the pile on both sides, parallel to the flow. This flow over the surface of the pile creates a boundary layer. Downstream to the pile, (on the lee side), the rotation of this boundary layer creates lee wake vortices on both sides of the pile (turbulence). The intensity of the wake vortices rapidly diminishes downstream of the pile. The horseshoe and lee wake vortices, combined with the amplified velocity of the flow around the pile, are the most important factors in the development of scour around the base of the pile. Figure 3.1 shows a schematic representation of the most important changes to the flow caused by the pile.

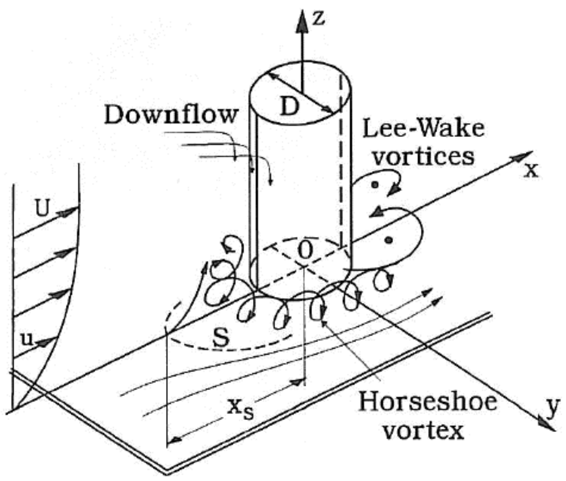


Figure 3.1 Illustration of the flow pattern around a circular pile, exposed to current. From Sumer et al. (2002)

3.1.1. Amplification of shear stresses and turbulence

The vortices and the contraction of the flow around the pile increase the erosion capacity of the flow. By amplifying the shear stresses on the seabed and increasing the capacity to transport sediments, due to a greater turbulence level, material is removed around the base of the pile and eventually a scour hole is developed. As material is removed, the shear stresses and the strength of the vortices are reduced until a state of equilibrium is reached. (Assuming enough time has passed to reach equilibrium). In general, this threshold is reached when the shear stress is equal to, or less than the critical shear stress of the seabed particles

$$\tau \leq \tau_{cr} \qquad [1]$$

where τ_{cr} is the shear force initiating bed movement. Instead of using the critical shear force as the parameter for initiation of the bed, Shields parameter, θ, or the velocity U_{cr} associated with the critical shear is often used. Tests have shown that the amplification of the shear stress caused by the piles obstruction to the flow, can be as much as 11 times the shear stress in the undisturbed flow, far from the pile, as seen in figure 3.2.

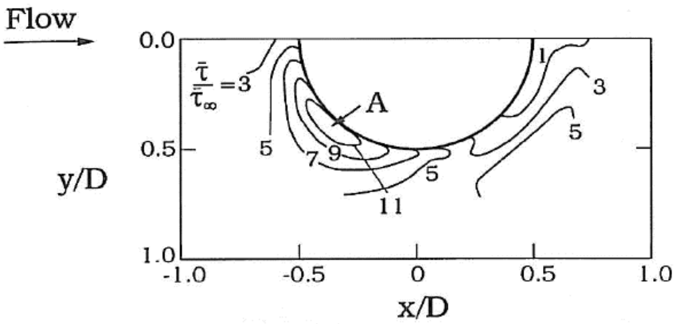


Figure 3.2 Amplification of bed shear stress in the vicinity of the pile, due to the increase in current velocity. From Sumer et al. (2002)

In figure 3.2 it is seen that the greatest amplification of the bed shear is found at an angle of approximately ±135° to the flow. This location of the maximum shear stress is caused by the combined action of the horseshoe vortex and the contraction of the flow near the pile surface. As this point is critical in relation to scour, the initial movement of material will be at this location.

3.1.2. Wide piles

The flow around wide piles is different from that of slender piles. The flow around large structures is in the so-called diffraction regime, and thereby the flow is unseparated. As the boundary layer flow does not separate, no horseshoe vortices are created. The horseshoe vortices are the main cause of scour around slender piles. Despite the absence of the horseshoe vortices, scour is observed at wide piles also. In the wide pile case scour depth is mainly influenced by the Keulegan-Carpenter, (KC) number, and the ratio of pile diameter-to-wave-lengt, D/L. Generally “wide pile effects”, are of importance when the water depth-to-pile-diameter, h/D exceeds 2-3. In this project focus is directed to the case of a slender pile.

3.2. Scour categories

In the following a description of the different scour categories, and conditions affecting the physical profile of the scour pit, are described.

3.2.1. Clear water scour and live bed scour

The scour around piles can be subdivided into two different types; clear water scour and live bed scour. In the following the two cases are described separately.

Clear water scour occurs when there is no sediment movement in the flow upstream of the pile. This means that there is no inflow of sediments to the scour zone at the base of the pile, and erosion is initiated by the changes of the flow around the pile. This is mainly the case for low discharges. When clear water scour is present, a constant scour depth will develop. Clear water scour is present when Shields parameter, $\theta < \theta_{cr}$. Where θ_{cr} is the Shields parameter corresponding to the initial motion of sediment

$$\theta = \frac{U_f^2}{g \cdot (s-1) \cdot d} \qquad [2]$$

where,

$$U_f = \sqrt{\tau_\infty / \rho} \qquad [3]$$

Here τ_∞ is the shear stress far from the pile. Exchanging τ_∞ with τ_{cr} gives the critical Shields parameter θ_{cr}. g is the acceleration due to gravity, s is the ratio of densities of grains and water and d is the grain size.

Live bed scour occurs when there is sediment movement upstream of the pile $(\theta > \theta_{cr})$. Live bed scour is generally present at higher discharges. When live bed scour is present, there is an inflow of sediment to the scour zone. Live bed scour develops a cyclic scour depth. Generally, equilibrium is reached faster for live bed conditions due to the higher discharge. The maximum scour depth for clear water conditions is approximately 10% greater than the mean live bed scour depth.

3.2.2. Local and global scour

Previously the local scour has been described. The local scour is a result of the obstruction of the flow by a single pile. In the case of several closely spaced piles global scour in addition to the local scour can occur. This global scour appears as a general lowering of the seabed near the piles. The global scour is caused by the combined effect of the piles, such as increased level of turbulence and contraction of the flow. Figure 3.3 shows a conceptual picture where local and global scour is illustrated.

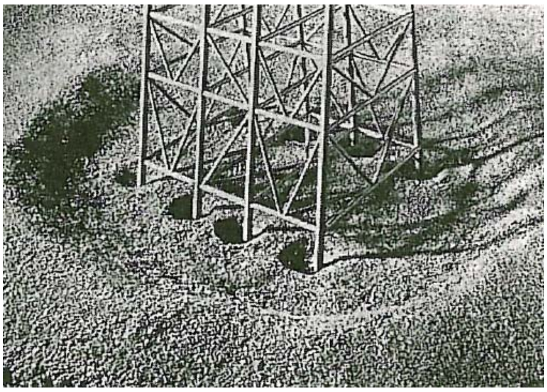


Figure 3.3 An illustration of local and global scour around a jacket structure. Taken from Sumer et al. (2002)

3.3. Scour around single slender piles

In the following a description of the most important parameters in regard to establishing a scour pit are described for piles subjected to currents and waves.

3.3.1. Piles subjected to currents

As the boundary layer separates in front of the upstream surface of the pile, a horseshoe vortex forms at the base of the pile. This horseshoe vortex is important for the creation of the scour hole. The size of this vortex is related to the magnitude of the scour hole. In conditions where large horseshoe vortices are induced greater scour depth is observed. Several factors influence the size (diameter) of the horseshoe vortex. To establish a horseshoe vortex two conditions must be met: A boundary layer must exist for the incoming flow, and the pressure gradient induced by the pile must be large enough to cause a separation of the boundary layer creating the horseshoe vortex. (The flow must be turbulent). The parameters of importance to the creation of a horseshoe vortex in a steady current are

$$\frac{\delta}{D},\ \mathrm{Re}_D \text{ or } \mathrm{Re}_\delta \text{ and pile geometry}$$

δ is the depth of the boundary layer, Re_D and Re_δ, are defined as the pile Reynolds number and the bed-boundary-layer Reynolds number respectively

$$\mathrm{Re}_D = \frac{U \cdot D}{\nu} \qquad [4]$$

$$\mathrm{Re}_\delta = \frac{U \cdot \delta}{\nu} \qquad [5]$$

where U is the velocity at the outer edge of the bed boundary layer.

The variation of δ/D depends on the uniformity of the incoming flow. When δ/D is small the separation of the bed boundary layer will be delayed and a small horseshoe vortex will be created. When δ/D is large there is a less uniform distribution of the velocity in the incoming boundary layer and greater vortices are expected. In figure 3.4 the effect of the boundary layer thickness is illustrated.

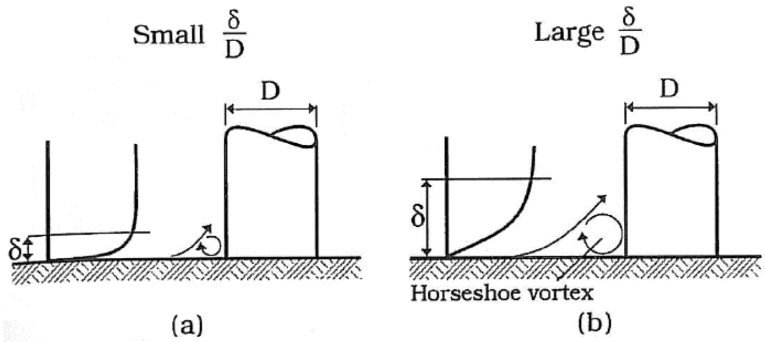


Figure 3.4 The effect on the size of the horseshoe vortex, as a function of the boundary layer depth. Taken from Sumer et al. (2002)

It is noted that as the diameter of the horseshoe vortex increases, the distance from the pile to the separation point of the incoming boundary layer is increased. For small values of δ/D a horseshoe vortex may not even develop. This is the situation in the case of a wide pile.

The variation of the horseshoe vortex with the Reynolds number in laminar boundary layers is similar to the δ/D effect. For small values of Re_D or Re_δ (large viscosity), the separation of the boundary layer will be delayed and a smaller horseshoe vortex is created. In the case of turbulent boundary layers**,** the relationship can be the opposite. When the Reynolds number increases the size of the horseshoe vortex may decrease. This is caused by the increased momentum exchange between the layers resulting in a delay of the separation of the boundary layer.

The cross sectional shape influences the adverse pressure gradient caused by the presence of the pile. Shapes that are “streamlined” will induce a smaller pressure gradient and thereby smaller horseshoe vortices. In figure 3.5 the distance from the structure to the separation point is tabulated for different pile geometries.

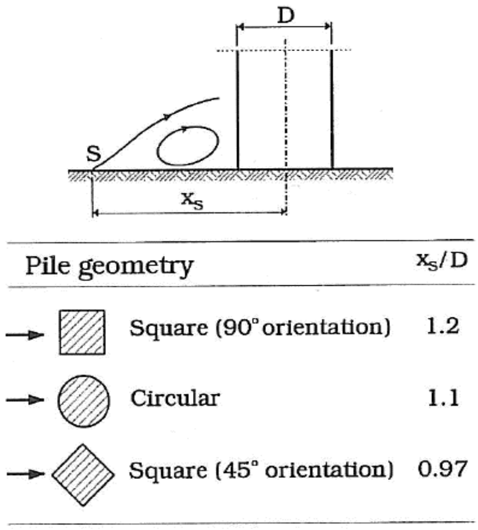


Figure 3.5 The effect of the pile geometry with regard to the separation point of the incoming boundary layer. Taken from Sumer et al. (2002)

Piles subjected to a steady flow also experience lee wake vortices. The lee wake vortices are mainly described by

$$\mathrm{Re}_D \text{ and pile geometry}$$

In the case of rough piles, the relative roughness k_s / D also becomes important for the lee wake flow. As the flow moves the sediments to the lee side of the pile the wake vortices transport the sediments out of the scour zone. As the vortices move downstream of the pile there is a deposit of sediments as the strength of the vortices decrease.

3.3.2. Piles subjected to waves

The parameters important for piles subjected to waves (orbital motion), are similar to those for piles subjected to steady currents. In the case of waves, there is one additional parameter associated with the development of scour, the Keulegan-Carpenter number, KC. The parameters relevant for piles subjected to waves are:

$$\mathrm{KC},\ \frac{\delta}{D},\ \mathrm{Re}_D \text{ or } \mathrm{Re}_\delta \text{ and pile geometry}$$

where,

$$KC = \frac{U_m \cdot T_w}{D} \qquad [6]$$

U_m is the maximum orbital velocity at the bed and T_w is the wave period. For very small KC numbers the length of the stroke might not be long enough for the incoming boundary layer to separate. This means that a horseshoe vortex is not created. As the KC value increases, the boundary layer separates and the horseshoe vortex is present until the motion is reversed. The initiation of the horseshoe vortex requires KC numbers of approximately 6. As a result of this, the horseshoe vortex only exists through part of the half period of the wave motion. In figure 3.6 the presence of the horseshoe vortex for one wave period as a function of the KC number is shown.

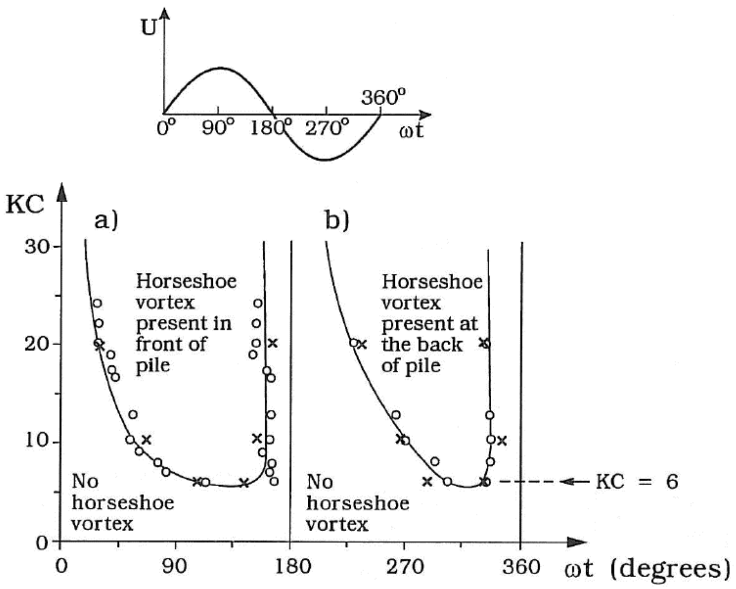


Figure 3.6 Existence of the horseshoe vortex, as a function of the KC number. Taken from Sumer et al. (2002)

It is seen from the figure that no horseshoe vortex is formed when KC < 6. The influence of pile geometry is also important in the case of piles subjected to waves. The limit for existence of the horseshoe vortex can be as low as KC = 4 in the case of square piles with $90°$ orientation, due to the increased adverse pressure gradient generated in front of the structure. In general the size of the horseshoe vortex, and thereby the separation distance from the pile, increases as the KC number increases. At the limit, a steady flow is obtained for KC = ∞, and the distance from the separation point to the pile is maximum. Generally, the amplification of the stresses around the pile increases as the orbital velocity U_m and the wave period T_w increases. (When KC increases).

Piles subjected to waves also develop lee wake vortices. In the case of piles, the lee wake vortices are important for the scour development. The following parameters are of importance to lee wake vortices in waves.

$$\text{KC},\ \text{Re}_D \text{ and pile geometry}$$

In wave conditions, the lee wake vortices govern the transportation of sediments out of the scour zone, and thereby the scour development. Generally, the onset of scour coincides with the onset of vortex shedding. The onset of shedding is reached for circular piles as the KC number approaches 6. In figure 3.7 the lee wake vortex development is illustrated. Figure 3.7 also illustrates the importance of the KC number in relation to vortex shedding.

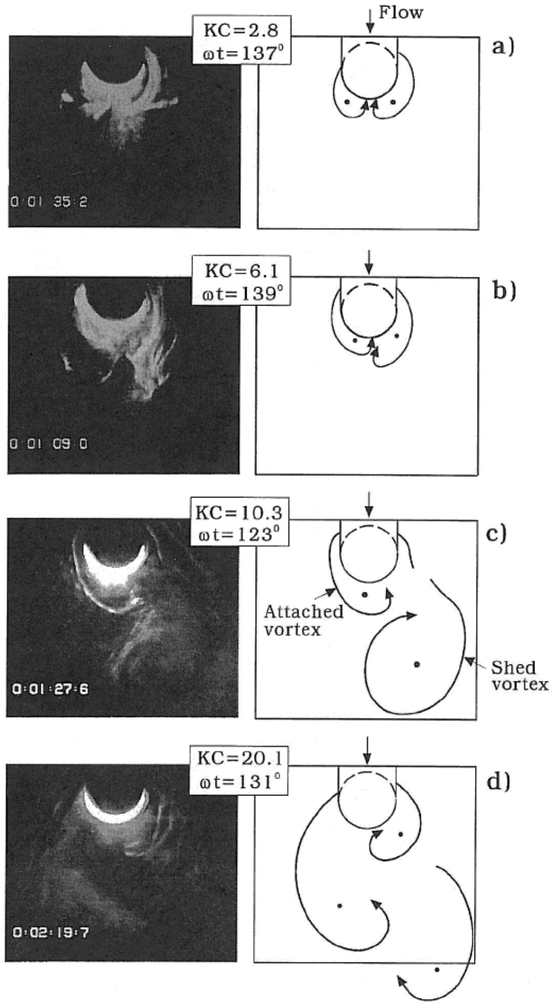


Figure 3.7 Illustration of the ability to transport sediment,
as the KC number increases. Taken from Sumer et al. (2002)

3.3.3. Piles subjected to waves and currents

Piles subjected to currents and waves experience scour depths similar for those of piles subjected to currents alone, indicating that the steady current is the most important factor for scour development. The equilibrium scour depth when superposing waves and currents is illustrated in figure 3.8.

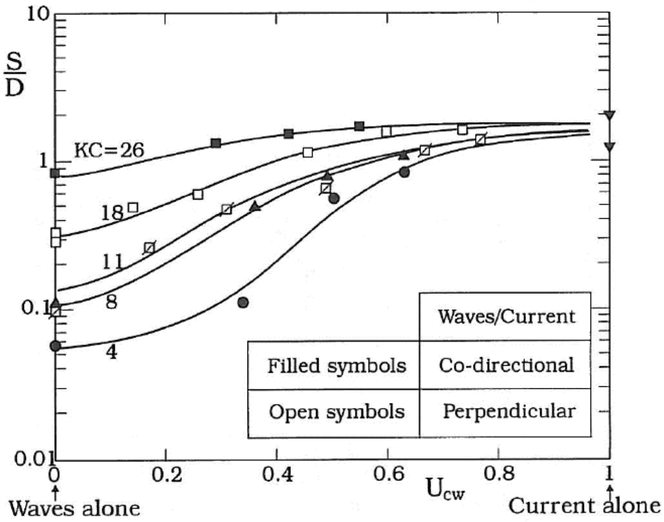


Figure 3.8 Scour depth in combined wave-current flow. Taken from Sumer et al. (2002)

3.3.4. Sediment size and gradation

The sediment size and gradation also affects the scour depth. Increasing the sediment gradation will decrease the scour depth. The scour depth is reduced because the critical velocity increases with the sediment gradation due to the armouring effect. Figure 3.9 illustrates the decrease of the scour depth as the geometric standard deviation, $\sigma_g = d_{84} / d_{50}$, increases. σ_g is an approximate measure for the gradation of the bed material. d_n is the grain diameter where n% of the grains by mass is finer. The two peaks in figure 3.9 represent clear water scour depth and live bed scour depth.

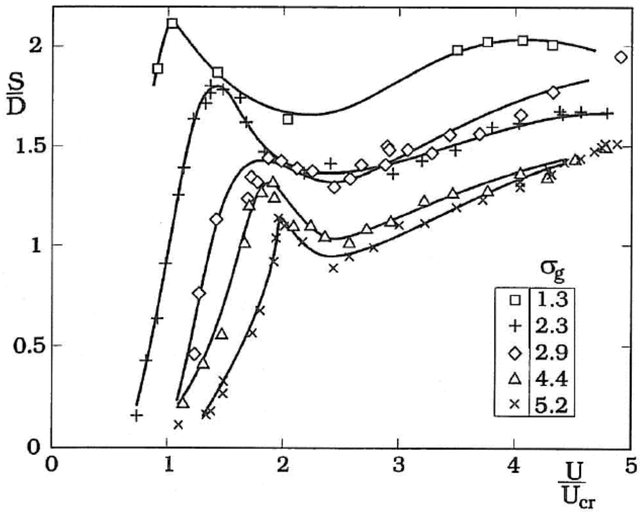


Figure 3.9 illustration of the armouring effect of sediment gradation. Taken from Sumer et al. (2002)

The sediment size is also an important factor for the scour depth. In figure 3.10 the relationship between sediment size and equilibrium depth is illustrated. As the sediment size increases, larger shear force is required for the bed to erode. In scour protection this concept is applied when finding the required size of the bed armouring boulders or concrete blocks. For a certain sediment size, (boulder dimension), the movement of the bed ceases, and protection against erosion is achieved.

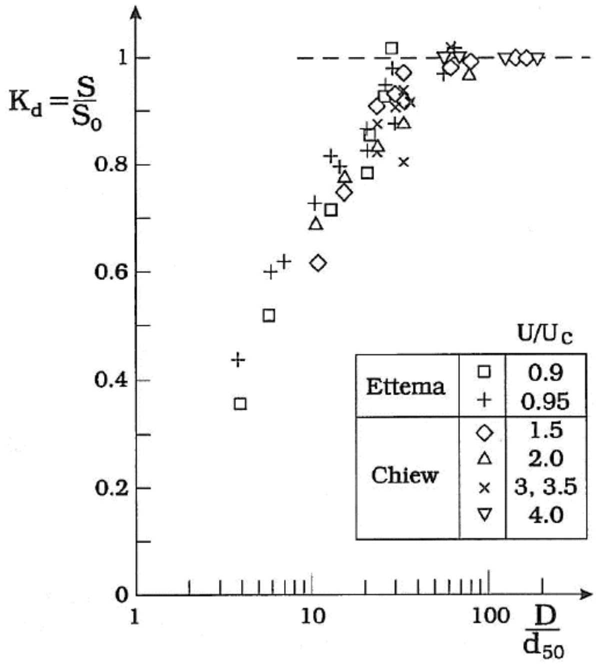


Figure 3.10 Effect of sediment size with regard to the equilibrium scour depth. Taken from Sumer et al. (2002)

For typical marine sediments where $D/d_{50}>100$ the effect of the sediment size becomes relatively small. For typical bed material, the effect of the grain size is more important in regard to the time scale of the scour process. Larger grains result in an increase in the time scale.

4. Scour equation review

Various equations have been developed to predict the scour depth. Equations have been developed for different conditions, but mostly they are applicable to steady flow conditions only. Apart from steady flow conditions, equations have also been developed for piles subjected to waves. In addition, equations for combined waves and currents exist. The section is partly based on a report by Offshore Center Denmark, OCD, (2006).

4.1. Scour equations

As previously discussed, the initiation of scour depends on the flow conditions. For scour to develop some current must exist, and the scour depth becomes a function of the current velocity. Some equations take this effect into consideration, but most of the equations are based on data from experiments carried out in live bed conditions where $U > U_{cr}$. Other equations predict the clear water scour depth $U < U_{cr}$. Equations produced from tests conducted in clear water conditions typically predict scour depths that are 10% greater than live bed equations. This difference in scour depths is mainly due to the backfilling of the scour hole as sediments are transported into the developing scour hole in live bed conditions. It is therefore important to be cautious when applying the equations. Also, most equations are developed in unidirectional flow. Considering the co-directional flow in a tidal environment these equations may not apply to such conditions.

In the case of unidirectional flow, several equations have been developed. No mathematical expression exists to analytically describe the scour around structures, and therefore all existing equations are empirical. As a result, there is some variation in the predicted scour depth from the equations. It is not the aim of this project to give a complete overview of existing equations, and therefore only a few of the most referred equations are listed below. The equations listed below have been recommended in a survey conducted in 2006 by Offshore Center Denmark, OCD, (2006).

4.1.1. Breusers et al. (1977)

This equation is the preferred equation in the Netherlands and is therefore sometimes referred to as the "Netherlands equation". Equation is due to Breusers et al.,(1977).

$$\frac{s}{D} = f \cdot k \cdot \tanh\left(\frac{h}{D}\right) \qquad [7]$$

where $f \cdot k$ is the depth independent equilibrium scour depth. The hyperbolic tangent function adjusts for the effect of the pile width. For slender piles, *D/h<1*, the hyperbolic tangent of h/D approaches 1, and the normalized scour depth *s/D* approaches the depth independent equilibrium scour depth $f \cdot k$.

$$\frac{s}{D} = f \cdot k \quad \text{for } D/h < 1 \qquad [8]$$

For wide piles, *D/h>1*, the hyperbolic tangent of *h/D* approaches *h/D*, and the equilibrium scour depth *s/D* approaches

$$\frac{s}{D} = f \cdot k \frac{h}{D} \quad \text{for } D/h > 1 \qquad [9]$$

Breusers et al. (1977), proposed *k = 1,3*. The coefficient *f* is a function dependent on the current velocity *U*, and is calculated as

$$\begin{aligned} f &= 0 && \text{for} \quad \left(\frac{U}{U_c}\right) \le 0.5 \\ f &= \left(\frac{2 \cdot U}{U_c} - 1\right) && \text{for} \quad 0.5 \le \left(\frac{U}{U_c}\right) \le 1.0 \qquad [10] \\ f &= 1.0 && \text{for} \quad 0.5 \le \left(\frac{U}{U_c}\right) \le 1.0 \end{aligned}$$

where U_c is the critical velocity for initiation of motion of the sediment. U_c can be calculated in several ways, but here the representation given by Hancu, (1971), is shown

$$\begin{aligned} U_c &= a \cdot \left(g \cdot (s-1) \cdot d_{50}\right)^{1/2} \left(\frac{h}{d_{50}}\right)^{0.2} \\ a &= \{1.4 \text{ to } 1.2\} && \text{for } d_{90} < 0.7 \text{ mm} \qquad [11] \\ a &= 1.0 && \text{for } d_{90} > 0.7 \text{ mm} \end{aligned}$$

4.1.2. Richardson & Davis (2001)

This equation is the standard used by most US Highway agencies for evaluating scour at bridges. It is also the recommended equation referred in the Coastal Engineering Manual. The equation is recommended for clear water and live bed conditions, as it takes the current velocity into consideration

$$\frac{s}{D} = 2.0 \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4 \left(\frac{h}{D}\right)^{0.35} Fr^{0.43} \qquad [12]$$

The coefficients K_1 and K_2 are equal to 1 for circular piles. K_3 is a correction factor taking the bed configuration into account. The correction factor K_3 varies from 1,1 to 1,3 depending on the bed condition. Se table 4.1.

Table 4.1 K_3 factor for different bed conditions

Bed condition	Dune height (m)	K_3
Clear water scour	N/A	1.1
Plane bed and antidune flow	N/A	1.1
Small dunes	3>height≥0.6	1.1
Medium dunes	9>height≥3	1.1-1.2
Large dunes	height≥9	1.3

The factor K_4 is an adjustment taking the gradation of the bed material into account. The coefficient corrects the scour depth for the armouring of the bed material. K_4 is calculated as follows.

$$\begin{aligned} K_4 &= 1.0 && \text{for } d_{50} < 2 \text{ mm} \\ K_4 &= 0.4 \cdot U_*^{0.15} > 0.4 && \text{for } d_{50} > 2 \text{ mm} \end{aligned} \qquad [13]$$

where U_* is calculated as

$$\begin{aligned} U_* &= \frac{U - U_{ic,d_{50}}}{U_{c,d_{50}} - U_{ic,d_{50}}} > 0 \\ U_{ic,d_{50}} &= 0.645 \left(\frac{d_{50}}{D} \right)^{0.053} U_{c,d_{50}} \\ U_{c,d_{50}} &= 6.19 \cdot h^{1/6} d_{50}^{1/3} \end{aligned} \qquad [14]$$

where $U_{ic,d_{50}}$ is the approach current velocity to initiate scour, and $U_{c,d_{50}}$ is the critical current velocity for initial motion of the grains. The Froude number, *Fr,* is calculated as

$$Fr = \frac{U}{(g \cdot h)^{1/2}} \qquad [15]$$

where U is the depth averaged current velocity, and h is the water depth.

4.1.3. Jones & Sheppard (2000)

Jones & Sheppard, (2000) provide predictive equations for the local scour depth taking the flow conditions, clear water or live bed into account. The equations are based on extensive large scale tests conducted at the United States Geological Survey Research Centre, Conte. Here the clear water scour equation is shown as the live bed equation is highly case specific, and will not be discussed further here.

For clear water conditions the scour (design value), can be calculated as

$$\frac{s}{D}=\frac{2}{3}k\cdot\left(\frac{5}{2}\left(\frac{U}{U_c}\right)-1\right)\quad \text{for } 0.4\leq\frac{U}{U_c}\leq 1.0 \qquad [16]$$

$$k=\tanh\left(2.18\left(\frac{h}{D}\right)^{2/3}\right)\cdot\left(-0.279+0.049\cdot\exp\left(\log\left(D/d_{50}\right)\right)+0.78\cdot\left(\log\left(D/d_{50}\right)\right)^{-1}\right)^{-1}$$

where U_c is the critical velocity for initiation of motion of the grains, and *log* is the logarithm to base 10.

4.1.4. Sumer et al.

The above mentioned equations are only a few of the existing equations developed for scour in steady currents. Sumer et al.(2002), has compressed data made by Breusers et al.(1977). The analysis resulted in a simple equation for prediction of the scour depth for slender piles. The equation is valid for live bed.

$$\frac{s}{D}=1.3 \text{ with } \sigma_{\mathrm{s/D}}=0.7 \quad \text{for } U>U_c \qquad [17]$$

4.1.5. Equilibrium scour depth, waves

For piles situated in wave dominated environments, ($U=0$), Sumer et al. (2002), link the scour depth to the KC number

$$\frac{s}{D}=1.3\cdot\left(1-\exp\left(-0.03\cdot(KC-6)\right)\right) \text{ for } KC>6 \qquad [18]$$

where KC is the Keulegan Carpenter number. KC is calculated as

$$KC=\frac{U_w\cdot T}{D} \quad \text{for regular waves.} \qquad [19]$$

$$KC=\frac{U_m\cdot T_p}{D} \quad \text{for irregular waves.} \qquad [20]$$

where U_w is the maximum orbital velocity under the wave at the bed surface and T is the wave period. The bed velocity is calculated as

$$U_w = \frac{\pi \cdot H}{T} \cdot \frac{\cosh\left(k \cdot (z+h)\right)}{\sinh\left(k \cdot h\right)} \qquad [21]$$

where H is the wave height, T is the wave period, z is the depth of interest (z=-h). k is the wave number calculated as

$$k = \frac{2 \cdot \pi}{L} \qquad [22]$$

where the wave length, L, is calculated as

$$L = \frac{g \cdot T^2}{2 \cdot \pi} \tanh\left(\frac{2 \cdot \pi \cdot h}{L}\right) \qquad [23]$$

U_m is calculated as

$$U_m = \sqrt{2} \cdot \sigma_U \qquad [24]$$
$$\sigma_U^2 = \int_0^\infty S(f)\, df$$

where $S(f)$ is the power spectrum of U_w, and f is the frequency. T_p is calculated as

$$T_p = \frac{1}{f_p} \qquad [25]$$

where f_p is the peak frequency.

4.1.6. Equilibrium scour depth, combined current and waves

Sumer et al. (2002) also propose a predictive equation for the scour depth when the pile is situated in a combined current and wave environment. It is noted that the equation is valid for live bed conditions

$$\frac{s}{D} = 1.3 \cdot \left(1 - \exp\left(-A \cdot (KC - B)\right)\right) \text{ for } KC \geq 4 \qquad [26]$$

The coefficients A and B are functions of the combined effect of the current velocity U_c and the orbital velocity under the wave at the sea bed, U_w or U_m.

$$A = 0.03 + 0.75 \cdot U_{cw}^{2.6} \quad [27]$$

$$B = 6 \cdot \exp\left(-4.7 \cdot U_{cw}\right) \quad [28]$$

where U_{cw} is calculated as

$$U_{cw} = \frac{U_c}{U_c + U_w} \text{ for regular waves.} \quad [29]$$

$$U_{cw} = \frac{U_c}{U_c + U_m} \text{ for irregular waves.} \quad [30]$$

4.1.7. Time scale of the scour process

Experiments have been conducted on the time scale of the scour process linking it to the current and/or wave induced bed shear stress as well as the grain size and density of the bed material. Whitehouse, (1998), proposed the following empirical expression relating the time scale, T, to the shields parameter, θ, where θ is the dimensionless bed shear stress. The expression is identical to an equation proposed by Sumer et al. (2002).

$$T = \frac{D^2}{(g \cdot (s-1) \cdot d_{50}^3)^{1/2}} \cdot T^* \quad [31]$$

where, T*, the normalized timescale for a vertical pile in a steady current is expressed as

$$T^* = 0.014 \cdot \theta^{-1.29} \quad [32]$$

Alternatively, T* can be estimated using a relation proposed by Sumer et al. (2002)

$$T^* = \frac{1}{2000} \cdot \frac{\delta}{D} \cdot \theta^{-2.2} \quad [33]$$

The later method for predicting T* includes an adjustment for the flow-depth-to-pile-diameter, δ/D.

When the time scale is established, Sumer et al. (2002) proposes the following exponential equation in regard to the time development of the scour:

$$S(t) = S_e \cdot \left(1 - \exp\left(-\frac{t}{T}\right)\right) \quad [34]$$

where $S(t)$ is the scour at time t, and S_e is the equilibrium state. S_e can be estimated from equations {7, 12, 16, 17, 18 and 26} depending on the environment. This approach has been developed for scour around piles exposed to steady currents or waves. The method is therefore not tested against combined current-wave conditions, but as the method utilizes the dimensionless Shields parameter, it is plausible that the method is valid for combined situations.

4.1.8. Shields parameter in currents (θ_c)

The shields parameter can be calculated in several ways, depending on the approach used when calculating the bed shear stress. Generally the Shields parameter is calculated as

$$\theta = \frac{\tau_\infty}{g\cdot(\rho_s-\rho)\cdot d_{50}} \qquad [35]$$

where τ_∞ is the bed shear stress away from the structure, and ρ_s , ρ are the densities of the sediments and water respectively. The Shields parameter can also be represented by the friction velocity, U_f , instead of the ambient bed shear stress

$$\theta = \frac{U_f^2}{g\cdot(s-1)\cdot d_{50}} \qquad [36]$$

where s is the specific gravity of the bed material. Sumer et al (2002), suggests that the bed friction velocity, U_f, is calculated as

$$U_f = \frac{\bar{U}}{2.5\cdot\left(\ln\left(\frac{30\cdot h}{k_s}\right)-1\right)} \qquad [37]$$

where k_s is calculated as $2.5d_{50}$. This approach is also suggested by Soulsby, (1997).

4.1.9. Shields parameter in waves (θ_w)

θ_w can be calculated as suggested by Soulsby, (1997).

$$\theta_w = \frac{\frac{f_w}{2}\cdot U_m^2}{g\cdot(s-1)\cdot d_{50}} \qquad [38]$$

$$f_w = 1.39\cdot\left(\frac{A}{z_0}\right)^{-0.52} \qquad [39]$$

$$A = \frac{U_m\cdot T_p}{2\pi} \qquad [40]$$

$$z_0 = \frac{2.5\cdot d_{50}}{30} \qquad [41]$$

where f_w is the dimensionless wave friction factor and z_0 is the hydraulic roughness length.

5. Scour development in currents

To monitor the effect of different current environments on the time scale of scour development and equilibrium scour depth, a series of scale model tests were conducted in the Hydraulic Laboratory at Aalborg University and Gent University, Belgium. The experiments were conducted on a scale model of a cylindrical mono pile with a diameter D=0,1m. The tests were conducted with different bed materials and with a range of current velocities. One test was conducted with a reversing current simulating a tidal environment. All tests were conducted with the same water depth as this is an important factor with regard to the time scale and scour physics. As the water depth is maintained in all tests, it is possible to compare the results.

5.1. Scour test results

The tests conducted to monitor the scour development are discussed in Appendix B. A summary of the experimental conditions are shown below

- Live bed scour, $U_{current}$=0,5m/s. (θ=0,2)
- Tidal current, live bed, $U_{current}$=0,3m/s. (θ=0,072)
- Clear water scour, $U_{current}$=0,2m/s. (θ=0,044)

The tests were performed to gain information on a series of questions relevant for the scour process. Two primary issues were addressed namely the effect of a tidal environment and the time scale for clear water currents. These two issues become very important in regard to the scour process in a natural environment due to the constant reversal of the current. The tidal conditions produce a oscillating current velocity with a period of approximately 6 hours. From this oscillating current condition, it is obvious that the scour process will consist of some clear water and some live bed scour during a typical tidal period. In figure 5.1 a typical current velocity profile from Horns Rev wind farm is shown. The water depth is approximately 6,5m.

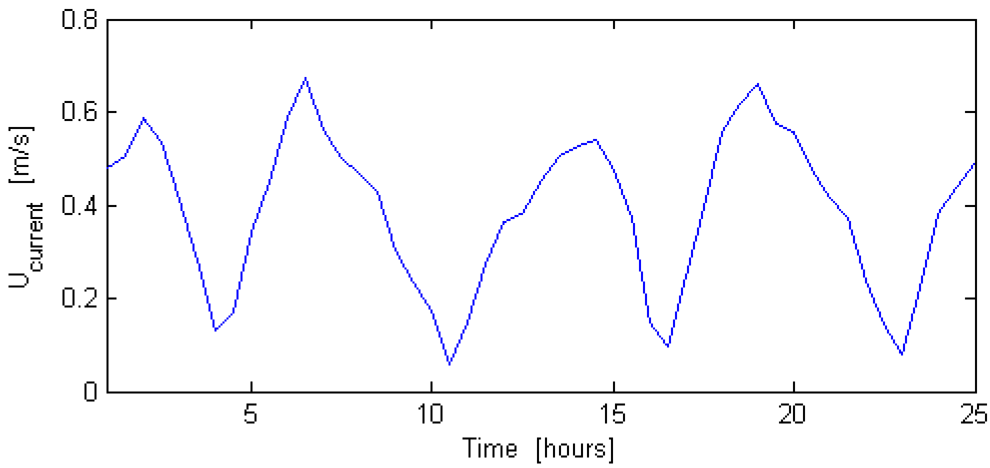


Figure 5.1 Typical current velocity profile, data from Horns Rev.

From the figure, it is clear that the tidal environment is governing the current velocity profile. In order to model the scour development for such an environment, two approaches are possible. The scour development could be modeled using the mean current velocity or the development could be estimated using a time stepping approach. (The later is utilized in the model resulting from this project.) Utilizing the time stepping approach improves the description of the scour development. This is due to the nonlinear relationship between current velocity and time scale of scour.

$$T \propto \frac{1}{U^k_{current}} \qquad [42]$$

where k is a constant, and T is the time scale of the scour process.

This relationship between the current velocity and the time scale of the scour process causes the current velocity to be of great importance, and it is therefore important to know if the existing equations for prediction of the time scale are valid for the lower range of the current velocities. (Clear water scour range). The existing equations are obtained from tests conducted with currents in the live bed regime. Also, the equations predict the time scale for unidirectional currents.

5.1.1. Time scale in tidal currents

From the scour development experiments with δ/D=3, a good relationship between the shields parameter and the time scale T was found. However, the resulting time scale was somewhat different from the expected time scale, estimated from equation [32] proposed by Whitehouse, (1998). This equation is designed for flow depths in the range of 6-10 times the pile diameter, D.

$$T^* = 0.014 \cdot \theta^{-1.29} \qquad [32]$$

This indicates that the scour process is relatively dependent on the δ/D-relationship. Sumer et al. (2002), have provided an equation that includes an adjustment for the flow depth, equation [33]

$$T^* = \frac{1}{2000} \cdot \frac{\delta}{D} \cdot \theta^{-2.2} \qquad [33]$$

In figure 5.2 the time scale from the scour tests are shown together with a trend line. The results are shown with the work of Sumer et al. (2002), Fredsøe et al. (1992), and Whitehouse, (1993).

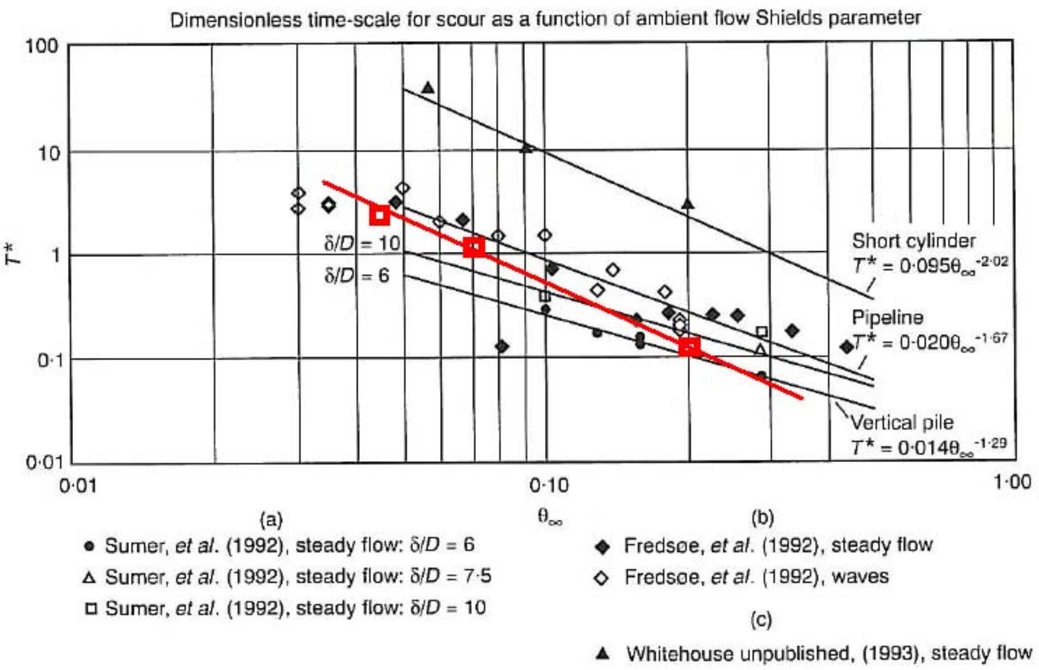


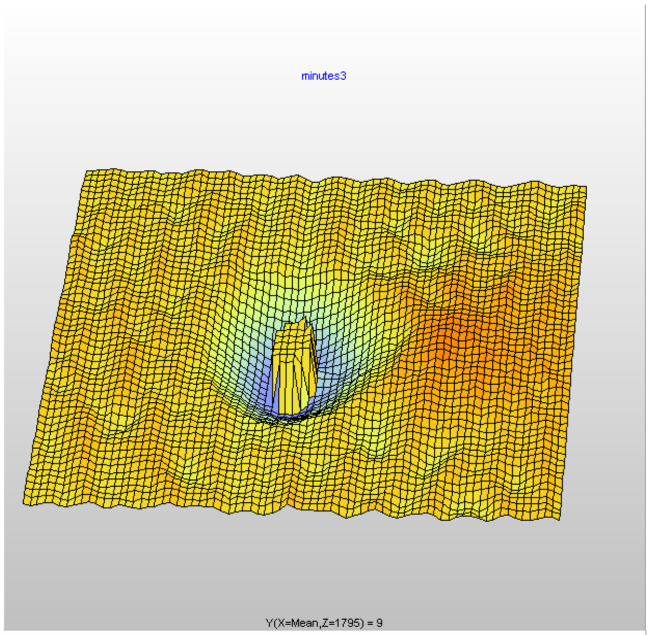
Figure 5.2 Non-dimensional time scale T, obtained from laboratory tests with δ/D=3, (marked in red), shown along with the results of others. Figure taken from Whitehouse, (1998)*

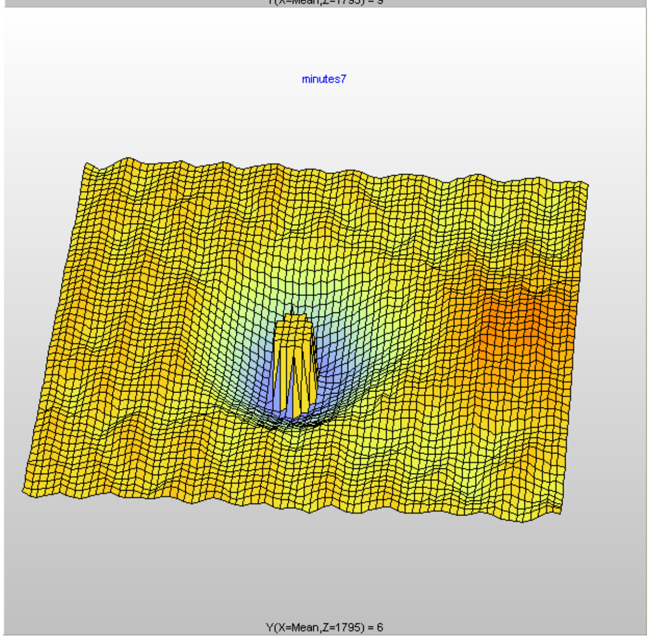
From the figure, it is seen that there is no apparent effect of a tidal current in relation to the time scale of the scour process, since the observed non-dimensional time scales are represented by a "straight line". From the figure the dimensionless time scale T* was estimated for δ/D=3

$$T^* = 0.0022 \cdot \theta^{-2.43} \qquad [43]$$

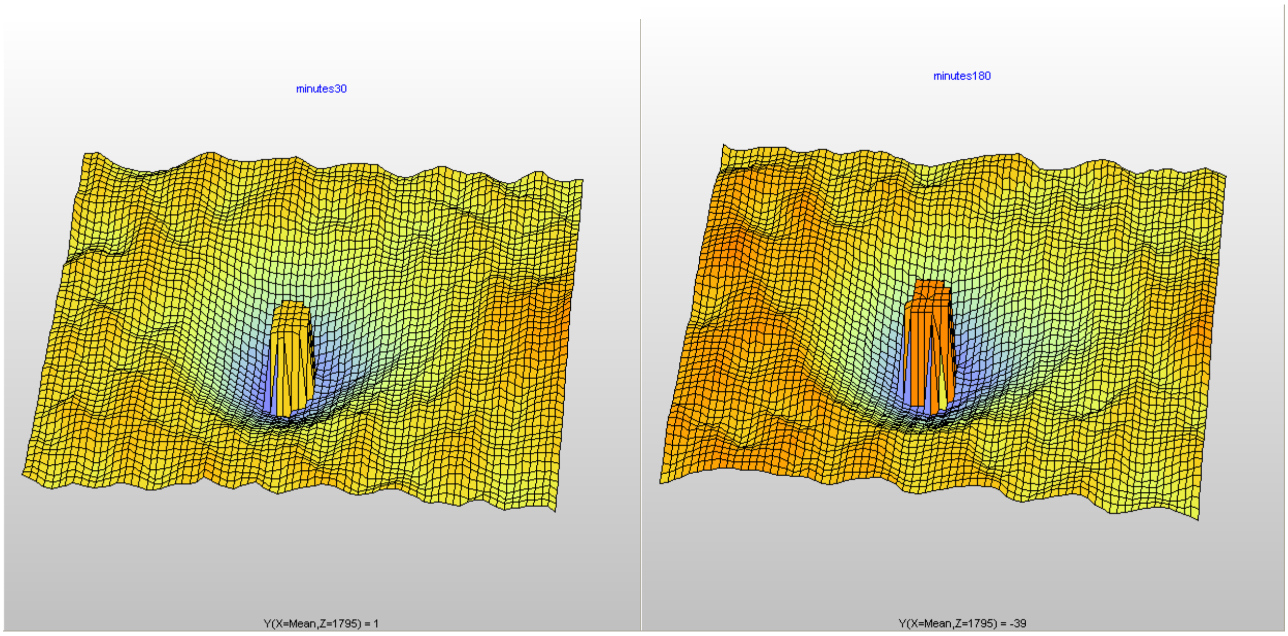
This relation between the shields parameter, θ, and the non-dimensional time scale, T*, is similar to the flow depth adjusted equation, proposed by Sumer et al. (2002) for δ/D=3. As no significant changes in the scour process were observed by reversing the current, it is concluded that the time scale in tidal currents can be estimated using the existing equations. It is also suggested that the time scale prediction equations are valid in the clear water regime. Based on these limited data, it is suggested that the scour development in a tidal environment can be estimated from the existing equations produced for unidirectional currents, using a time stepping approach when calculating the scour development. In figure 5.3 and figure 5.4 a series of profiles from tests are shown illustrating the differences between unidirectional and tidal scour conditions.

Unidirectional current U=0,5m/s





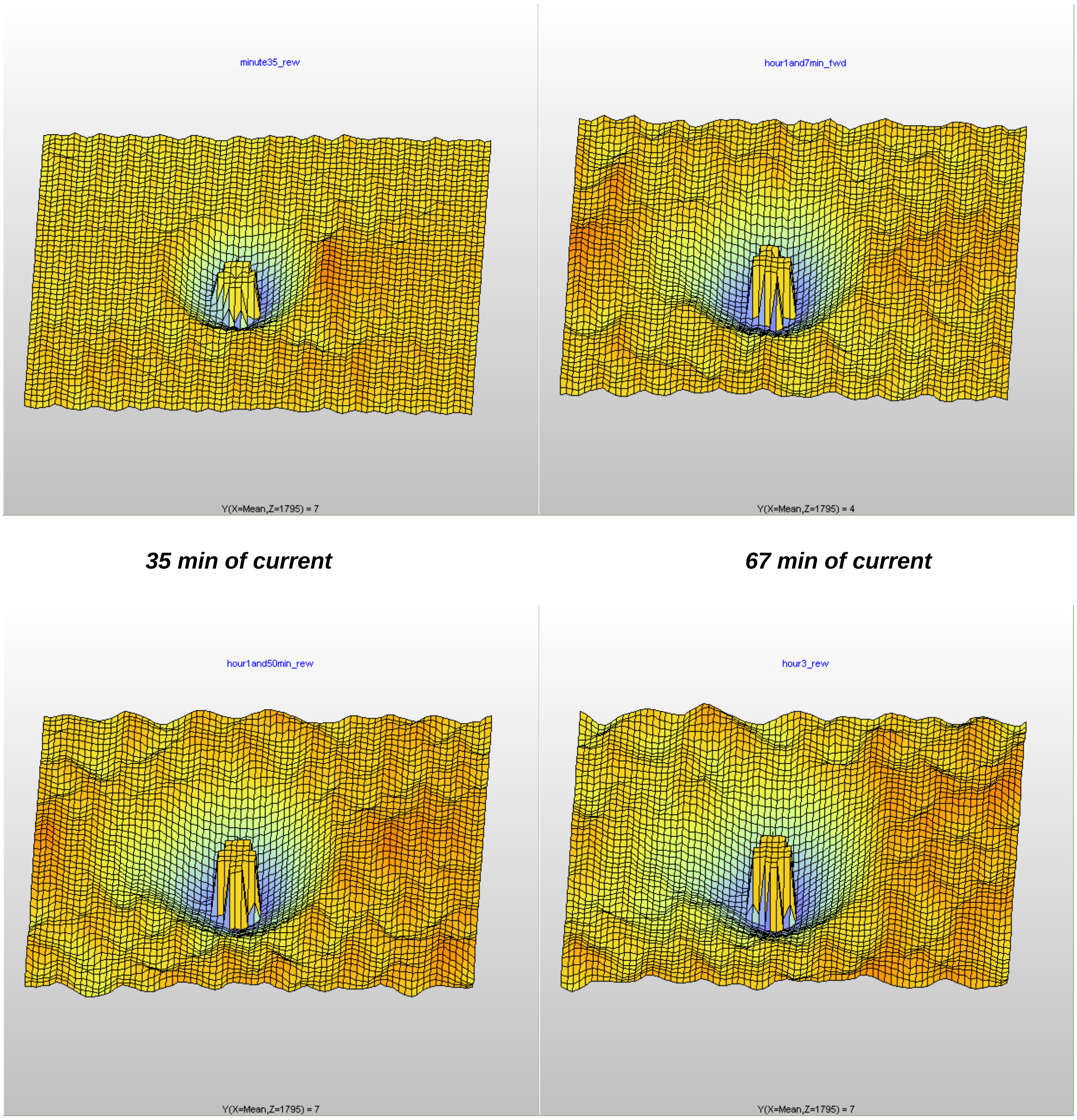
3 min of current ***7 min of current***



30 min of current ***180 min of current***

Figure 5.3 Scour development in uni-directional current, U=0,5 m/s
Data obtained from profiling of the scour during test

Tidal current U=0,3m/s



35 min of current **_67 min of current_**

110 min of current **_180 min of current_**

Figure 5.4 Scour development for co-directional current, U=0,3 m/s
Data obtained from profiling of the scour during test

Comparing the measured profiles from the unidirectional and tidal current tests it is seen that the physical shape of the scour hole is virtually unaffected by the current environment. On the lee side of the scour hole a hump tends to develop for unidirectional currents. This phenomenon can be seen from the profiles taken 3 and 7 min. into the scour development for the unidirectional case. From the tidal current test, it is seen that this hump develops on both sides of the scour hole due to the reversal of the current. Apparently, this has no influence on the development of the scour hole, in aspect to the time scale of the scour process. All tests show a good relationship between the current velocity and the observed time scale. With regard to the scour depth, there appears to be no significant effect of the current environment. Generally, the tests reveal an equilibrium scour depth of 1,3-1,4 times the pile diameter D. Based on this equilibrium scour depth, it is suggested that the scour depth is well described by equation [17] proposed by Sumer et al. (2002) for currents in the clear water, live bed and tidal regime.

$$\frac{s_e}{D} = 1.3 \text{ with } \sigma_{\mathrm{s/D}} = 0.7 \qquad [17]$$

The scour development can be estimated from equation [34],

$$s(t) = s_e \cdot \left(1 - \exp\left(-\frac{t}{T}\right)\right) \qquad [34]$$

and the time scale of the scour process, T, can be found from equation [31],

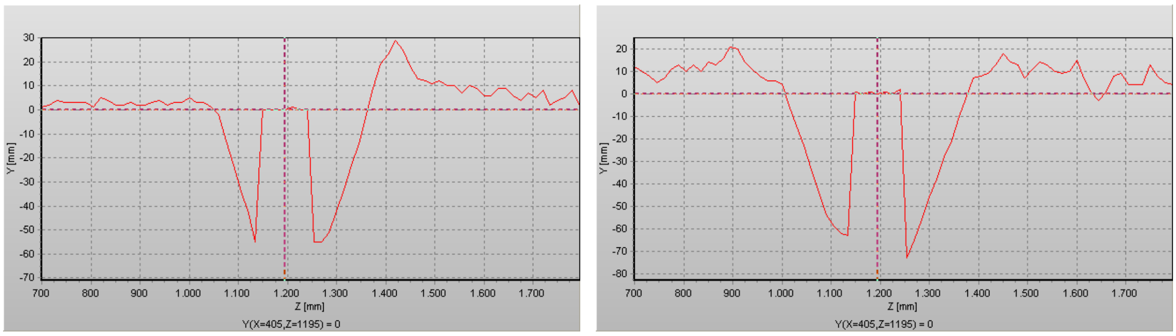
$$T = \frac{D^2}{(g \cdot (s-1) \cdot d_{50}^3)^{1/2}} \cdot T^* \qquad [31]$$

where the non-dimensional time scale T* is found from equation [33],

$$T^* = \frac{1}{2000} \cdot \frac{\delta}{D} \cdot \theta^{-2.2} \qquad [33]$$

5.1.2. Discussion of results

From the tests conducted with tidal currents it is seen that the tidal environment does not cause an increase in the equilibrium scour depth. It could be expected that the reversal of the current would increase the horizontal dimension of the scour hole and thereby create a potential for greater scour depths due to the asymmetry of a scour hole, when comparing the upstream and downstream part of the cavity. However, the tests conducted in this project show that the reversal of the current reestablishes this asymmetry by back filling of the scour hole. This mechanism is illustrated in figure 5.5 where it is seen that the upstream and downstream asymmetry of the scour hole reestablishes when the current is reversed.



30 min. current → ***+30 min current ←***

Figure 5.5 Illustration of the re-establishment of the asymmetry of a scour hole, as the current reverses. Data from the profiling during tidal current test

From the figure, it is concluded that a reversing current (tidal current) does not produce greater scour, and that the sediments carried into the scour zone, deposit (back fill) to re-establish the asymmetry of the cavity. It is also noted that this deposition of sediments has no effect on the time scale of the scour process, and it is concluded that there appears to be no significant effect of a tidal current with regard to the engineering issues of the scour process. This is also illustrated in figure 5.6 where the results from the scour development tests are shown.

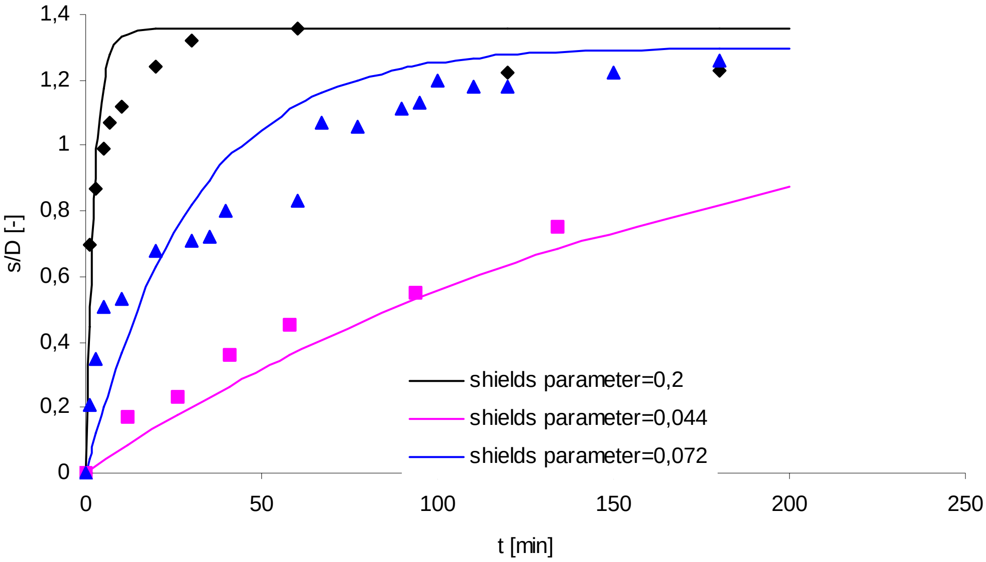


Figure 5.6 Scour development obtained from laboratory tests, with Live bed- (black), Tidal current- (blue) and Clear water-scour conditions (red). Shields parameter in test, is shown in the legend

From figure 5.6, it is concluded that the scour process is mainly dependent on the current velocity (shields parameter), and that a reversing current has little effect on the scour development, since the tidal development fits relatively well to the predicted development, (blue trend line compared to blue measurements).

6. Back filling in a marine environment

To obtain information on the effect of wave activity with regard to the scour process in a marine environment a series of tests have been conducted in the Hydraulic Laboratory at Aalborg University and Gent University, Belgium. The tests were conducted to study if the back filling of scour holes around marine structures, was a significant process. If the back filling rate was of a magnitude comparable to the scour rate, this would lead to a general reduction of the expected scour depth and thereby opening up for the concept of unprotected offshore structures. The focus of this work, was to quantify the back filling for use in a scour development model. Below the primary tests conducted with regard to quantifying the back filling process are summarized.

- Equilibrium scour depth in irregular waves
- Back filling of current induced scour holes, due to wave activity
- Equilibrium scour depth, combined current-wave environment

6.1. Back filling

To simulate a natural environment, the back filling experiments were conducted with irregular wave series representative of the North Sea, by generating the waves series from the JONSWAP spectrum. In table 6.1 the characteristics of the waves used in test are tabulated.

Table 6.1 Specifications for the irregular wave series used in all back filling tests conducted in the laboratory

Wave Specifications	
Wave type	Irregular
Spectrum	JONSWAP
H_s	0,12
T_p	1,64
Peak enh. factor	3,3

6.1.1. Equilibrium scour depth, irregular waves

To estimate the “upper limit” of back filling, a wave scour test was conducted. This was needed because existing equations for equilibrium scour depth in waves, are based on results obtained with regular waves. Furthermore, it was observed during the back filling tests that the back filled scour depth approached an equilibrium state different from s/D=0. The existing equation for prediction of scour in waves due to Sumer et al. (2002)

$$\frac{s}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot (KC - 6)\right)\right) \text{ for } KC > 6 \qquad [18]$$

states that wave scour is achieved only when KC>6. However, this was not observed from the back filling experiments using irregular waves with KC=3,2. A combined scour and back filling test was conducted to approach the equilibrium scour depth from "above" by back filling, and from "below" by wave scouring. The results of this test are illustrated in figure 6.1.

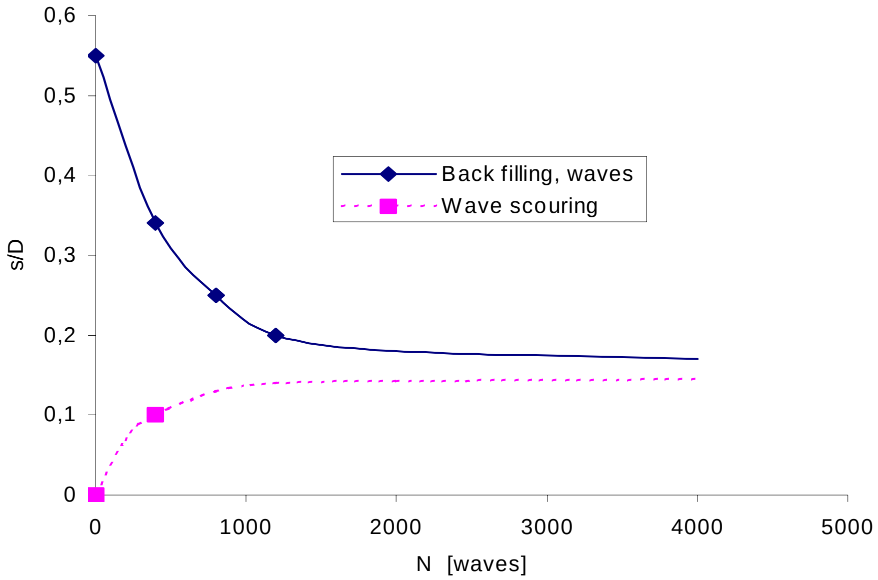
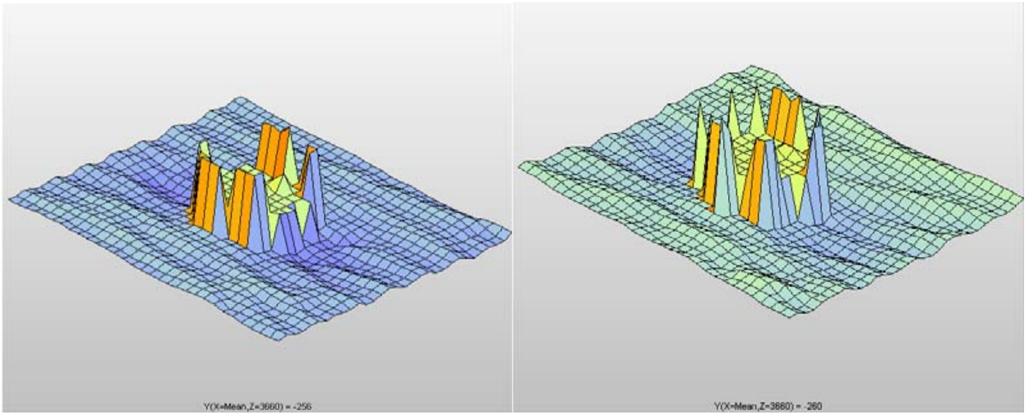


Figure 6.1 Results of back filling/scour test, to estimate the wave induced equilibrium scour depth in irregular waves

The results clearly showed that the equilibrium scour depth (upper limit of back filling) was different from the predicted value of zero. The limited data suggested an alternative formulation of equation [18]

$$\frac{s}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot KC\right)\right) \qquad [44]$$

This predictive equation is limited to irregular waves. This is believed to be a conservative formulation as it generally predicts a larger scour depth than the original formulation proposed by Sumer et al. (2002). The equilibrium scour hole from the wave scouring and back filling experiment is shown in figure 6.2.



Wave scour, 400 waves **_Back filling, 1200 waves_**

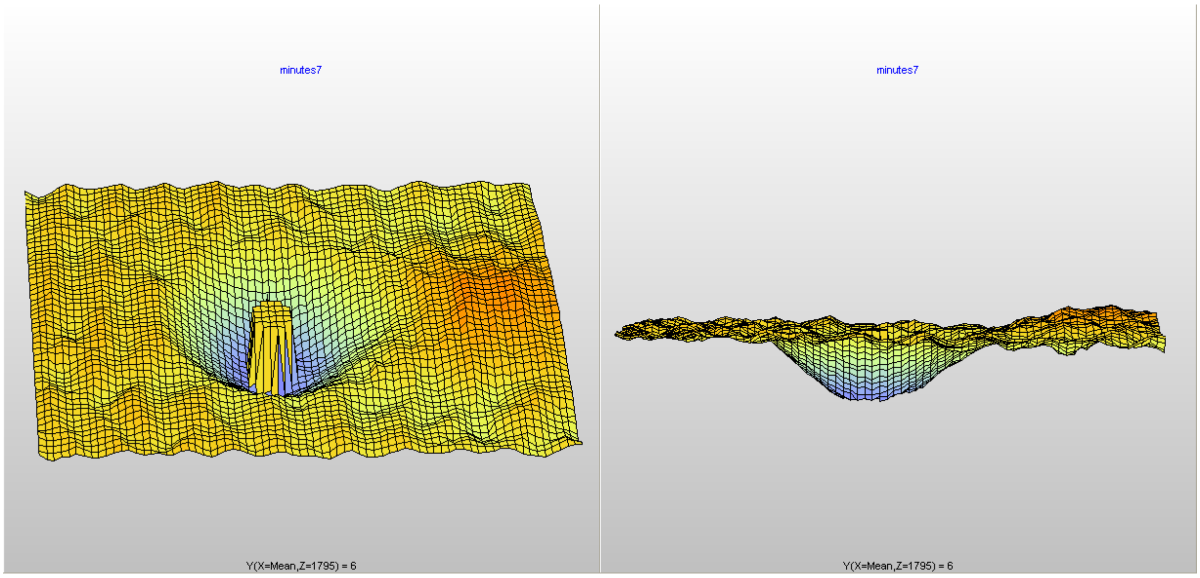
Figure 6.2 The established scour formation from wave Scouring, and back filling, respectively

From the figure it is seen that the largest scour is located on each side of the pile in the direction of the wave propagation, showing that the increased velocity/shear force from the contraction of the wave-flow around the pile produces some scour. This scour is limited, however it is important for back filling as it defines the limit of the process. From this observation it follows that some degree of scour will always be present in a natural environment.

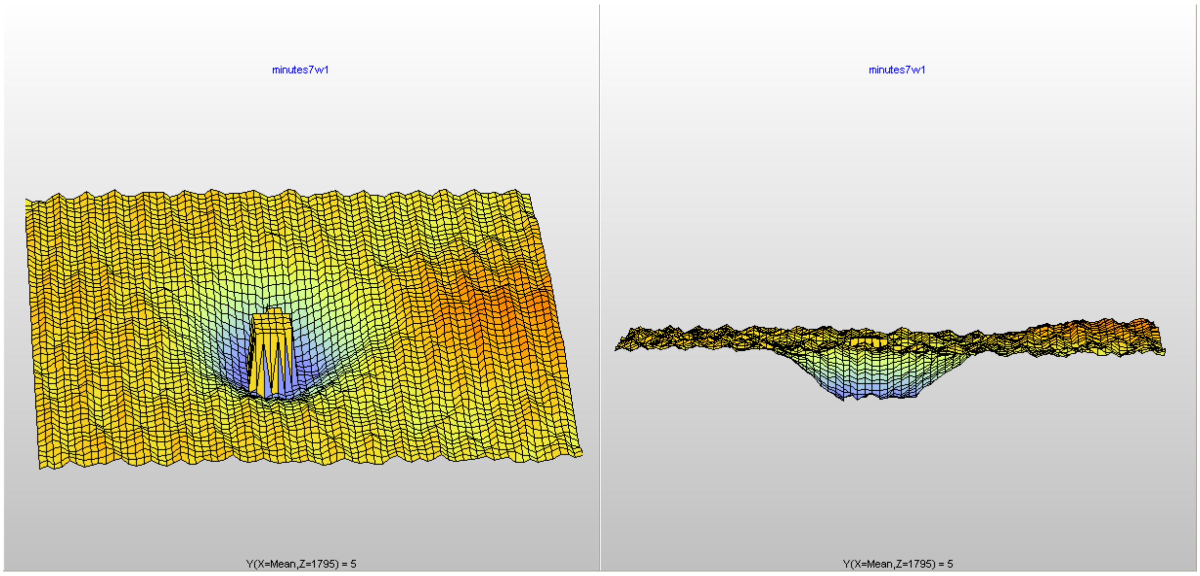
6.1.2. Back filling of current induced scour holes

To quantify the effect of wave activity with regard to the back filling of current induced scour holes, a series of tests on back filling were conducted. Back filling was initiated on scour holes with depths in the range of s=0,5-1,3 times the pile diameter D. The results were analyzed in several ways, revealing an exponential decree of the scour depth as a function of the number of waves sweeping the scour hole. The results show that the back filling of the scour hole is related to the initial depth of the scour hole, indicating that back filling is related to the ability of the waves to stir up sediments. As a small scour hole has less “volume” than a larger, it is obvious that it will fill faster, as the inflow of sediment to the scour hole is constant. In the following, back filling of a scour hole is illustrated.

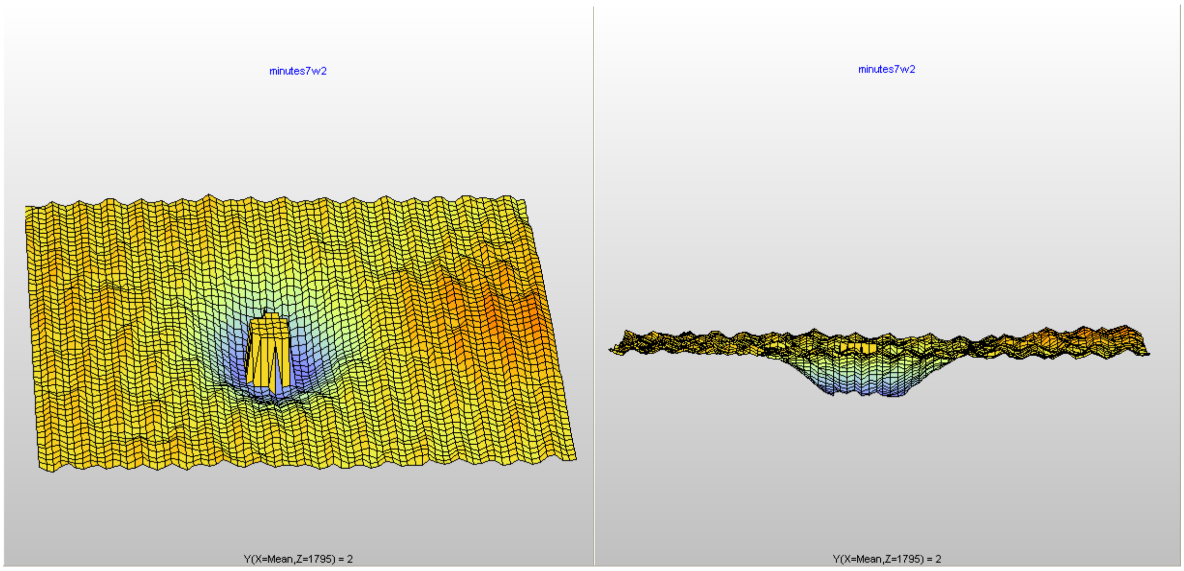
Back filling of a current induced scour hole



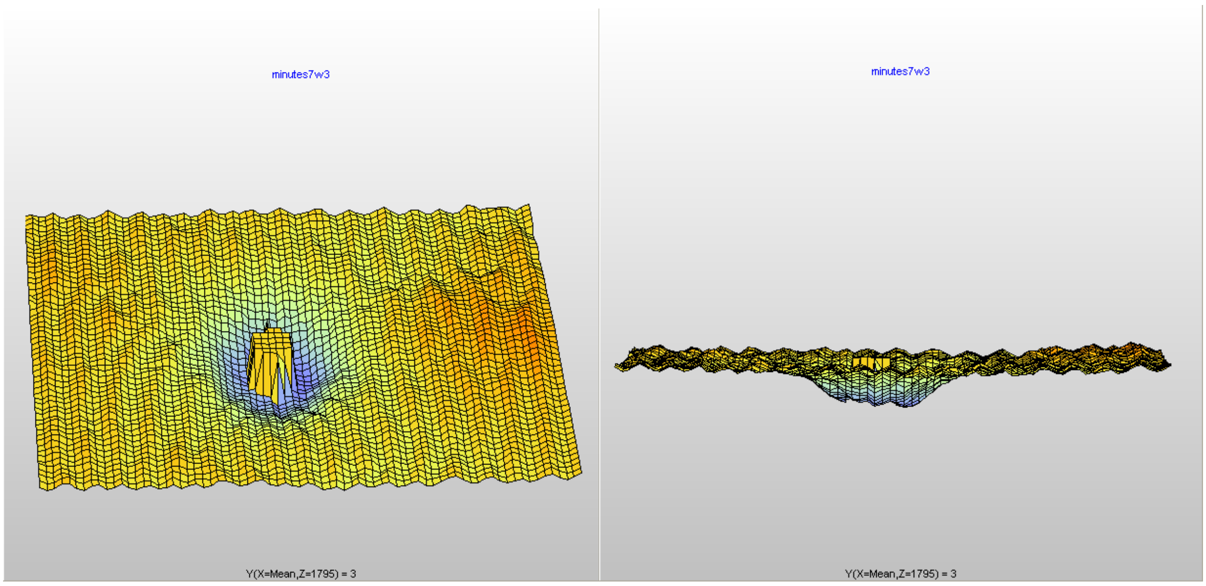
Initial current induced scour hole, s/D=1,07



Back filling, 400 waves, s/D=0,93



Back filling, 800 waves, s/D=0,82



Back filling, 1200 waves, s/D=0,72

Figure 6.3 Illustration of wave induced back filling of a scour hole

It is seen from figure 6.3 that the effect of back filling is significant. Generally, the back filled material is distributed equally on the up- and downstream side of the scour hole. In figure 6.4 the back filling, results are shown for all conducted experiments, along with a line of best fit.

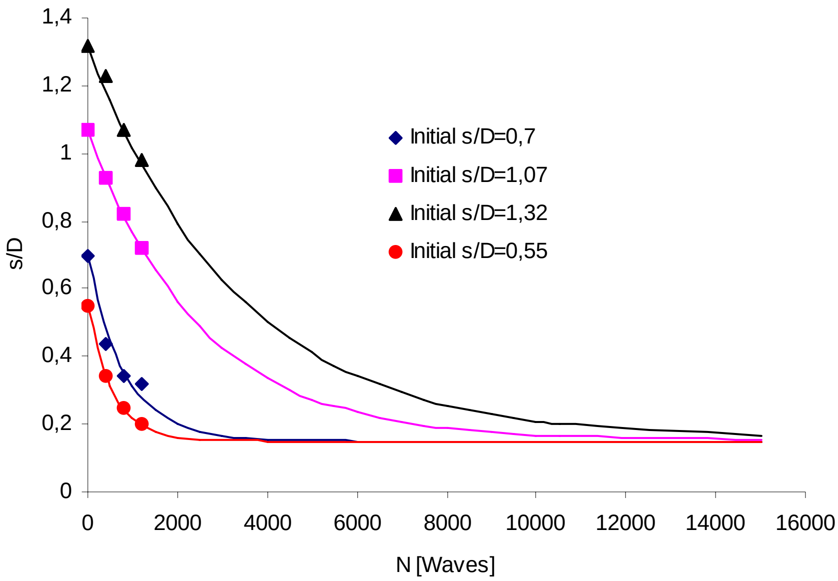


Figure 6.4 Results from the back filling of scour holes with different initial depth, s/D, along with a best fit to an exponential decree

From the back filling tests, following exponential function quantifying the back filling rate, has been found.

$$\frac{s}{D}(N) = \left(\frac{s_i - s_e}{D}\right) \cdot \exp\left(a \cdot N\right) + \left(\frac{s_e}{D}\right) \qquad [45]$$

where s_i and s_e are the initial, and wave induced equilibrium scour depths, and a is a parameter dependent on the initial scour depth. The coefficient a is related to the initial scour depth and is calculated from the following expression

$$a\left(\frac{s}{D}\right) = -0.0026 \cdot \left(\frac{s}{D} - 1.3\right)^2 - 0.00031 \qquad [46]$$

where s/D is the dimensionless scour depth, and the value 1,3 represents the dimensionless maximum (equilibrium) scour depth.

6.1.3. Scour depth in a current-wave environment

To study the effect of a combined current-wave environment with respect to the equilibrium scour depth, two tests were conducted at the Hydraulic Laboratory at Gent University, Belgium. To quantify the effect of waves superposed on a current, two different current velocities were used, $U_{current}$=0,25m/s and 0,21m/s. The irregular waves used were the same as all previous tests. The purpose of the test was to study if the current would dominate the scour process in a combined current-wave environment. The primary effect of the combined current-wave environment was a significant change in the equilibrium scour depth as seen in figure 6.5.

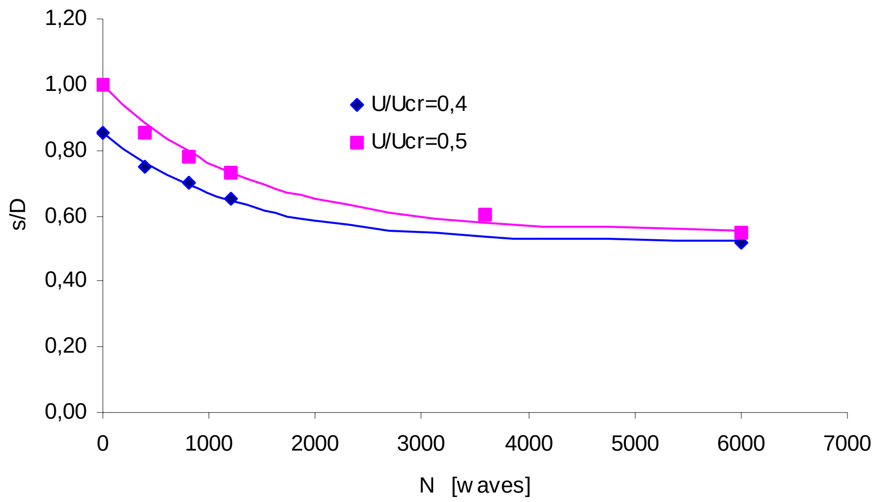


Figure 6.5 Test results from the combined wave-current test, with clear water current conditions

From the experiment, it was found that the current-wave environment affected the equilibrium scour depth as expected and most importantly, that back filling still toke place. From this test, it can be concluded that back filling is not affected by the current. It is also seen from figure 6.5 that the time scale of the back filling (the number of waves necessary to achieve the equilibrium scour depth) is similar to the time scale of back filling without current, compare with figure 6.4. This indicates that the waves dominated the environment. In other words, a current velocity of 0,25m/s (shields parameter, θ, equal to approximately 0,07), has relatively limited effect on the back filling rate. The equilibrium scour depth found in the experiment has shown to agree with the predicted scour depth found from the equation [26].

$$\frac{s}{D}(U_{cw}) = \left(\frac{s_c}{D}\right)\left(1-\exp\left(-A\left(KC-B\right)\right)\right) \qquad [26]$$

$$A = 0.03 + \frac{3}{4}\cdot U_{cw}^{2.6}$$

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

$$U_{cw} = \frac{U_c}{U_c + U_m}$$

where s_c is the equilibrium scour depth in current only, and U_{cw} is the relation between the current and wave velocities at the seabed. The function is valid for KC values around or larger than 4. The results from the combined current-wave scour test are shown together with the predictive expression in figure 6.6

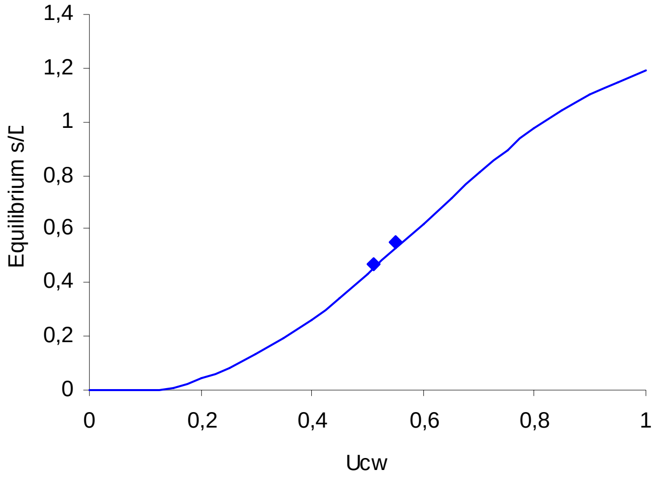


Figure 6.6 Predicted and measured, equilibrium scour depth, from the combined wave-current scour test

In conclusion, it has been found that back filling is significant also in a combined current-wave environment, and it has been shown that for the current-wave environment in the experiment, the scour depth was less than 50% of the current only case. This indicates that back filling is important with regard to the scour depth, as well as the current, in a marine environment.

7. Case study, Horns rev

Based on the back filling experiments made in the Hydraulic Laboratories at Aalborg University and Gent University a case study on the time variation of the scour depth at an unprotected mono pile at Horns Rev has been performed. The scour depth was simulated for a measuring platform, installed prior to the construction of the wind farm. The measuring platform was mounted on a monopole with a diameter of D=1,5 m, driven into the sea floor. The mono pile is considered slender relative to the water depth, h. The water depth on site is approximate 6,3m and the h/D relationship is approximately 4,2 which is within the slender pile regime that existing equations are valid for.

7.1. The Horns Rev

The Horns rev wind farm includes 80 2MW wind turbines situated 14-20 km of the coast of Blåvands Huk. The wind turbines are located in 6-14 meters of water. The environment at the location is characterized by breaking waves and tidal currents. The water depth varies 1,2 m. due to tidal conditions. The tidal and wind induced current reaches velocities of 0,5 m/sec and the waves exceed heights of 6 m once per year. The wind turbines are based on circular mono piles with a diameter D=4 m, driven 22-24 meters into the sea floor. All wind turbine foundations are constructed with scour protection in the form of rock dumping at the base of the piles. This information is taken from www.hornsrev.dk (2006).

7.1.1. Survey data

Prior to the installation of the wind farm, an instrumented platform was constructed at the site to record information on the wind, wave, depth, and current conditions. Measurements for one full year have been made available. Periodically one or more of the recording instruments have failed, and consequently data has not been recorded during the downtime. As a result, there are approximately 170 days with intact measurements when the downtime is subtracted. These data are the input to the model developed as a part of this study.

During the survey period when TECHWISE (The company conducting the survey), visited the site the scour depth at the base of the measuring platform was measured. The scour depth was recorded 7 times in total. The exact scour depths from these observations have unfortunately been lost or misplaced. However, the engineers recall that there was

“Practically no scour” [less than 0,5m.]

at 6 of the times they visited the site, and

“Some scour” [1-2m.]

on one occasion. (Source: Peter Frigaard, Aalborg University)

These observations are not particularly scientific, but they indicate that a state of equilibrium scour does not develop (current induced equilibrium scour). Since the current on site was adequate for scour to develop, the observations indicate that back filling had taken place. The objective of this case study was to indicate if this observation could be linked to the back filling due to wave activity at the site.

In table 7.1 an overview of the data available from the Horns Rev site is given.

Table 7.1 Some parameters, characteristic for the environment on site

Recorded data, Measuring platform			
Parameter	Measuring frequency [hours^{-1}]	Max value	Mean value
Water depth	2	9,13 m	6,80 m
H_s	1	3,83 m	1,21 m
T_p	1	16,7 s	6,53 s
Current	2	0,89 m/s	0,35 m/s

7.1.2. Time stepping scour model

The model from the present study estimates the scour depth as a function of the current-wave climate, utilizing a simple time stepping approach described in Appendix E. The time step used in the case study was *Δt=30 min*. The back filling equations used in the model are unaffected by the length of the time step, as this part of the programme is non-dependent on *Δt*. However the scour part of the model, is time step dependent as seen below from the scour development component of the model, equation [47].

$$\frac{s(t+\Delta t)}{D} = \left(\frac{s(t)}{D}\right) + \left(\frac{s_e - s(t)}{D}\right) \cdot T^{-1} \cdot \Delta t \qquad [47]$$

As *Δt* becomes large relative to the time scale T, the model over-estimates the scour development. To obtain an idea of the error produced in one time step a simple calculation of the scour development in one time step has been performed. The control calculation was performed for T=119 min. This value of the time scale, T, is the lowest value that could be calculated from the current measurements on site. Below the calculation of the error produced within the model is shown

Model conditions,

$$t = 0$$
$$s(t) = 0$$
$$s_e = 1.3 \cdot D$$
$$T = 119\,\text{min}$$
$$\Delta t = 30\,\text{min}$$

$$\textit{Exact development}:$$
$$\frac{s(t+\Delta t)}{D} = \frac{s_e}{D} \cdot \left(1 - \exp\left(-\frac{t+\Delta t}{T}\right)\right)$$
$$\frac{s(30)}{D} = \frac{1.3}{D} \cdot \left(1 - \exp\left(-\frac{30}{119}\right)\right) = \underline{0.29}$$
$$\textit{Scour model development}:$$
$$\frac{s(t+\Delta t)}{D} = \left(\frac{s(t)}{D}\right) + \left(\frac{s_e - s(t)}{D}\right) \cdot T^{-1} \cdot \Delta t$$
$$\frac{s(30)}{D} = \left(\frac{1.3}{D}\right) \cdot 119^{-1} \cdot 30 = \underline{0.33}$$
$$\textit{Error}:$$
$$E = \frac{0.33 - 0.29}{0.33} \cdot 100\% = \underline{\underline{12\%}}$$

As the model over-predicts the scour depth by 12% as a worst case this error is considered to be of no practical importance. The median value of the time scale of the scour process has been estimated from the data to be T=4,5 days. Concluding the time step *Δt=30 min.* is considered adequate.

With regard to the scaling of the back filling, a conservative relationship was chosen. To scale the back filling following linear relationship was used to scale laboratory conditions to the on site conditions.

$$\beta = \frac{\theta_{\text{w-Case study}}}{\theta_{\text{w-Scale-model}}} \qquad [48]$$

Since this relationship is not supported by experiments, it is associated with a great deal of uncertainty, however it is believed from observations in the laboratory that back filling is related to the ability of the waves to transport (stir up) sediments into the scour zone, which supports the β-relationship. The β-value is considered conservative as the ability to stir up sediments is exponentially related to the wave-shields-parameter as shown below. Liu, (2001)

$$\textit{stirr up} \propto \exp(-k \cdot \theta_{wave}) \qquad [49]$$

where *k* is a constant.

7.2. Result from Case study

Based on the environmental data the variation in scour depth at the base of the measuring platform has been modelled. To give an impression of the environment at the site the current, water depth and wave activity, H_s and T_p, for the 170 days modelled, are shown below:

Current

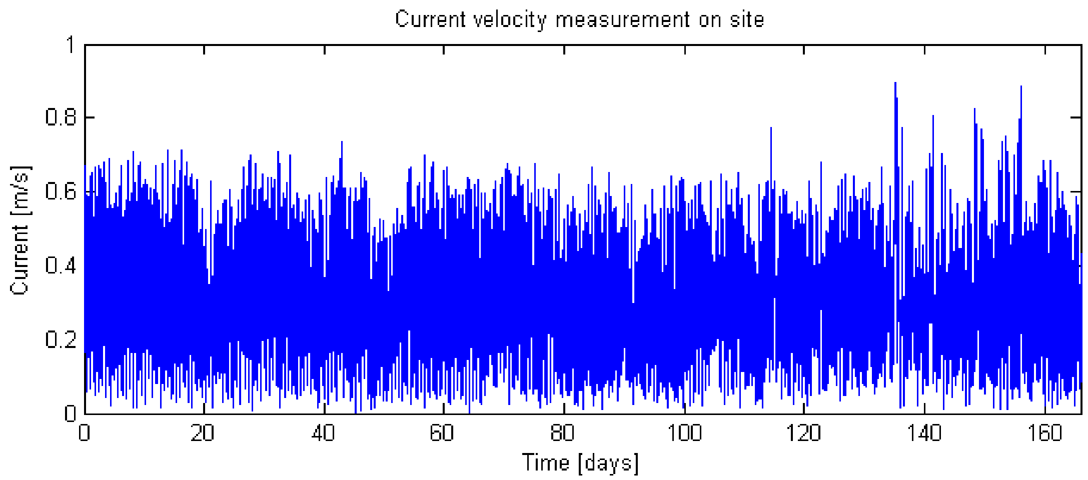


Figure 7.1 On site current velocity variation
170 days of measurements

Water depth

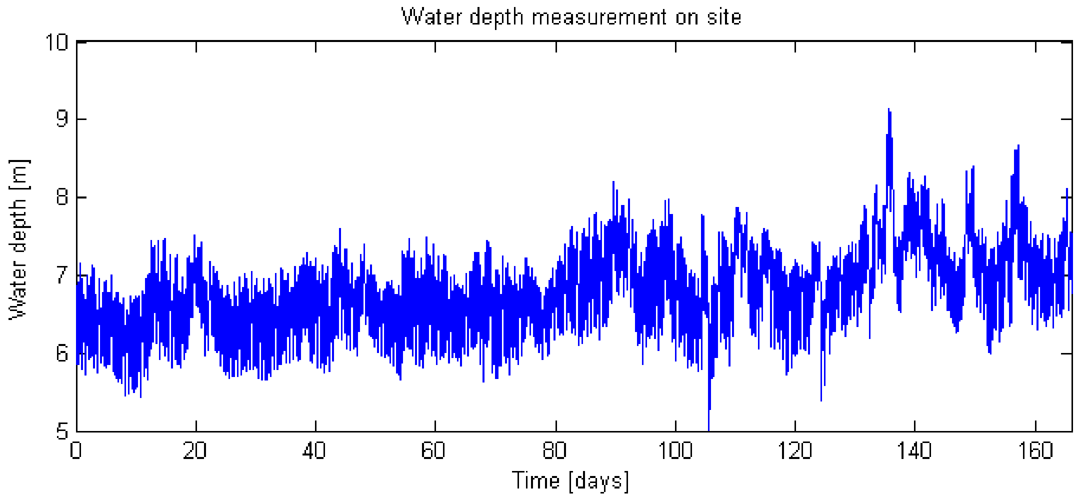


Figure 7.2 Water depth variation on site
170 days of measurements

Wave activity

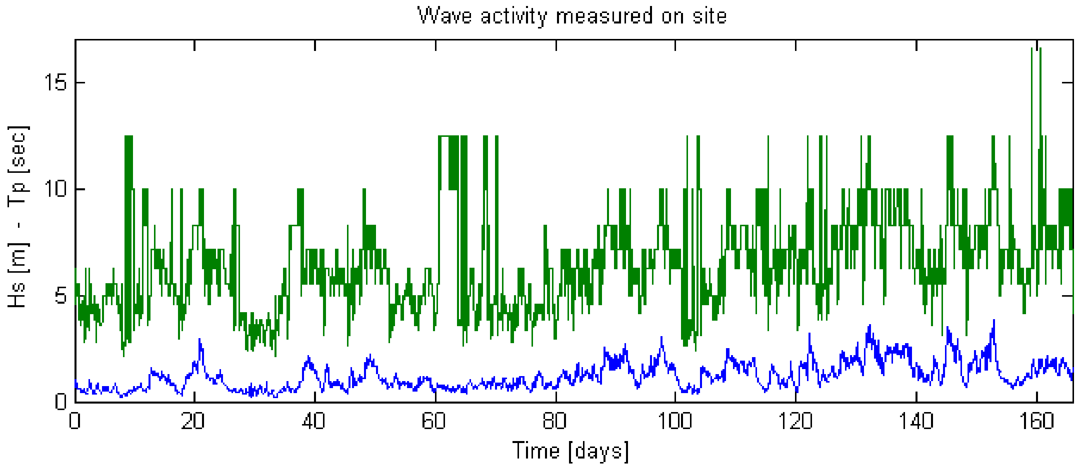


Figure 7.3 Wave activity on site, T_p (green) and H_s (blue), 170 days of measurements

From the plots, it is clear that the environment becomes increasingly aggressive towards the end of the measured data. This increase in the peak values of the environmental data is related to the season. The last 60 days of measurements are recorded during January –February 2000.

From the recorded data it has been found that the significant wave height was 2,7 m with a peak period of 10 s. on December 3, 1999. The 10 min. mean-wind-velocity 62 m above sea level was 45 m/s. This is the date of the famous storm of 1999, which caused massive damages in large parts of Denmark.

7.2.1. Scour model results

Based on the environmental data the variation in scour depth at the measuring platform was calculated using the time stepping model. In figure 7.4 the variation of the non dimensional scour depth, s/D, is shown.

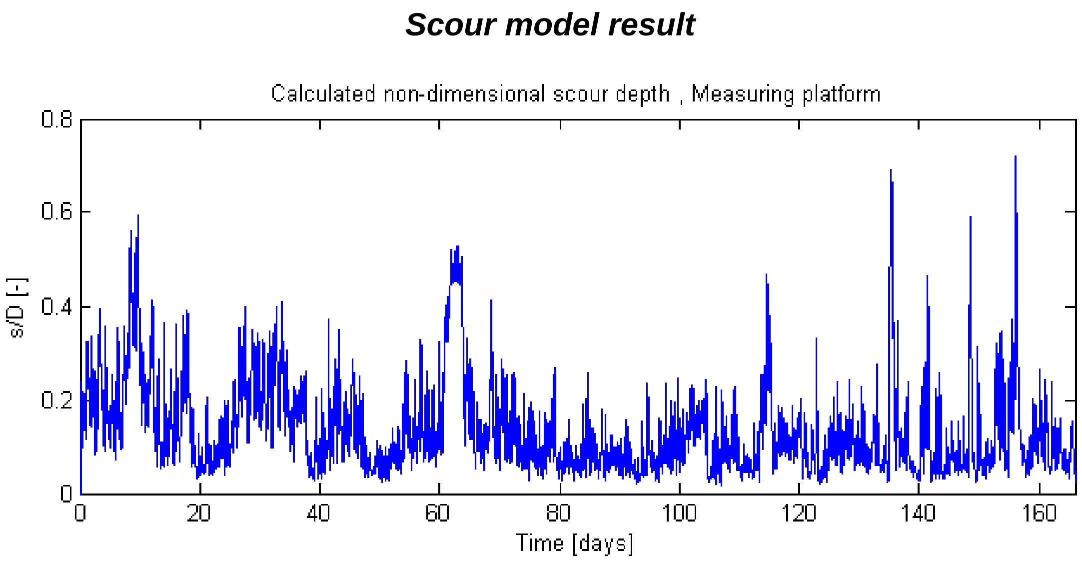


Figure 7.4 Scour model output, s/D(t), simulated from the environmental input; current velocity, water depth and wave activity

From the variation in the scour depth it is seen that the current becomes dominant during stormy periods. This is seen from the peaks of the scour depth, as they are in phase with the peaks of the current velocity time series plot, figure 7.1.

From the model the min., mean, and max. non-dimensional scour depth, s/D, has been found. In table 7.2 these results are tabulated. From the table it is clear that the back filling effect is dominating the scour depth distribution.

Table 7.2 Some characteristic values, obtained from the modelled time series

Scour model, Results	
$(s/D)_{min}$	0,02
$(s/D)_{mean}$	0,14
$(s/D)_{max}$	0,72

A histogram of the non-dimensional scour depth is shown in figure 7.5.

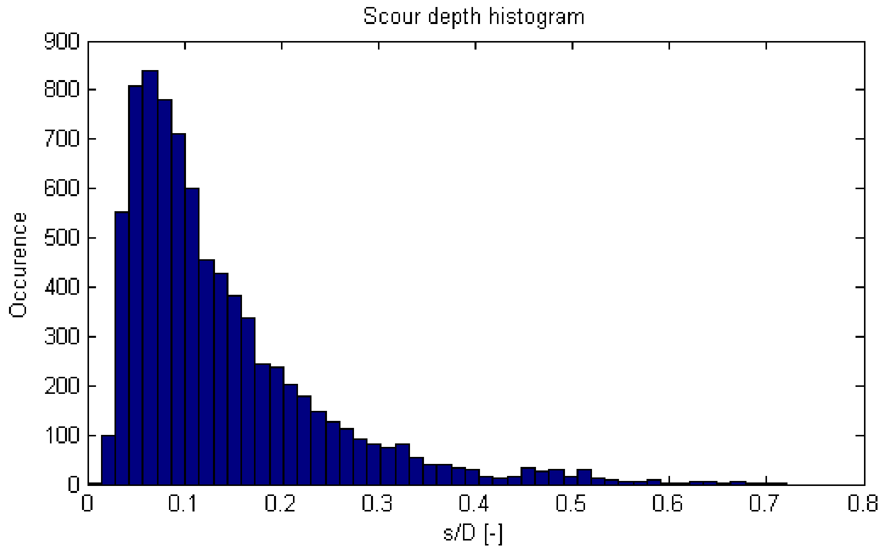


Figure 7.5 Histogram of the scour depth, obtained from the scour model

By non-dimensionalizing the histogram, a two-parameter fit to the distribution has been found. This is done to give an estimate of the significant scour depth, $(s/D)_{1/3}$ and the scour depth with a exceedence probability of 1/1000, $(s/D)_{0,1\%}$

The following extreme value probability density function (Weibull distribution) was fitted.

$$f_X(x) = \frac{k}{u} \cdot \left(\frac{x}{u}\right)^{k-1} \exp\left(-\left(\frac{x}{u}\right)^{k}\right) \quad \text{where} \quad x = \frac{s/D}{\overline{\overline{s/D}}}$$

$$u = 1.1$$

$$k = 1.2$$

The probability density distribution from the model and the two-parameter fit is shown in figure 7.6.

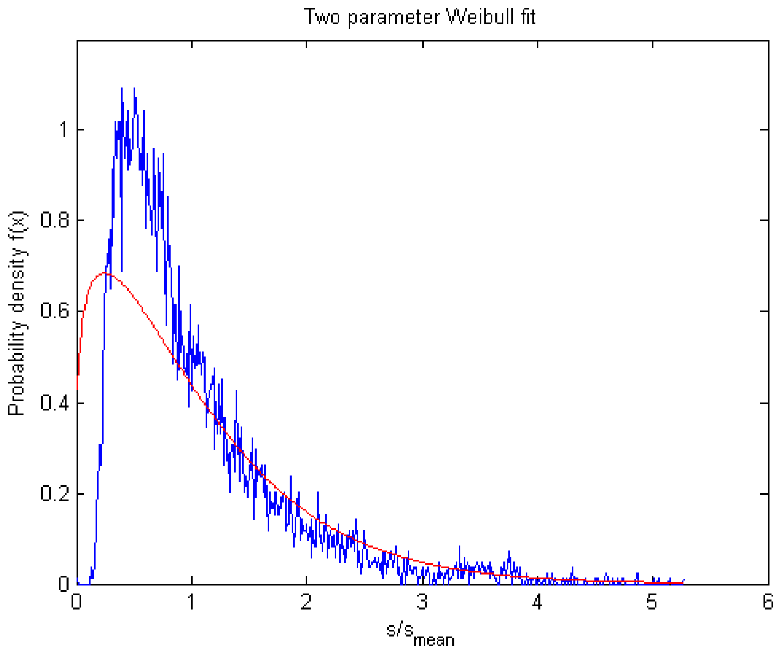


Figure 7.6 Probability density distribution from scour model plotted together with the two parameter Weibull fit

It is seen from the figure, that the two-parameter fit fails to reproduce the peak of the calculated probability density distribution. However, it is considered adequate to estimate the probability distribution for the tail of the distribution. Below the cumulative distribution function, associated with the two-parameter Weibull fit, is given.

$$F_X(x) = 1 - \exp\left(-\left(\frac{x}{u}\right)^k\right)$$

In figure 7.7 the cumulative distribution function is compared to the cumulative distribution of the modelled scour depth.

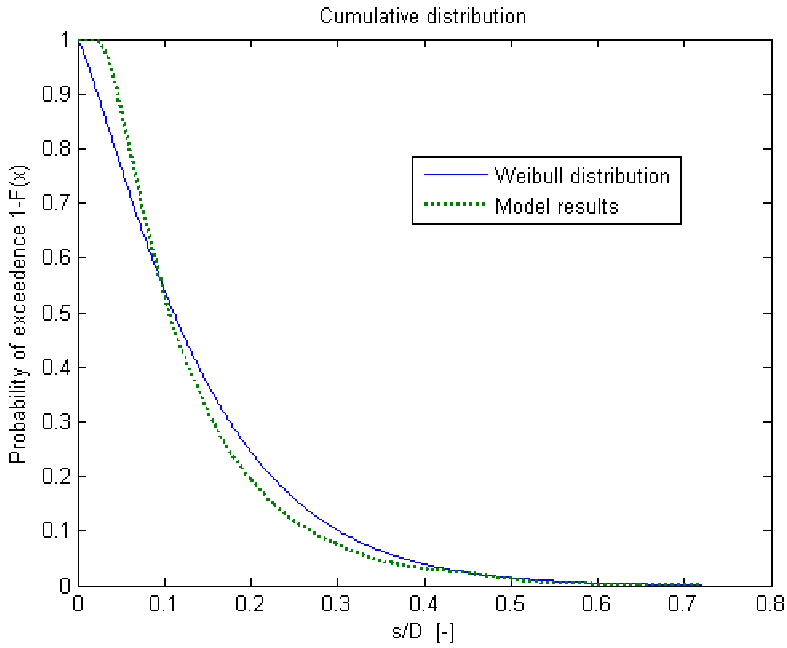


Figure 7.7 Cumulative scour depth distribution from scour model, plotted against the two parameter Weibull distribution

From figure 7.7 it is seen that the Weibull distribution fits the actual results quite well, and it is conservative for values of s/D>0,1. From the two-parameter fit the following characteristic scour depths have been estimated:

$$\left(\frac{s}{D}\right)_{1/3} = 2.01 \cdot \overline{\left(\frac{s}{D}\right)} \approx \underline{0.28}$$

$$\left(\frac{s}{D}\right)_{0.1\%} = 5.51 \cdot \overline{\left(\frac{s}{D}\right)} \approx \underline{0.77}$$

7.2.2. Data manipulation

To investigate the effect of the environment with regard to the scour depth, different studies were conducted.

To evaluate the importance of the phase of the input data, the current and wave data were offset with respect to each other (the current was offset by 85 days). From this simulation, little effect on the scour depth distribution was found, as seen in figure 7.8.

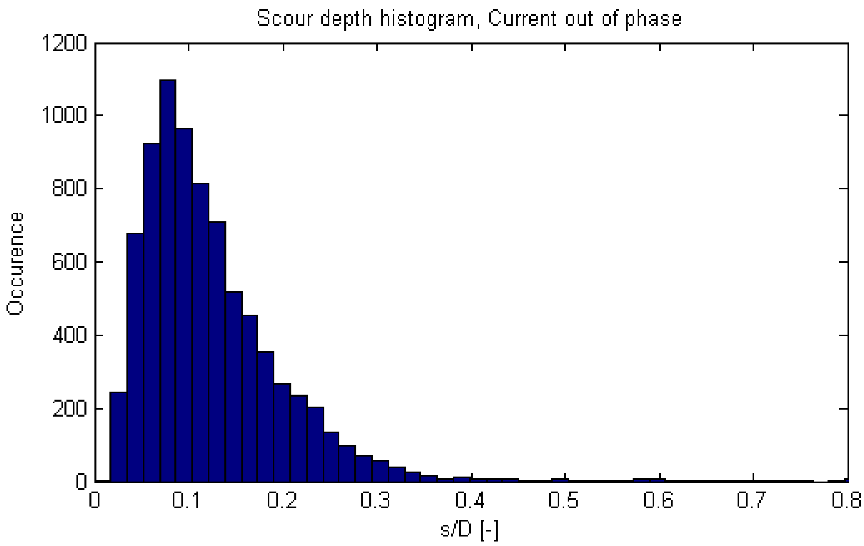


Figure 7.8 Histogram of the scour depth, obtained from the scour model, with a current offset by 85 days relative to the wave data

This result indicates that there is only little correlation between the phase of the environmental input and the scour depth distribution. This is an important result as it indicates that the scour depth distribution can be modelled, using non correlated environmental data. From the simulation with an offset of the current the following results shown in table 7.3 were obtained.

Table 7.3 Some characteristic values, obtained from the scour model with a current offset by 85 days relative to the wave data

Scour model, Current offset by 85 days	
$(s/D)_{min}$	0,02
$(s/D)_{mean}$	0,13
$(s/D)_{max}$	0,87

The largest effect from the offset was with regard to the max. scour depth. Since the magnitude of currents and waves are correlated with the wind velocity in a marine environment it is, however, preferable to maintain the initial phase when simulating the scour depth variation.

7.2.3. Effective range of back filling

Assuming the environmental data made available to this study are representative for the wave current climate on site, a series of simulations with scaled current velocities and wave heights have been performed. The mean value of s/D for different scenarios have been calculated in order to estimate the effective range of back filling. The scaling of the wave current climate is carried out according to Froudes model law,

$$\lambda_L = scale$$
$$\lambda_T = \sqrt{\lambda_L} = \sqrt{scale}$$

The current velocity and wave activity was scaled in the range from 1 to 2 times the actual conditions. The following results were obtained, indicating that the current velocity generally determines the scour depth, expressed as the mean scour depth $(s/D)_{mean}$. The results are tabulated in table 7.4.

Table 7.4 Mean scour depth $(s/D)_{mean}$
for different wave-current scenarios

	-	$(s/D)_{mean}$				
U_{max} [m/s]	1,79	1,10	1,04	0,99	0,94	Current dominated environment
	1,55	0,93	0,84	0,77	0,71	Wave dominated environment
	1,26	0,54	0,46	0,40	0,36	
	0,89	0,14	0,12	0,11	0,10	
	-	3,83	5,10	6,38	7,65	
-	Hs_{max} [m]					

From the table it follows that the wave activity has a greater effect on the mean scour depth when the current velocity is relatively low. As the current velocity increases, the back filling effect of the waves becomes unimportant compared to the scouring effect of the current. The results are also shown in figure 7.9.

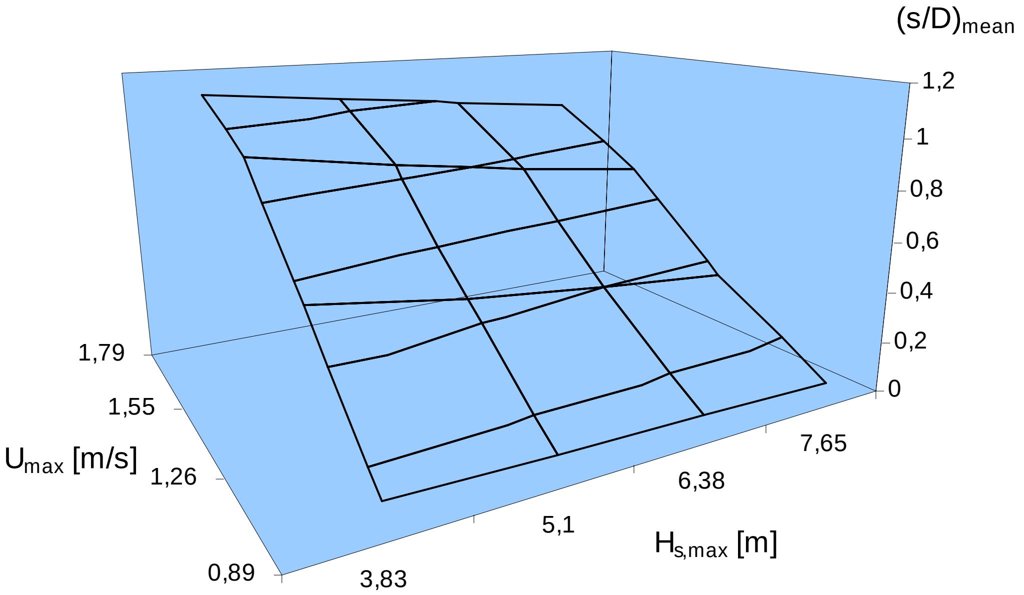


Figure 7.9 3-dimensional plot of the mean scour depth as a function of the wave-current environment

From figure 7.9 it is seen that the current velocity generally determines the mean scour depth, and that an increase in the wave activity has little influence on the scour depth. From this observation the transition from wave-dominated to current dominated scour conditions can be estimated. As the wave activity has been shown to be less important than the current velocity the following transitional condition is suggested.

$$\overline{U}_{current} = \begin{cases} >0.7 & \text{Current dominated environment} \\ (0.6-0.7) & \text{Transition} \\ <0.6 & \text{Wave dominated environment} \end{cases} \qquad [50]$$

From this simplification, it can be concluded that environments with mean currents below 0,6 m/s are candidate for unprotected offshore structures, as the wave activity greatly reduces the mean scour depth. However, peak scour depths in the range of 1,3D must be considered in the design process.

Appendix A.
Laboratory work

To gather information on the scour process in tides and current-wave environments a series of scour and back filling tests were conducted in the laboratory. As most existing equations and knowledge in regard to scour is achieved from scale model tests, this is inevitable when investigating these issues. Therefore, all results in this project are more or less achieved from scale model tests, and because of this, a large part of the time invested in this project has been spent in the laboratory. In the following a description of the practical work and set ups in the laboratory will be described, to give an impression of this part of the project.

A.1. Test set up

The experiments were conducted in combined wave and current flumes, enabling all tests to be carried out in one set up. Some work was carried out in Aalborg in the Hydraulic Laboratory, and some tests were carried out in Belgium at Gent University. The facilities in Aalborg and Gent were similar to each other (the dimensions of the flumes are different, but the general design is the same), and in figure A.1 and figure A.2 the set ups from Aalborg and Gent are shown respectively. Both flumes are 1,2 meters wide.

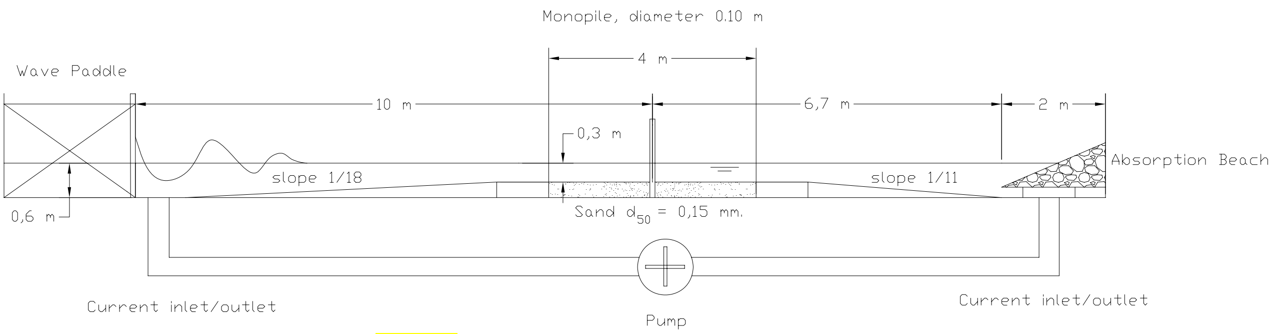


Figure A.1 Test set up Hydraulic Laboratory, Aalborg University

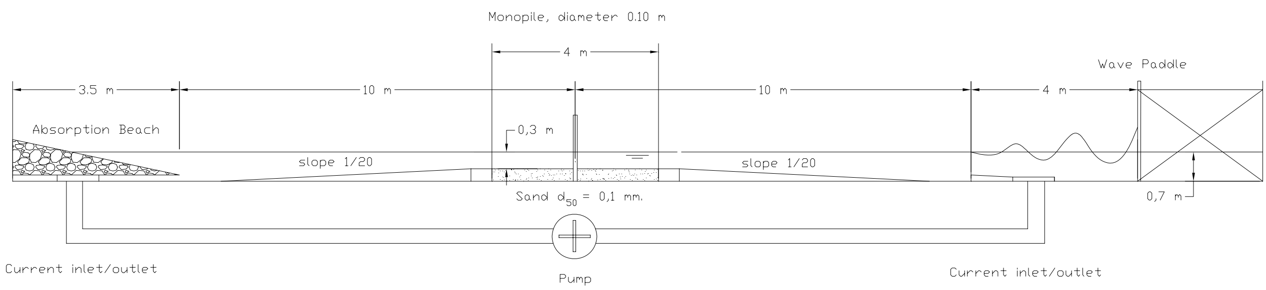


Figure A.2 Test set up Hydraulic Laboratory, Gent University

A.2. Practical work in the lab

The top part of the scale model piles could be removed to enable measurements continuously. Measurements were performed with an Erosion Profiler (EP), mounted on the walls of the flume. With the EP it is possible to measure the contours of the bed around the pile without removing water from the flume. This gives a large reduction in the time spent in the laboratory, and improves the quality of the measurements, as the scour holes are not damaged by drainage of the flume. The EP in action is seen in figure A.3.

Figure A.3 Illustration of the EP, profiling a back filled scour hole

Between scour tests, the bed was levelled to the initial flat bed state, before a new test could be performed. Due to the current and waves in tests, bed material was carried outside the "sand box" and therefore sand was added or moved back from the slopes of the set up. In figure A.4 a picture taken during a re-establishment of the scour bed is shown.

Figure A.4 Working on the re-establishment of the bed, between tests

The tests conducted at Gent University were taped with a video recorder. This was done to produce some live footage of the scour and back filling process, for illustrative purposes. The video recording was also useful, when long duration tests were conducted, as it was possible to leave the laboratory and maintain the monitoring of the test at the same time. In figure A.5 the video set up is shown.

Figure A.5 Video recording of the Clear water scour test

A.3. Scaling in test

The tests were performed with a physical model of a pile scaled according to Froudes model law. Typical piles are in the range 1-6 meters. The model was constructed with a pile diameter of 0,1 meter. This results in an approximate scale in test of:

Length: $\lambda_L = \{10 - 60\}$

Time: $\lambda_T = \lambda_L^{1/2} = \{3.2 - 7.5\}$

A.4. Test properties

Tests were performed on a circular pile with a diameter D=0,1 m. in a water depth h=0,3 m. From the previously mentioned scale, the tests could be simulating a pile in nature with a diameter of 4 meters situated in 12 meters of water. The properties of the variables in the test are chosen, so they represent the scale when possible. However there are limitations regarding sediment size, due to cohesive effects, when the grain size is reduced. Due to this effect, it is not possible to scale the bed material according to the scale outlined above. In the model tests, bed material with d_{50} = 0,10-0,15mm, has therefore been used. In the tests, fresh water has been used. The properties are summarized in table A.1.

Table A.1 Properties in experiments

Test properties	
D	0,1 m.
h	0,3 m.
d_{50}	0,10-0,15 mm.
ρ_s	2650 kg/m^3
Fluid	Fresh water

A.5. Measurements

The wave activity in tests was preserved by measuring the wave elevation, and the current was monitored with an ultrasonic flow meter. Both measurements were taken near the pile. In the Hydraulic Laboratory at Aalborg University, the wave elevations and current velocities were measured two meters in front of the pile, and at Gent University, the elevation was measured 0,5 m. from the pile, and the current was measured two meters from the pile.

A.5.1. Irregular waves

The irregular waves used in the back filling experiment are generated using a JONSWAP spectrum.

Table A.2 Specifications for the irregular wave series, used in all tests

Wave Specifications	
Wave type	Irregular
Spectrum	JONSWAP
H_s	0,12
T_p	1,64
Peak enh. factor	3,3

When generating the irregular waves with the wave paddle, some variation from the output and input occurs. This is caused by several things, such as the calibration of the paddles hydraulic piston to the output from the computer generating the paddle motion signal. In addition, effects such as shoaling and perhaps breaking of the waves as they move towards the test area are influencing this effect.

To preserve information on the waves that are present in test, the wave elevations have been recorded. Due to the large amount of recorded time series, only one will be shown here, as they are similar to each other. In figure A.5 a typical wave elevation time series and resulting variance spectrum is shown.

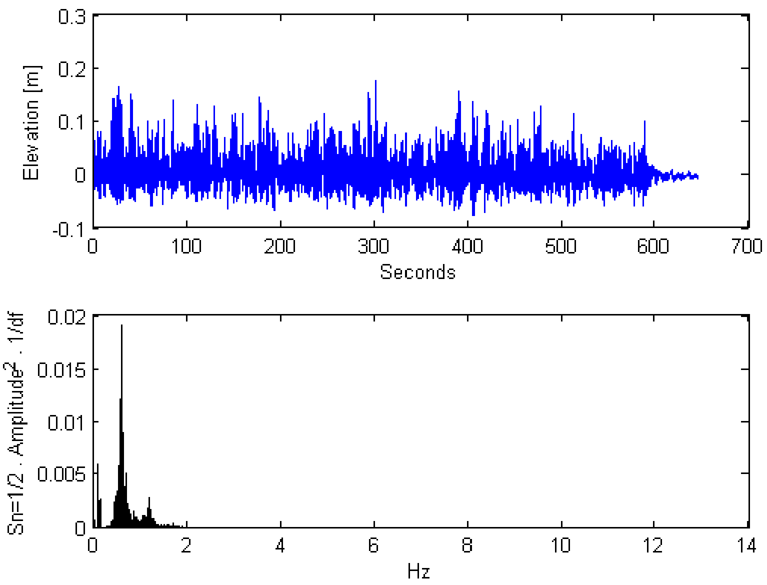


Figure A.5 Typical elevation time series and associated energy spectrum, obtained from test

From the variance spectrum obtained from the recorded time series following information, tabulated in table A.3, has been obtained.

Table A.3 Recorded characteristic values, irregular wave series from test

Recorded irregular wave	
H_s	0,126
T_p	1,6

The result from the power spectrum shows that the specified wave characteristics are satisfactorily achieved. Some variation in the wave series from test to test was recorded, however this is to be expected and not of great importance to the results, as the variation was limited.

A.5.2. Velocity profile

Using an ultrasonic flow meter, the velocity profile for U=0,5 m/s. has been recorded. This is done to give an impression of the flow. Measurements were taken every 5 cm. (5, 10, 15, 20 and 25 cm. from the bed.) Due to the turbulence in the flow, measurements are shown as mean values.
In figure A.6 the velocity measurements are shown along with a velocity profile created from a simple power law, suggested by Whitehouse, (1998)

$$U(z) = \left(\frac{z}{0.32 \cdot h}\right)^{1/7} \bar{U} \qquad 0 \le z \le 0.5 \cdot h$$
$$U(z) = 1.07 \cdot \bar{U} \qquad 0.5 \cdot h \le z \le h$$

where $\bar{U}$ is the depth averaged velocity, $U(z)$ is the velocity at height z above the bed, and h is the water depth. The power law has shown to agree well with measurements from many locations.

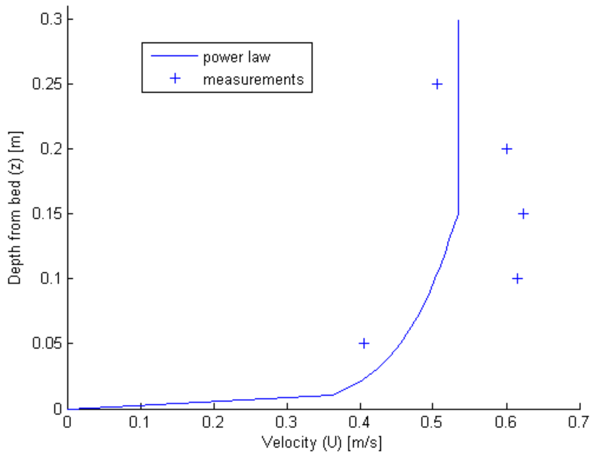


Figure A.6 Comparison between ideal, and measured velocity profile

From figure A.6 it is seen that the power law and the measured velocities are somewhat different, illustrating the difficulty of achieving “natural” conditions when testing on scale models. It is noted that the power law is not intended for this use, but serves as comparison. It is validated against measurements in “real” currents.

Appendix B.
Current scour

To achieve information on the time scale of scour in a current dominated environment several tests have been carried out in the Hydraulic Laboratory at Aalborg University and at Gent University, Belgium. Tests have been conducted with uni-directional current, in the clear water, and live bed regime. Also one test has been conducted with the purpose of simulating a tidal (reversing) current.

B.1. Live bed current test; U=0,5 m/s:

The scale model test on time development of scour in a unidirectional live bed current $\theta > \theta_{cr}$ was conducted to estimate the time scale for the scour process in strong currents, according to the specifications outlined in table B.1. In the test, it has been the aim to obtain a description of the time development, and therefore the time steps between measurements were chosen to be small in the beginning and increase towards the end of the test. This way, greater detail is achieved at the beginning of the process, where the scour rate is greater.

Table B.1 Outline of test specifications,
Live bed scour test U=0,5 m/s

Live bed scour *U=0,5 m/s*	
Velocity	0,5 m/s
Water depth	0,3 m.
Grain size (d_{50})	0,15 mm.
Flow description	Live bed.
Current	Unidirectional
Duration	180 minutes
Measurement time	
Initial bed	
1 min. current	
3 min. current	
5 min. current	
7 min. current	
10 min. current	
20 min. current	
30 min. current	
60 min. current	
120 min. current	
180 min. current	

B.2. Clear water current test; U=0,2 m/s:

Experiments with scour in clear water conditions $\theta < \theta_{cr}$ were conducted, to obtain information on the time scale in small velocity currents. Due to the timeframe of the experiment, the test was stopped after approx. 2 hours of current. The measurements however are adequate to estimate the time scale. The test on time development of scour in unidirectional clear water current was conducted according to the specifications outlined in table B.2.

Table B.2 Outline of test specifications,
Clear water scour test U=0,2 m/s

Clear water scour *U=0,2 m/s*	
Velocity	0,2 m/s
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Flow description	Clear water.
Current	Unidirectional
Duration	134 minutes
Measurement time	
Initial bed	
12 min. current	
26 min. current	
41 min. current	
58 min. current	
94 min. current	
134 min. current	

B.3. Tidal current test; U=0,3 m/s:

The purpose of the co-directional current test was to give information on the time development of the scour hole when the current is periodic, as it is the case in a tidal environment common to most offshore wind farms. Also, the experiment is conducted to investigate if the scour depth is affected when the current is co-directional. To simulate the cyclic nature of a tidal environment the current is reversed every 30 min. Consequently the current is constant over one half period, which is not the case in nature. (In nature, this current velocity would be sinusoidal). Again the time steps between measurements were chosen to be small in the beginning and increase towards the end of the test to achieve greater detail at the beginning of the process, where the scour rate is greater. The test program is seen in table B.3.

Table B.3 Outline of test specifications,
Tidal current test, U=0,3 m/s

Tidal scour *U=0,3 m/s*	
Velocity	0,3 m/s
Water depth	0,3 m.
Grain size (d_{50})	0,15 mm.
Flow description	Live bed.
Current	Co-directional
Half period	30 minutes
Duration	180 minutes
Measurement time	**Measurement time**
Forward →	**Reverse ←**
1 min. current	
3 min. current	
5 min. current	
10 min. current	
20 min. current	
30 min. current	
	35 min. current
	40 min. current
	60 min. current
67 min. current	
77 min. current	
90 min. current	
	95 min. current
	100 min. current
	110 min. current
	120 min. current
150 min. current	
	180 min. current

B.4. Time scale results

In the following, the results from the 3 scour development tests are shown, and the time scale from the scale model tests are compared to existing predictive formulations

B.4.1. Results, Live bed current U=0,5 m/s

In table B.4 the results, obtained from the EP measurements of the bed are tabulated for the time development of the scour in the unidirectional live bed current.

Table B.4 Results from Live bed scour test, U=0,5 m/s

Live bed scour *U=0,5 m/s*				
Current time	Global erosion [mm]	s [mm]	s/D [-]	Scour volume [m^3]
Results				
1 min.	0	70	0,70	0,0021
3 min.	0	87	0,87	0,0040
5 min.	0	99	0,99	0,0062
7 min.	2	107	1,07	0,0074
10 min.	3	112	1,12	0,0082
20 min.	5	124	1,24	0,0110
30 min.	10	132	1,32	0,0134
60 min.	20*	136	1,36	0,0164
120 min.	35*	122	1,22	0,0130
180 min.	40*	123	1,23	0,0134

Values marked with (*) are subject to a great deal of uncertainty, due to severe global erosion. The global erosion has been cancelled out to the extent possible, yet it is difficult to cancel out this effect, since it influences the time scale of the scour hole. (It is not possible to separate the timescale for the global erosion and the local scour.)

B.4.2. Results, Clear water current U=0,2 m/s

From the EP, following data shown in table B.5, were obtained from the clear water scour test.

Table B.5 Results from Clear water scour test, U=0,2 m/s

Clear water scour *U=0,2 m/s*		
Current time	s [mm]	s/D [-]
Results		
Initial bed	0	0,70
12 min.	17	0,87
26 min.	23	0,99
41 min.	36	1,07
58 min.	45	1,12
94 min.	55	1,24
134 min.	75	1,32

Due to a limited time frame for the clear water test, it was decided to reduce the profiling to a minimum. As the scour hole was larger than the profiled area, it has not been possible to calculate the eroded volume for this test. There appeared to be no global erosion in the clear water test, due to the clear water condition.

B.4.3. Results, Tidal current U=0,3 m/s

In table B.6 the results for the co-directional test are tabulated. Arrows indicate direction of the current.

Table B.6 Results from Tidal current scour test, U=0,3 m/s

Tidal current *U=0,3 m/s*			
Current time	Scour depth [mm]	s/D [-]	Scour volume [m^3]
Results			
→			
1 min.	21	0,21	0,0004
3 min.	35	0,35	0,0008
5 min.	51	0,51	0,0013
10 min.	53	0,53	0,0018
20 min.	68	0,68	0,0024
30 min.	71	0,71	0,0025
←			
35 min.	72	0,72	0,0025
40 min.	80	0,80	0,0036
60 min.	83	0,83	0,0040
→			
67 min.	107	1,07	0,0091
77 min.	106	1,06	0,0081
90 min.	111	1,11	0,0084
←			
95 min.	113	1,13	0,0089
100 min.	120	1,20	0,0106
110 min.	118	1,18	0,0106
120 min.	118	1,18	0,0115
→			
150 min.	122	1,22	0,0111
←			
180 min.	126	1,26	0,0139

There appeared to be no significant global erosion. This is probably due to the reduced current in the co-directional test.

B.5. Data analysis

Based on the 3 scale model tests the time scale can be estimated from existing formulas given in Whitehouse (1998), and the expected scour development in time, can be calculated from a method produced by Sumer et al. (2002). Common for all calculations is that it is assumed that the boundary layer equals the flow depth. $(\delta = h)$.

B.5.1. Time scale, Live bed current U=0,5 m/s

Calculating the time scale using the empirical expressions gives following result for the laboratory test on time development of scour in live bed uni-directional current, assuming that the boundary layer is 0.3 m.

$$\bar{U} = 0.5\ m/s$$

$$d_{50} = 0.15\ mm$$

$$h = 0.3\ m$$

$$U_f = \frac{0.5}{2.5\cdot\left(\ln\left(\frac{30\cdot 0.3}{2.5\cdot 0.15\cdot 10^{-3}}\right)-1\right)} = 0.022\ m/s$$

$$\theta_{\bar{U}=0.5} = \frac{0.022^2}{9.81\cdot(2.65-1)\cdot(0.15\cdot 10^{-3})} = 0.20$$

$$T^* = 0.014\cdot 0.2^{-1.29} = 0.11$$

$$T = \frac{0.1^2}{(9.81\cdot(2.65-1)\cdot 0.00015^3)^{1/2}}\cdot 0.11 = 151\ s$$

In figure B.1 a comparison of the expected time development, and the measured is seen. It is seen that the expected time scale is less than what is observed in test.

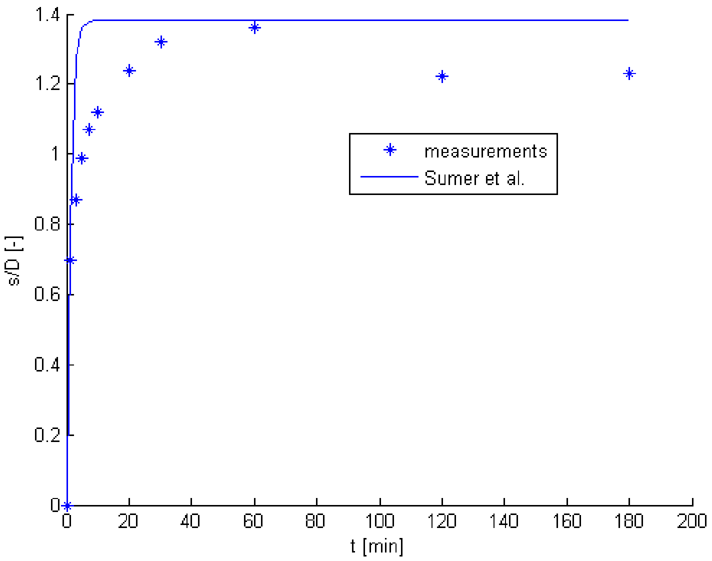


Figure B.1 Measured scour development in Live bed current, U=0,5 m/s and the predicted scour development from existing equations

B.5.2. Time scale, Clear water current U=0,2 m/s

The empirical time scale expressions give following result for the laboratory test on time development of scour in clear water uni-directional current, assuming that the boundary layer is 0.3 m.

$$\bar{U} = 0.2\ m/s$$
$$d_{50} = 0.10\ mm$$
$$h = 0.3\ m$$
$$U_f = \frac{0.2}{2.5 \cdot \left(\ln\left(\frac{30 \cdot 0.3}{2.5 \cdot 0.10 \cdot 10^{-3}} \right) - 1 \right)} = 0.0084\ m/s$$
$$\theta_{\bar{U}=0.2} = \frac{0.0084^2}{9.81 \cdot (2.65-1) \cdot (0.10 \cdot 10^{-3})} = 0.044$$
$$T^* = 0.014 \cdot 0.044^{-1.29} = 0.79$$
$$T = \frac{0.1^2}{(9.81 \cdot (2.65-1) \cdot 0.00010^3)^{1/2}} \cdot 0.79 = 2485\ s \approx 41 \min.$$

In figure B.2 the measured development and the exponential expression as shown. Again it is seen that the exponential expression under predicts the time scale of the scour process.

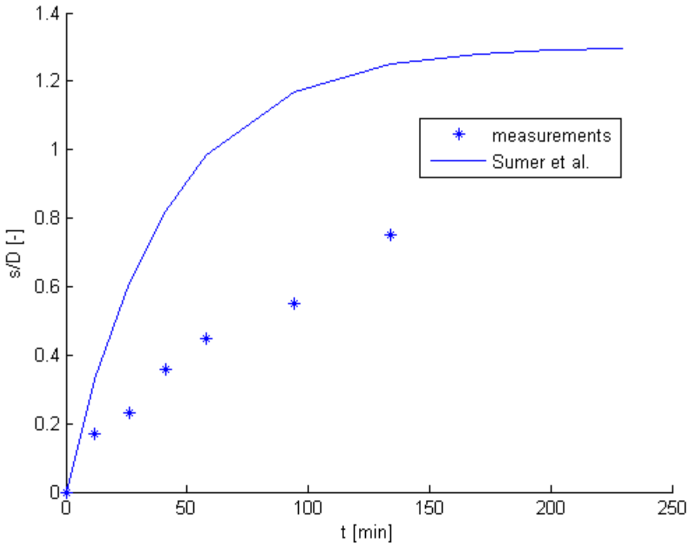


Figure B.2 Measured scour development in Clear water current, U=0,2 m/s and the predicted scour development from existing equations

B.5.3. Time scale, Tidal current; U=0,3m/s

Assuming again that the boundary layer is equal to the flow depth h=0,3 m. The time development in co-directional current is compared to the expression suggested by Sumer et al. (2002).

$$\bar{U} = 0.3\ m/s$$
$$d_{50} = 0.15\ mm$$
$$h = 0.3\ m$$
$$U_f = \frac{0.3}{2.5 \cdot \left(\ln\left(\frac{30 \cdot 0.3}{2.5 \cdot 0.15 \cdot 10^{-3}} \right) - 1 \right)} = 0.013\ m/s$$
$$\theta_{\bar{U}=0.3} = \frac{0.013^2}{9.81 \cdot (2.65-1) \cdot (0.15 \cdot 10^{-3})} = 0.072$$
$$T^* = 0.014 \cdot 0.072^{-1.29} = 0.42$$
$$T = \frac{0.1^2}{(9.81 \cdot (2.65-1) \cdot 0.00015^3)^{1/2}} \cdot 0.42 = 564\ s \approx 9.5\ \min.$$

In figure B.3 the time development in test is compared to the empirical expression. From the figure, it is seen that the expected time development is rather different from what is observed in the scale model test.

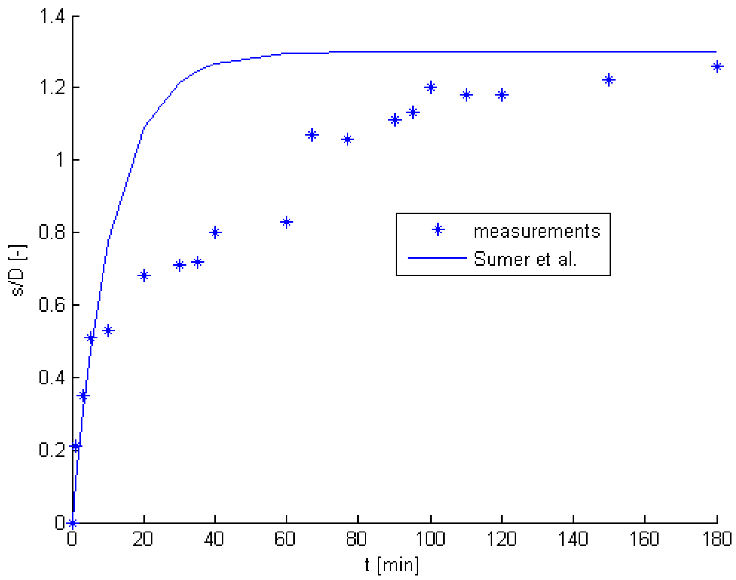


Figure B.3 Measured scour development in Tidal current conditions, U=0,3 m/s and the predicted scour development from existing equations

B.6. Time scale adjustment, δ/D=3

From the scale model tests it is seen that the expression given by Sumer et al. (2002) under-predicts the time scale of the scour process. The time scale T, is defined as the time after which the scour depth has developed to 63 % of the equilibrium scour depth. Whitehouse, (1998). Therefore, an alternative formulation of the time scale is suggested, based on the 3 experiments conducted in this project. In figure B.4 the 3 tests are shown in one figure with indications of the location where 63 % of the equilibrium scour is achieved. The trend lines are added manually for illustrative purposes.

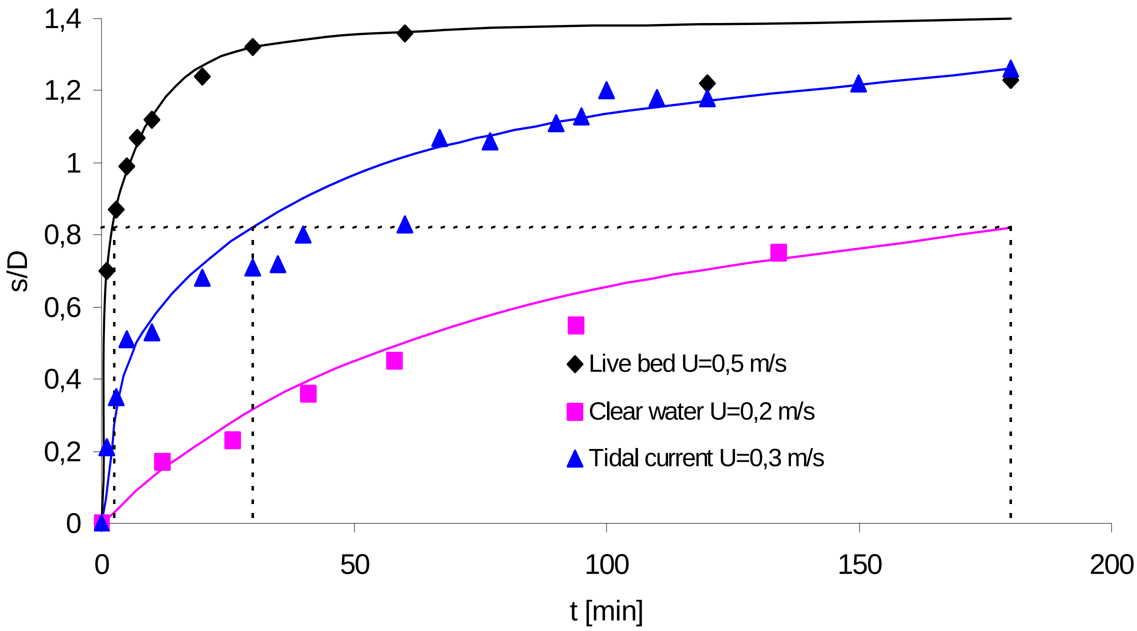


Figure B.4 Results of scour development tests, along with indications of the characteristic time scale T. (dotted lines)

Using 63 % of the equilibrium scour to define the characteristic time scale T, following time scales from figure B.4 are found:

$$T(\theta = 0.2) \approx 2.5\,\text{min}$$
$$T(\theta = 0.072) \approx 30\,\text{min}$$
$$T(\theta = 0.044) \approx 180\,\text{min}$$

Based on the observed time scale T, the dimensionless time scale, T* can be calculated as,

$$T^* = T \cdot \left(g \cdot (s-1) \cdot d_{50}^3\right)^{1/2} \cdot D^{-2}$$

Using above expression gives:

$$T^*(\theta = 0.2) = 0.11$$
$$T^*(\theta = 0.072) = 1.33$$
$$T^*(\theta = 0.044) = 4.35$$

Assuming the time scale for unidirectional and tidal currents are comparable, the results from the lab tests can be added to the results of Sumer et al. (2002), Fredsøe et al. (1992), and Whitehouse, (1993). In figure B.5 the results from the lab tests have been added to the existing results.

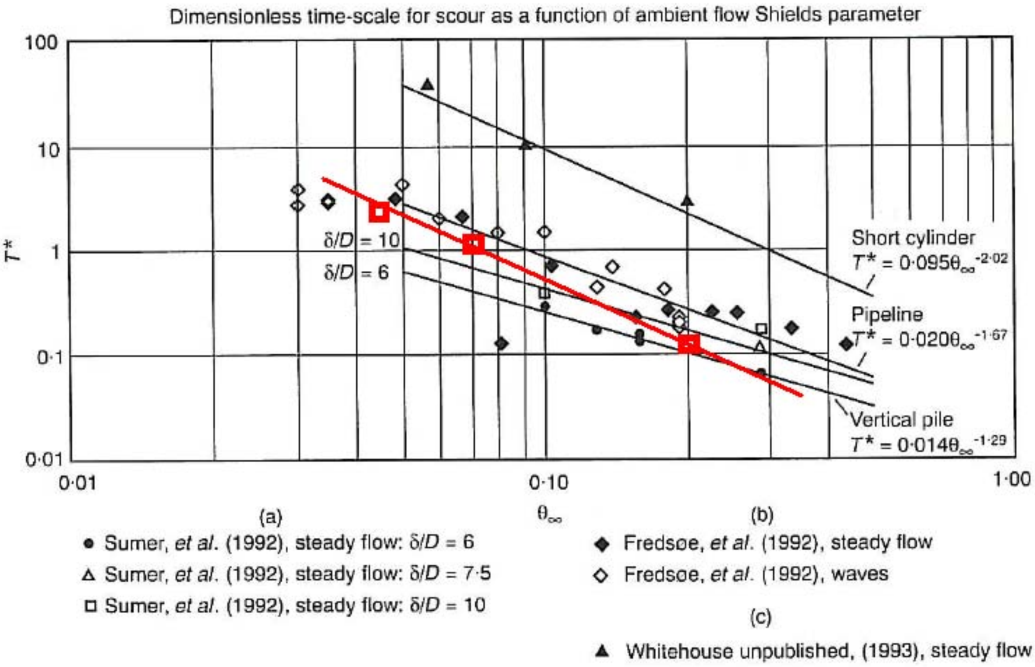


Figure B.5 T obtained from scour test with Live bed, Tidal and Clear water conditions, as a function of Shields parameter (θ) for δ/D=3. Plotted with the results of others.*

From figure B.5 it is noted that there appears to be no significant effect of a tidal current in relation to the time scale of the scour process, since the observed non dimensional time scales are represented by a linear function in the figure. From the figure the dimensionless time scale T* can be estimated for δ/D=3. From the figure, it is seen that the tests conducted in this project predict a larger time scale for the scour process, related to the shields parameter θ. A best fit to the limited data from the scale model test conducted for δ/D=3 reveal following relation for the dimensionless time scale T*, as a function of the shields parameter θ:

$$T^*_{\delta/D=3} = 0.0022 \cdot \theta_\infty^{-2.43}$$

Since only 3 tests have been performed, the formula is obviously associated with some uncertainty, however the existing equation under-predicts the time scale in such a degree that it might be reasonable to use the adjustment for conditions where δ/D≈3. In figure B.6 the modified empirical expression for time development has been inserted in the exponential time development equation, and is presented along with the measurements from the scale model tests.

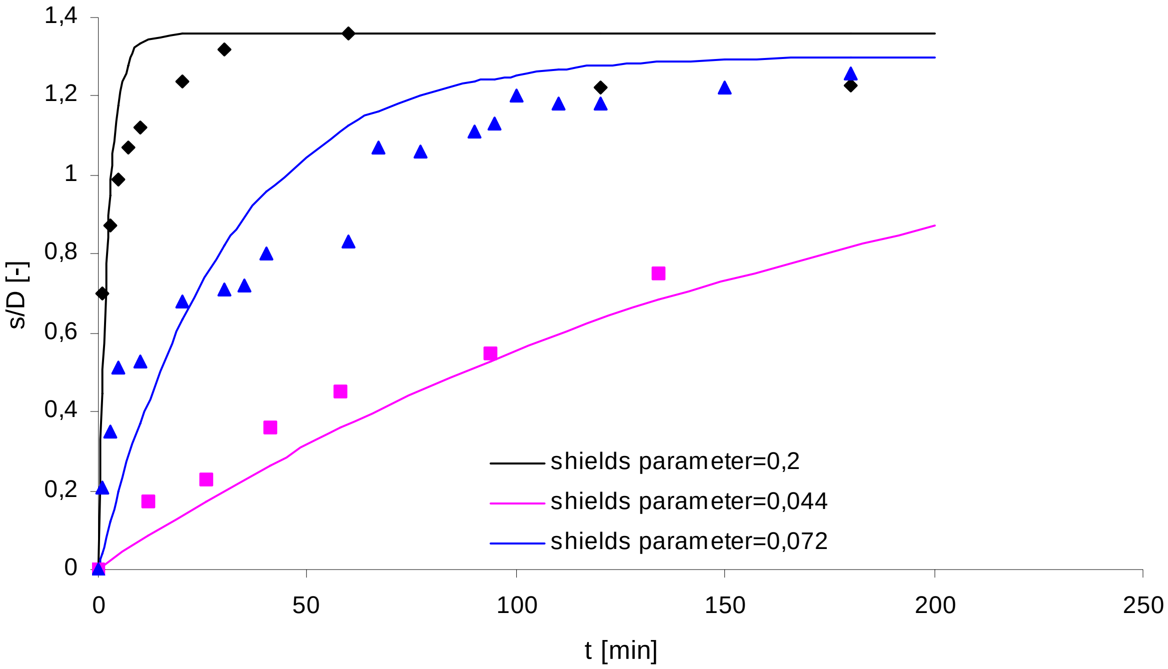


Figure B.6 Test results along with the modified predictive scour development equation for δ/D=3

Based on the scale model tests it is suggested to estimate the non dimensional time scale T*, according to the flow-depth-to-pile-diameter ratio δ/D.

In the deep water case, it is suggested to use the existing formulation,

$$\delta / D \geq 6 \quad \rightarrow \quad T^* = 0.014 \cdot \theta^{-1.29}$$

For shallow water, it could be considered to use the adjustment as a more appropriate formulation,

$$\delta / D \approx 3 \quad \rightarrow \quad T^* = 0.0022 \cdot \theta^{-2.43}$$

Appendix C.
Back filling

To achieve information on the effect and time scale of back filling of scour holes, due to wave motion, a series of initial tests have been performed in the Hydraulic Laboratory, Aalborg University. Back filling was performed in actual scour holes created with currents. This was done to ensure “natural” scour holes. The initial tests with back filling due to wave motion, revealed that the time scale of back filling was comparable to the time scale of scouring. Therefore additional tests were performed at the Hydraulic Laboratory, Gent University Belgium, on back filling of scour holes in a combined current wave climate. An additional test on the equilibrium scour depth for irregular waves was performed to achieve the upper limit of back filling. This test was performed because most of the back filling experiments were stopped before the equilibrium scour depth was achieved, due to the time frame of the experiments. All back filling experiments were conducted with the same irregular wave series, specified in table C.1.

Table C.1 Specifications, irregular wave series, used in all back filling experiments

Wave Specifications	
Wave type	Irregular
Spectrum	JONSWAP
H_s	0,12
T_p	1,64
Peak enh. factor	3,3

C.1. Equilibrium scour depth for irregular waves

A scour test with irregular waves was performed, to give an estimate of the minimum scour depth to be expected in a wave-dominated climate. The approach was to back fill an existing scour hole, and scour a plane bed with an irregular wave series. The concept was to approach the equilibrium from “above”, with back filling, and from “below”, with wave scouring. The outline of the test is seen in table C.2.

Table C.2 Outline, back filling/wave scouring test

Back filling	
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Duration	30 minutes
Initial scour, (s/D)	0,55
Measurement time	
Initial bed	
10 min. waves	
20 min. waves	
30 min. waves	
Wave scouring	
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Duration	10 minutes
Measurement time	
Initial bed	
10 min. waves	

The results from the test are shown in table C.3.

Table C.3 Results from back filling/wave scouring test

Results		
Wave time	s [mm]	s/D [-]
Back filling		
Initial bed	55	0,55
400 waves.	34	0,34
800 waves.	25	0,25
1200 waves.	20	0,2
Wave scouring		
Initial bed	0	0
400 waves.	10	0,10

From the results, it is obvious that the wave-scouring test should have been extended for more than 400 waves. However, it is adequate to indicate the equilibrium scour for the irregular wave series. In figure C.1 the results for the back filling and wave scouring are plotted.

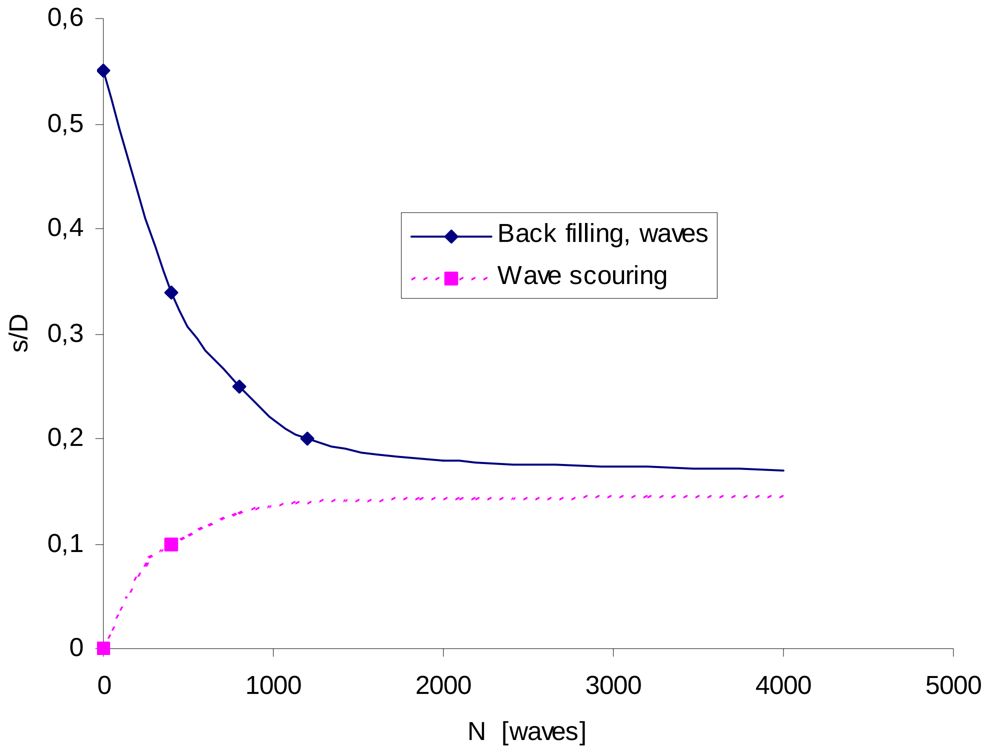


Figure C.1 Back filling and wave-scouring, wave induced equilibrium scour depth

From figure C.1 it is estimated that the equilibrium scour depth for the irregular waves used in test is s/D=0,15. The equilibrium scour depth found in test is compared to the empirical formulation for scour in irregular waves produced by Sumer et al. (2002)

$$\frac{S_{ew}}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot (KC - 6)\right)\right) \text{ for } KC > 6$$

where s_{ew} is the wave equilibrium scour depth. KC is calculated as,

$$KC = \frac{U_m \cdot T_p}{D}$$

U_m is calculated as

$$U_m = \sqrt{2} \cdot \sigma_U$$

$$\sigma_U^2 = \int_0^\infty S(f)\,df$$

In which $S(f)$ is the power spectrum of U_w, and f is the frequency.

In figure C.2 the measured elevation signal and the calculated velocity spectre is shown.

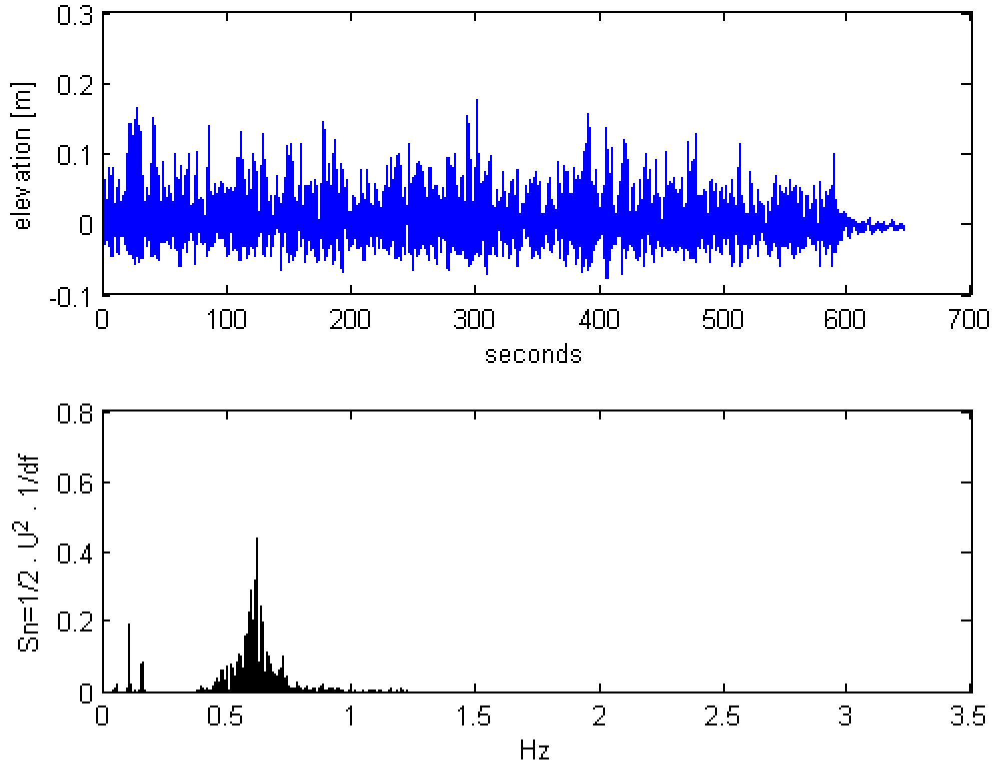


Figure C.2 Recorded elevation signal and calculated velocity spectre, from wave scour test

From the spectre the characteristic orbital velocity at the bed and the peak period are found, and the KC number is calculated:

$$U_m = 0.2 \ m/\sec$$
$$T_p = 1.6 \ \sec$$
$$KC = \frac{0.2 \cdot 1.6}{0.1} = 3.2$$

Using the empirical expression proposed by Sumer et al. (2002), the expected scour depth should be zero. Since the irregular wave series produced some scour it is suggested that the formulation for equilibrium scour in irregular waves is adjusted. Since the irregular wave series is made up of larger and smaller waves, the adjustment for waves with KC<6 is removed from the equation:

$$\frac{S_{ew}}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot KC\right)\right)$$

Using this representation gives following equilibrium scour depth for the irregular wave series used in test:

$$\frac{S_{ew}}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot 3.2\right)\right)$$

$$\frac{S_{ew}}{D} = 0.12$$

This adjustment should be verified by more tests, but since it predicts an upper value of the scour depth, it is considered conservative. Since it is unlikely in a natural environment to observe wave scouring on a flat bed, the adjustment is primarily of interest when estimating the upper limit of back filling.

C.2. Wave induced back filling

To obtain information on the effect of back filling, due to waves, tests have been conducted in the lab. Different scour holes generated by a steady current have been exposed to series of irregular waves, representing typical storms in the North Sea. The effect of the duration of the storm in regard to back filling of the existing scour hole has been examined. Tests have been performed on 2 different bed materials (grain sizes), to monitor the back filling rate as a function of the grain size, d_{50}. In table C.4 the outline of the tests are seen.

Table C.4 Outline of back filling tests, for d_{50}=0,10-0,15mm.

Back filling (d_{50}=0.15mm)	
Water depth	0,3 m.
Grain size (d_{50})	0,15 mm.
Duration	30 minutes
Initial scour, (s/D)	0,7 / 1,07 / 1,32
Measurement time	
Initial bed	
10 min. waves	
20 min. waves	
30 min. waves	
Back filling (d_{50}=0.10mm)	
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Duration	30 minutes
Initial scour, (s/D)	0,55
Measurement time	
Initial bed	
10 min. waves	
20 min. waves	
30 min. waves	

All tests are conducted with the same irregular wave series, and therefore the results can be compared directly. Back filling tests with d_{50}=0,15mm. were conducted in the Hydraulic Laboratory at Aalborg University, and the test with d_{50}=0,10mm. was conducted at the Hydraulic Laboratory at Gent University, Belgium. All of the four tests were conducted with no current. In table C.5 the results from the tests are tabulated

Table C.5 Results of back filling tests

Bed material (d_{50})	**Initial scour**		**Back filling**					
			10 min. waves		20 min. waves		30 min. waves	
	s [mm]	V [m^3]	s [mm]	V [m^3]	s [mm]	V [m^3]	s [mm]	V [m^3]
0,15mm.	70	0,0021	44	0,0015	34	0,0013	32	0,0012
0,15mm.	107	0,0074	93	0,0064	82	0,0057	72	0,0048
0,15mm.	132	0,0134	123	0,0120	107	0,0106	98	0,0099
0,10mm.	55	0,00019	34	0,00013	25	9,5e-5	20	7,5e-5

When calculating the back filling rate (volume rate) a small grid around the scour hole is monitored, and then only the volume of the local scour hole is included. The test conducted with d_{50}=0,10mm. is associated with some uncertainty since the volume of the scour hole is very small. As a result of this, measuring errors effect the volume calculation relatively much compared to the other tests.

C.2.1. Back filling, time-development s/D

In figure C.3 the time-development of the back filling, is shown. Here the measure of back filling is given as the change in scour depth as a function of the number of waves the scour hole has been exposed to. An analysis of the irregular wave series used in test revealed that 10min. of waves equals approximately 400 waves.

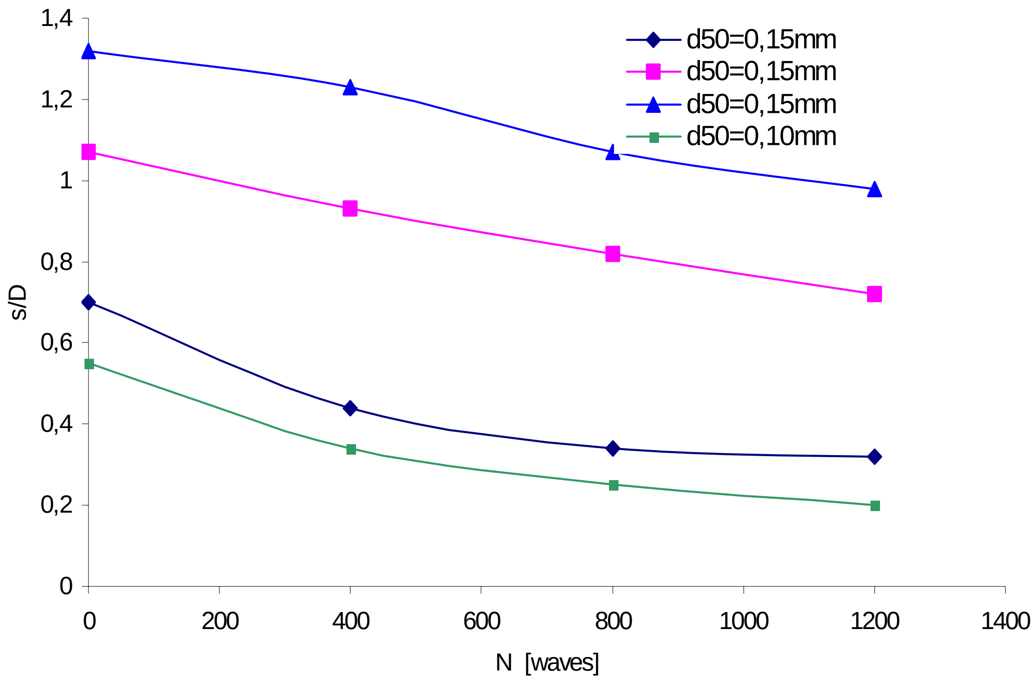


Figure C.3 Decree of current induced scour holes, as a function of number of waves N

From figure C.3 it is seen that the back filling rate is relatively nondependent on the initial scour depth, for large scour holes. The measurements obtained from scale model tests with an initial s/D=0,7 and s/D=0,55 suggest an asymptotic behaviour. This may well indicate that the scour depth is approaching the equilibrium scour depth. From the data, two approaches are possible. Either the back filling is linear or it is described by an exponential function. In the following, both approaches are shown.

C.2.2. Linear representation, s/D

Extending the 4 individual data sets into one time series gives the curve shown in figure C.4. From the figure it appears that a complete back filling due to a storm requires in the range of 4000 waves, assuming the initial s/D=1,3. All remaining scour is expected to be the wave induced equilibrium scour.

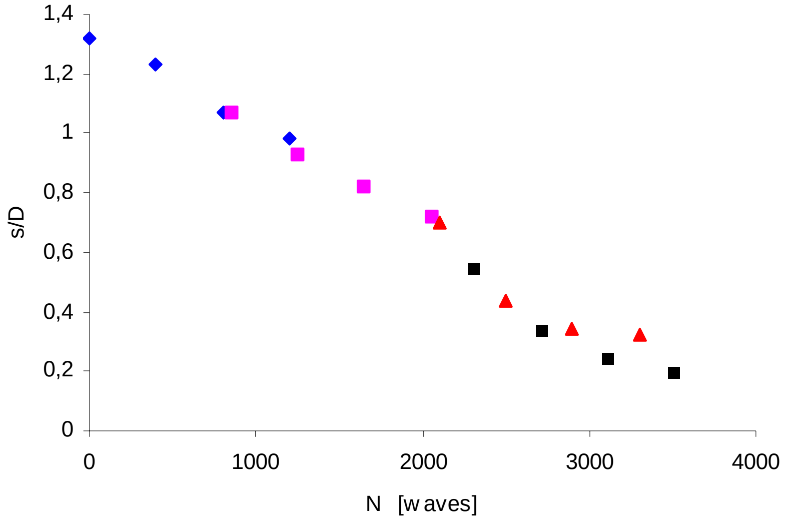


Figure C.4 Linear representation of back filling results

This representation appears to represent the data reasonably, however it is seen from the back filling experiments with s/D={0,55-0,7} that an asymptotic behaviour appears as the scour depth approaches the wave induced equilibrium state. From this observation, it is suggested that an exponential decree of the scour hole provides a better representation for the back filling process.

C.2.3. Exponential representation, s/D

Fitting an exponential function to the test data gives the result shown in figure C.5. From the exponential representation, it is seen that the back filling rate appears to be dependent on the initial scour depth.

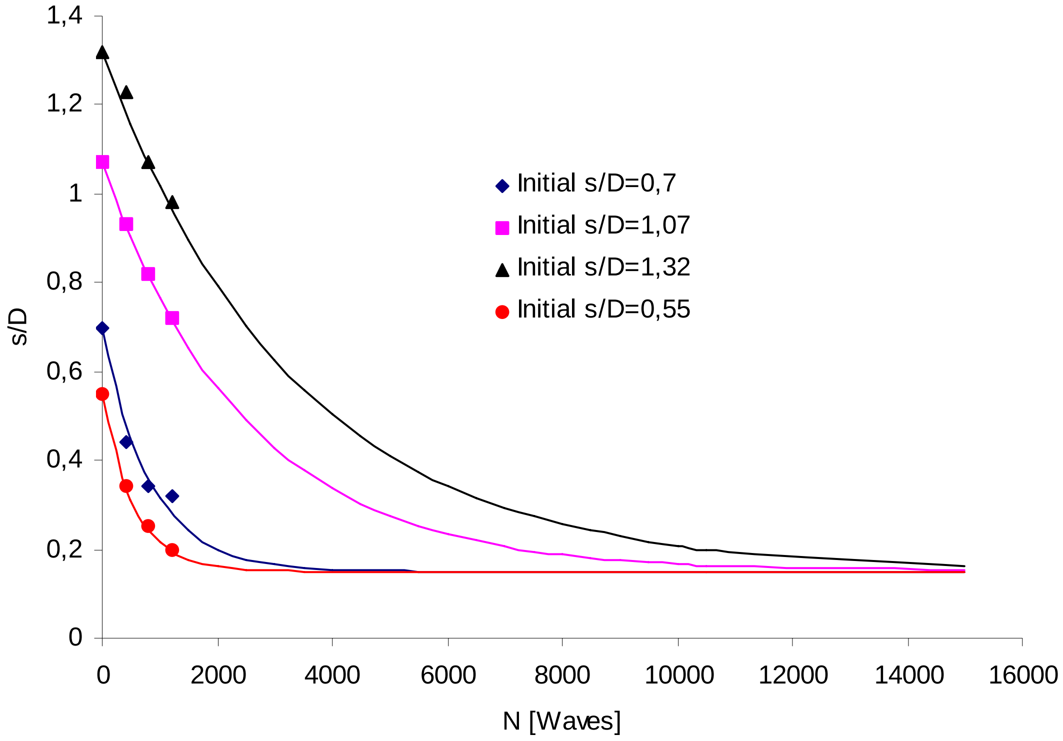


Figure C.5 Exponential representation of the back filling, as a function of the number of waves N

The trend lines added to the test data in figure C.5 are represented by following function:

$$\frac{s}{D}(N) = \left(\frac{s_i - s_{ew}}{D}\right) \cdot \exp(a \cdot N) + \left(\frac{s_{ew}}{D}\right)$$

Here s_i and s_{ew} are the initial, and wave induced equilibrium scour depth, and a, is a parameter dependent on the initial scour depth.

In table C.6 the values of the coefficient a are given.

Table C.6 Coefficient a, for different initial scour depths

Initial scour depth	**a**
s/D=1,32	-0,0003
s/D=1,07	-0,0004
s/D=0,7	-0,0012
s/D=0,55	-0,0018

From table C.6 the relation between the coefficient a, and the initial scour depth s/D can be estimated. In figure C.6 this relation, along with a best fit is shown.

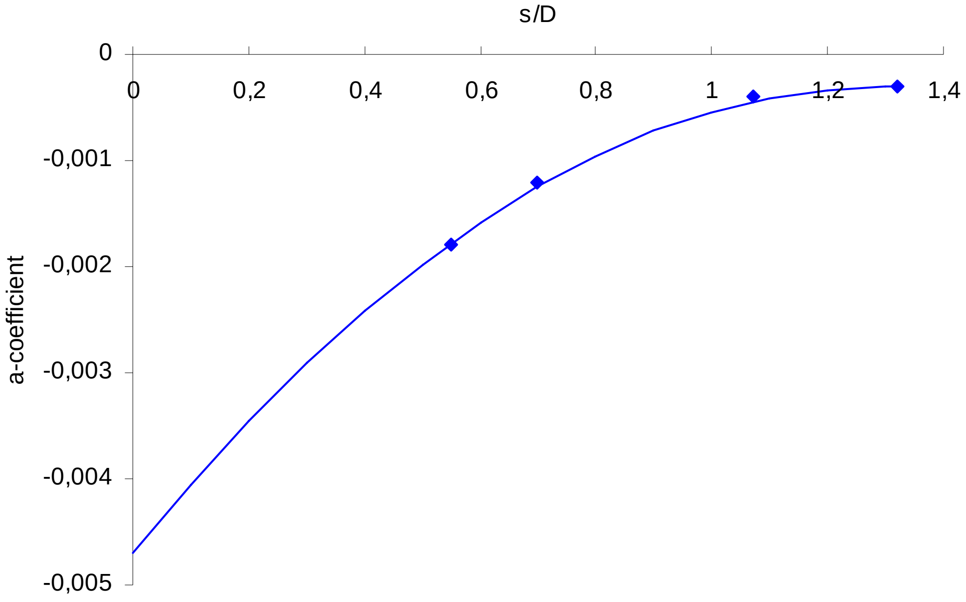


Figure C.6 Relationship between initial scour depth s/D, and coefficient a

From the figure, a line of best fit has been found. The coefficient a, appears to be represented by following expression:

$$a\left(\frac{s}{D}\right) = -0.0026 \cdot \left(\frac{s}{D} - 1.3\right)^2 - 0.00031$$

where s/D is the dimensionless scour depth, and the value 1,3 represents the dimensionless maximum (equilibrium), scour depth.

C.2.4. Back filling volume rate, Volume/D^3

Measuring the back filling as the volume rate gives the relation in figure C.7. Test data from back filling with the finer bed material (d_{50}=0,10mm.) is not included as the volume calculations for this test are of poor quality, due to the reduced measuring frame, when profiling.

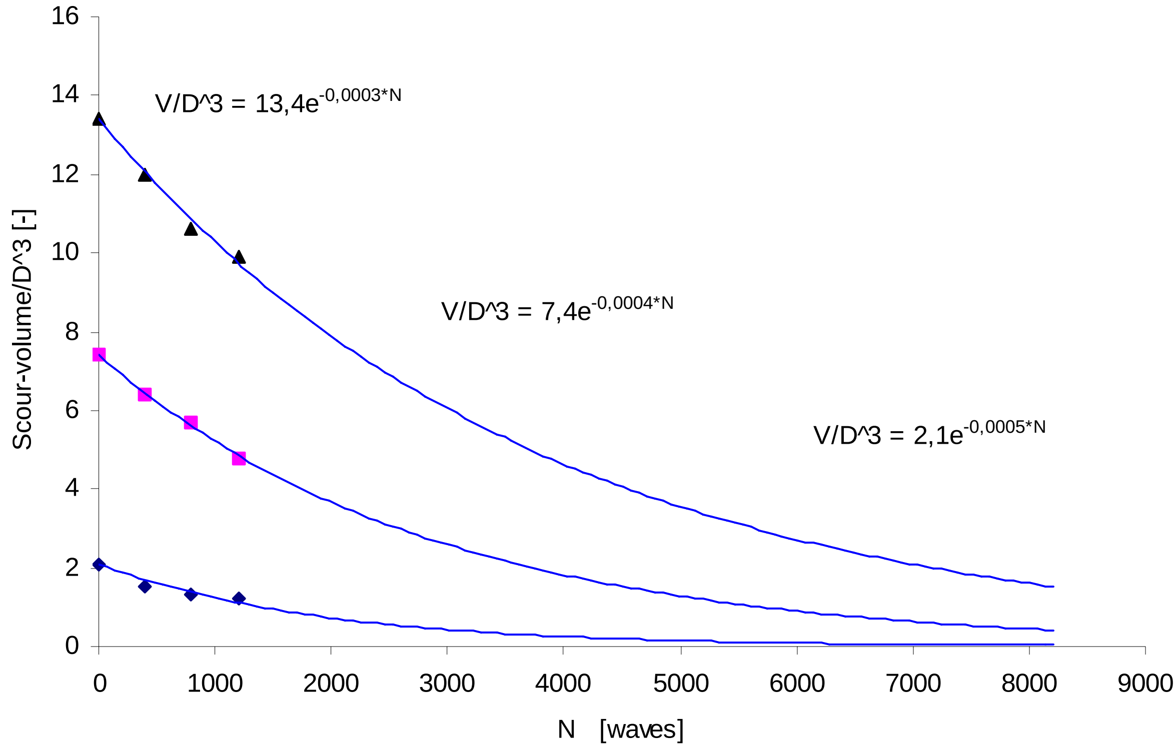


Figure C.7 Back filling of current induced scour holes, represented as the scour volume V/D^3, as a function of the number of waves N

From the figure the backfilling represented as the scour-volume/D^3 rate, appears to be exponentially decreasing as a function of the number of waves applied to the scour hole. The figure also shows that the volume of sediments that settle into the scour hole pr. wave decreases as the depth (volume) of the scour hole decreases. This indicates that the waves stir up more sediment far from the scour hole than in the actual cavity.

Appendix D.
Current-wave scour

To achieve information on the back filling process in a current-wave climate, a series of tests have been conducted on back filling by superimposing irregular waves on the current. The tests were performed in the Hydraulic Laboratory at Gent University, Belgium. The tests were conducted with the same irregular wave series as previous tests. The tests were conducted with two different currents (different shields parameter), to monitor the effect of the current in regard to back filling.

D.1. Back filling, wave-current climate

In table D.1 the outline of the test is seen.

Table D.1 Outline of current-wave scour/back filling test, with different current velocities

Back filling wave-current climate U=0,25 m/s	
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Current	0,25 m/s
Duration	150 minutes
Initial scour, (s/D)	0,85
Measurement time	
Initial bed	
10 min. waves	
20 min. waves	
30 min. waves	
150 min. waves	
Back filling wave-current climate U=0,21 m/s	
Water depth	0,3 m.
Grain size (d_{50})	0,10 mm.
Current	0,21 m/s
Duration	150 minutes
Initial scour, (s/D)	1,0
Measurement time	
Initial bed	
10 min. waves	
20 min. waves	
30 min. waves	
90 min. waves	
150 min. waves	

D.2. Results, wave-current climate

The currents used in test produce a shields parameter θ, approximately 3:2 between the tests. The shields parameters in the two tests are calculated below.

Shields parameter U=0,25 m/s:

$$\bar{U} = 0.25\ m/s$$
$$d_{50} = 0.10\ mm$$
$$h = 0.3\ m$$
$$U_f = \frac{0.25}{2.5 \cdot \left(\ln\left(\frac{30 \cdot 0.3}{2.5 \cdot 0.10 \cdot 10^{-3}} \right) - 1 \right)} = 0.0105\ m/s$$
$$\theta = \frac{0.0105^2}{9.81 \cdot (2.65 - 1) \cdot (0.10 \cdot 10^{-3})} = 0.069$$

Shields parameter U=0,21 m/s:

$$\bar{U} = 0.21\ m/s$$
$$d_{50} = 0.10\ mm$$
$$h = 0.3\ m$$
$$U_f = \frac{0.21}{2.5 \cdot \left(\ln\left(\frac{30 \cdot 0.3}{2.5 \cdot 0.10 \cdot 10^{-3}} \right) - 1 \right)} = 0.0089\ m/s$$
$$\theta = \frac{0.0089^2}{9.81 \cdot (2.65 - 1) \cdot (0.10 \cdot 10^{-3})} = 0.048$$

In table D.2 the results from the tests are shown. Due to a limited measuring grid when profiling, there is no information on the scour volume development.

Table D.2 Results of combined current-wave scour test,
With different current velocities

Results		
Measurement time	s [mm]	s/D [-]
Back filling wave-current climate θ = 0,069		
Initial bed	85	0,85
400 waves.	75	0,75
800 waves.	70	0,70
1200 waves.	0,65	0,65
6000 waves.	52	0,52
Back filling wave-current climate θ = 0,048		
Initial bed	100	1,0
400 waves.	85	0,85
800 waves.	78	0,78
1200 waves.	73	0,73
3600 waves.	60	0,60
6000 waves.	55	0,55

In figure D.1 the results from the test are shown.

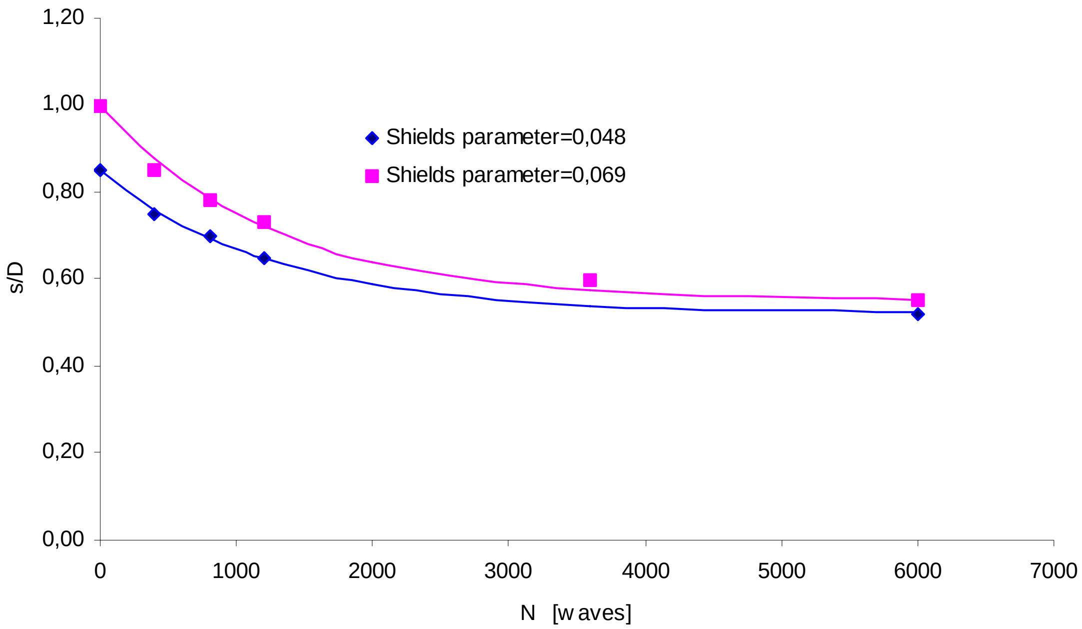


Figure D.1 Equilibrium scour depth for combined current-wave environment

From the figure, it is noted that the time scale of back filling in the wave current climate is approximately the same as that of back filling in waves alone. From this observation, it is suggested that the current only affects the equilibrium scour depth.

In figure D.2 the equilibrium scour depth, found for the wave-current test is shown along with the expression produced by Sumer et al. (2002), for the relation between wave-current climate and equilibrium scour depth.

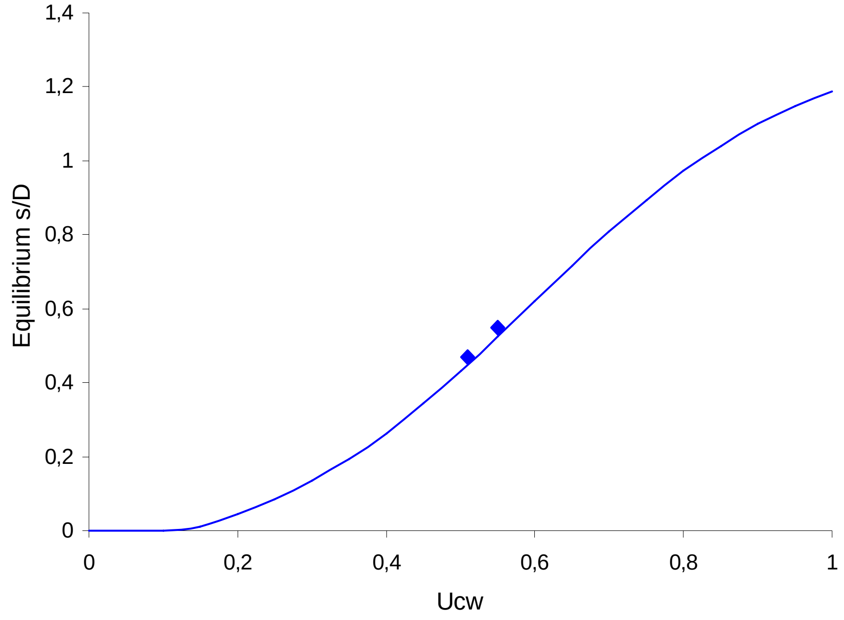


Figure D.2 Equilibrium scour depth for combined current-wave environment, compared to predicted value, proposed by Sumer et al. (2002).

From the figure, it is seen that the results from the test fit to the predicted value. This indicates that the function is valid for irregular waves, when replacing the wave velocity at the bed, U_w with U_m. The trend line shown in figure D.2 is the formulation given by Sumer et al. (2002), with KC=3,2. The function is presented below.

$$\frac{s}{D}(U_{cw}) = \left(\frac{s_c}{D}\right)\left(1 - \exp\left(-A\left(KC - B\right)\right)\right)$$

$$A = 0.03 + \frac{3}{4} \cdot U_{cw}^{2.6}$$

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

$$U_{cw} = \frac{U_c}{U_c + U_m}$$

Here s_c is the equilibrium scour depth in current only, and U_{cw} is the relation between the current and wave velocities at the seabed. The function is valid for KC values around or larger than 4.

Representing the equilibrium scour depth as a function of the current-wave shields parameter relation gives the result shown in figure D.3. This representation was used in search for a similar relation as in the current-wave velocity representation. From the results, no good relations have been found, as seen in figure D.3.

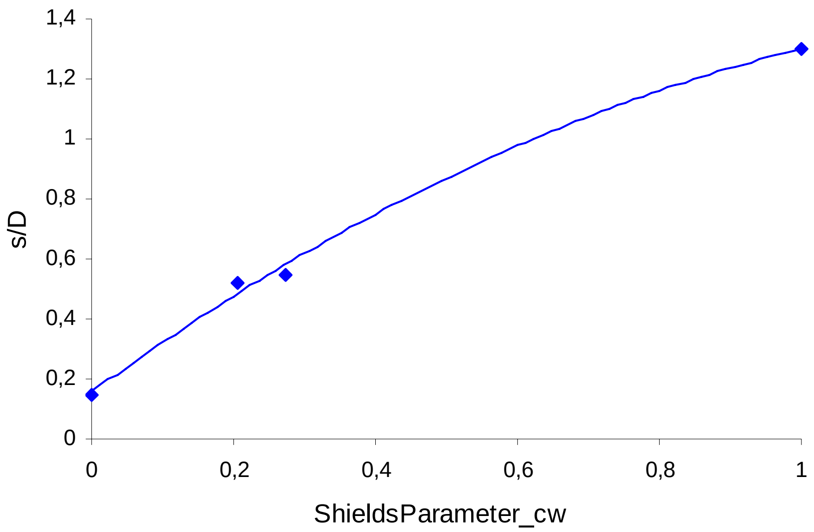


Figure D.3 Equilibrium scour depth, as a function of the current-wave shields parameter θ_{cw}

A best fit to the data gives the relation shown below.

$$\frac{s}{D}(\theta_{cw}) = -0.6\cdot\theta_{cw}^2 + 1.7\cdot\theta_{cw} + \left(\frac{s_w}{D}\right)$$

$$\theta_{cw} = \frac{\theta_c}{\theta_c + \theta_w}$$

Here θ_w is calculated as suggested by Soulsby, (1997)

$$\theta_w = \frac{\frac{f_w}{2}\cdot U_m^2}{g\cdot(s-1)\cdot d_{50}}$$

$$f_w = 1.39\cdot\left(\frac{A}{z_0}\right)^{-0.52}$$

$$A = \frac{U_m\cdot T_p}{2\pi}$$

$$z_0 = \frac{2.5\cdot d_{50}}{30}$$

where f_w is the dimensionless wave friction factor, and z_0 is the hydraulic roughness length.

Appendix E.
Scour model

Based on the results from the scale model test on scour development and back filling a time stepping model for prediction of scour in a current-wave climate has been produced. From the experiments conducted in the laboratory at Aalborg University and Gent University, a series of functions, for prediction of scour development in a current-wave climate has been produced.

E.1. Scour development in tidal currents

From the data made available to this project from the Horns Rev offshore wind farm, it is clear that the currents on site are of a wind induced and tidal nature. As a consequence of this environment the current constantly changes direction, not only “back and forth” as in a tidal environment, but at a random angle, due to the effect of the wind direction.

Based on the results from the scour development tests (Appendix B.), it is found that the effect of a reversing current is relatively limited in regard to the time scale of the scour process. The equilibrium scour depth in a tidal current also appears to be uninfluenced. Based on this observation, the time stepping scour model produced in this project, contains no adjustment for the time scale of scour due to changing current direction. This is considered to be a conservative approach.

E.2. Equilibrium scour depth, Irregular waves

Based on the results from the wave scour tests with irregular waves (Appendix C.), it has been shown that scour does appear for wave series where $KC<6$. A value of $KC<6$ is known to be the limit for scour in linear waves. The result of the test is not particularly important for scour due to waves, as the equilibrium scour is relatively small. However, it is very important in regard to back filling since it defines the upper limit of back filling. Consequently, the mean scour depth is increased by adjusting the equilibrium back filling depth in irregular waves.

E.3. Back filling, Irregular waves

From the tests conducted on back filling of scour holes due to waves (Appendix C.), it is seen that back filling does take place, and that the time scale of back filling is comparable to that of scour development. The back filling tests conducted for equilibrium scour depth in a current-wave environment show that superimposing waves on a current reduces the equilibrium scour depth. From this observation, it is believed that the back filling is related to the ability of the waves to transport sediment into the scour region.

E.4. The time stepping scour model

In the following a description of the produced scour model is given. The model uses a time stepping approach with an update frequency, f_{update} equal to a scour update every $\Delta t=1/f_{update}$. The inputs to the model are the recorded wave parameters, the current velocity and the water height variation, measured on site. Apart from the conditional input, the model contains parameters representing the bed material (d_{50}), and the water depth (h). As the model Steps trough time it updates the scour depth s/D, according to the environmental inputs; wave activity, water depth and current velocity.

E.4.1. Scour development

The scour development in one time step is calculated by following equation, presented by Whitehouse, (1998)

$$\frac{s(t+\Delta t)}{D}=\left(\frac{s(t)}{D}\right)+\left(\frac{s_e-s(t)}{D}\right)\cdot T^{-1}\cdot\Delta t$$

where s(t) is the scour at the beginning of the time step and s_e is the equilibrium scour depth. The scour depth calculated with this equation gives the same result as the model proposed by Sumer et al. (2002), (shown below), when Δt is relatively small, compared to the time scale of the scour process T.

$$\frac{s(t)}{D}=\frac{s_e}{D}\cdot\left(1-\exp\left(-\frac{t}{T}\right)\right)$$

where $s(t)$ is the scour at the time t. The timescale of the scour process for each time step Δt, is calculated as:

$$T=\frac{D^2}{(g\cdot(s-1)\cdot d_{50}^3)^{1/2}}\cdot T*$$

where the non dimensional timescale T* is calculated as:

$$T^*=\frac{1}{2000}\cdot\frac{\delta}{D}\cdot\theta^{-2.2}$$

This representation for T* proposed by Sumer et al. (2002), is used as it contains an adjustment for the flow depth to pile diameter δ/D. The shields parameter θ is calculated for each time step from following formula suggested by Soulsby, (1997),

$$\theta=\frac{U_f^2}{g\cdot(s-1)\cdot d_{50}}$$

where s is the specific gravity of the bed material. The bed friction velocity, U_f is calculated as,

$$U_f = \frac{\bar{U}}{2.5 \cdot \left(\ln\left(\frac{30 \cdot h}{k_s} \right) - 1 \right)}$$

in which k_s is calculated as $2.5 d_{50}$ and $\bar{U}$ is the mean current during the time step. This method is also taken from Soulsby, (1997).

E.4.2. Back filling

The change in scour depth due to back filling in one time step is calculated according to the function established from the back filling experiments:

$$\frac{s(t+\Delta t)}{D} = \beta \cdot \left(\frac{s(t) - s_{ew}}{D} \right) \cdot \exp\left(a \cdot N(\Delta t) \right) + \left(\frac{s_{ew}}{D} \right)$$

Here $s_i(t)$ and s_{ew} are the initial, and wave induced equilibrium scour depth, and a, is a parameter dependent on the initial scour depth. β is a coefficient scaling the back filling rate from the laboratory tests to the case data. The parameter a, is calculated as:

$$a\left(\frac{s(t)}{D} \right) = -0.0026 \cdot \left(\left(\frac{s(t)}{D} \right) - 1.3 \right)^2 - 0.00031$$

where the value 1,3 represents the dimensionless maximum (equilibrium), scour depth. $N(\Delta t)$ is the number of waves during one time step, calculated as

$$N(\Delta t) = \frac{1.2 \cdot \Delta t}{T_p}$$

The wave induced equilibrium scour depth is calculated from the adjustment made for irregular waves (Appendix C.),

$$\frac{s_{ew}}{D} = 1.3 \cdot \left(1 - \exp\left(-0.03 \cdot KC \right) \right)$$

where KC is calculated as

$$KC = \frac{U_m \cdot T_p}{D}$$

U_m is calculated as

$$U_m = \sqrt{2} \cdot \sigma_U$$
$$\sigma_U^2 = \int_0^\infty S(f)\,df$$

In which $S(f)$ is the power spectrum of U_w, and f is the frequency.

As it is believed that the back filling is related to the ability of the waves to transport sediments, the coefficient β is calculated as the wave shields parameter relationship from scale model tests to the case data.

$$\beta = \frac{\theta_{\text{w-Case study}}}{\theta_{\text{w-Scale-model}}}$$

Since all back filling tests were conducted with the same irregular wave series, this relationship is unsupported by data. It is noted that this relationship greatly simplifies the scaling from model to case study, as θ_w is not dependent on the scale, when calculated.

θ_w is calculated as suggested by Soulsby, (1997),

$$\theta_w = \frac{\frac{f_w}{2} \cdot U_m^2}{g \cdot (s-1) \cdot d_{50}}$$
$$f_w = 1.39 \cdot \left(\frac{A}{z_0}\right)^{-0.52}$$
$$A = \frac{U_m \cdot T_p}{2\pi}$$
$$z_0 = \frac{2.5 \cdot d_{50}}{30}$$

where f_w is the dimensionless wave friction factor, and z_0 is the hydraulic roughness length.

E.4.3. Scour update

Based on the scour development and back filling in one time step the model updates the scour depth at the end of the time step. The scour development and the back filling, use the same initial scour depth as input, and as a result of this the change in scour depth at the end of the time step is calculated as

$$\frac{s\left(t+\Delta t\right)}{D}=\underbrace{\left(\frac{s(t)}{D}\right)+\left(\frac{s_e-s(t)}{D}\right)\cdot T^{-1}\cdot\Delta t}_{\text{Scour}}-\underbrace{\beta\cdot\left(\left(\frac{s(t)}{D}\right)-\left(\left(\frac{s(t)-s_{ew}}{D}\right)\cdot\exp\left(a\cdot N(\Delta t)\right)+\left(\frac{s_{ew}}{D}\right)\right)\right)}_{\text{Back filling}}$$

$$\frac{s\left(t+\Delta t\right)}{D}=\left(\frac{s(t)}{D}\right)+\left(\frac{s_e-s(t)}{D}\right)\cdot T^{-1}\cdot\Delta t-\beta\cdot\left(\left(\frac{s(t)-s_{ew}}{D}\right)\cdot\left(1-\exp\left(a\cdot N(\Delta t)\right)\right)\right)$$

For the next time step, the routine is repeated. The initial scour depth is then the result of the previous scour depth calculation.

E.4.4. Discussion of the model

The model utilizes the ratio of wave-shields parameter θ_w to scale the effect of back filling from experiment to case study. Since no tests were conducted to support this relation, a further study of the relation between wave activity and back filling rate would be appreciable. However, it is noted that when scaling the back filling relative to the wave-shields parameter, the sediment grain size d_{50} becomes unimportant in regard to the time variation of the scour depth. In other words, the time scale of back filling and scour development is affected equally. This observation from changing the grain size within the model, supports the concept of back filling being related to the ability to transport sediments. The model has been tested against the results from the equilibrium scour tests for current-wave conditions, (Appendix D.) From the model test it is seen that there is good comparison between the measured equilibrium scour and the calculated result. In figure E.1 the measurements and model results are plotted. The input to the model is listed below.

$$\bar{U} = 0.25 m/s$$
$$d_{50} = 0.1 mm$$
$$h = 0.3 m$$
$$H_s = 0.12 m$$
$$T_p = 1.64 s$$

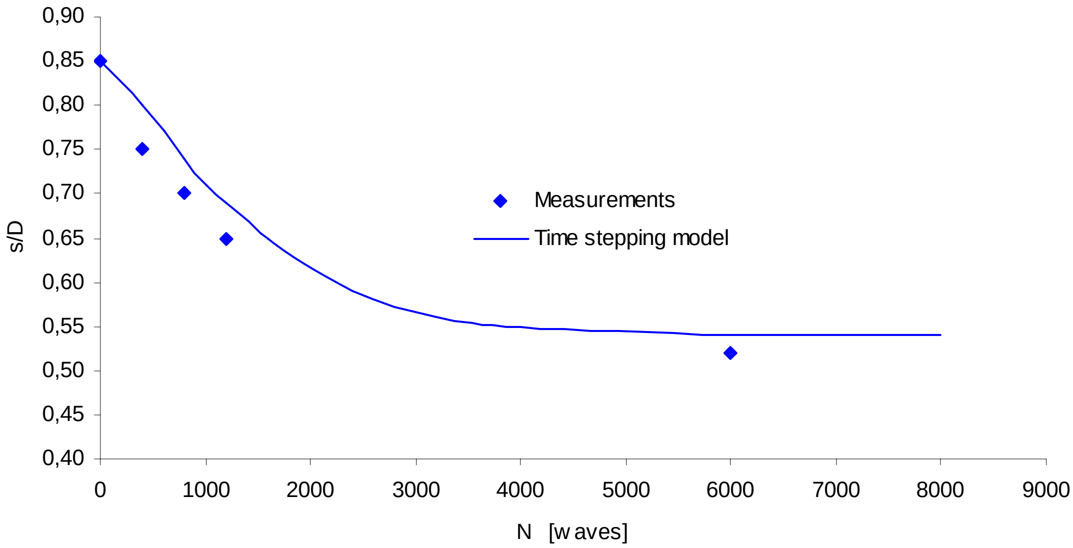


Figure E.1 Comparison between the measured scour development for combined current-wave test, and the development for equal conditions in the scour model

From the figure, it is concluded that the scour and back filling can be modeled separately, and superimposed. This is a very important result in regard to the time variation of the scour process. From the result it is also concluded that the scour- and back filling-process apparently do not affect each other. From the figure, it is seen that the model underestimates the decree of the scour hole, suggesting from the limited data, that the model is conservative in regard to the back filling rate.

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