Final report

1.1 Project details

Project title	Management of seabed and wind farm interaction
Project identification (program abbrev. and file)	12068
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	DHI, Agern Allé 5, 2970 Hørsholm
Project partners	DTU-MEK
CVR (central business register)	DK37057819
Date for submission	30 April 2018

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1.2 Short description of project objective and results

The project aim was to improve the long-term management of scour around offshore wind turbines in terms of costs and environmental impact.

The objectives of the project were three folded: (a) an improved method for predicting long-term scour around monopiles, (b) improved understanding of the mechanics of scour protections, and (c) better modelling of the interaction between offshore wind farms and large-scale morphology.

The improved methods for predicting long-term scour will lead to more foundations to be installed without scour protection saving the associated costs. Effect of waves have been included in a reliable CFD-based model for long-term scour prediction as well as the effect of bed stracification.

The understanding of the mechanisms of scour protections has been improved. The findings can be used for cheaper and more effective designs of scour protections

The numerical model of the interaction between offshore wind farms and sand banks will make it possible to improve layouts of wind farms and prevent possible negative impacts by the wind farm.

Dansk:

Projektets mål var at forbedre langtidsmanagement af erosion omkring havvindmøller både hvad angår økonomiske omkostninger og miljøbelastning.

Projektet havde tre hovedmål: (1) en forbedret metode til forudsigelse af langtids erosion omkring monopæle, (2) forbedret forståelse af mekanismerne for erosionsbeskyttelse og (3) bedre modellering af samspillet mellem offshore havmøller og storskala morfologi.

De forbedrede metoder til bestemmelse af langtids erosion vil føre til opstilling af flere havvindmøller uden erosionsbeskyttelse med dertil hørende besparelser. Effekten af bølger er blevet inkluderet i en pålidelig CFD-baseret model til forudsigelsen af langtidsudviklingen af erosion såvel som effekten af lagdeligen af havbunden.

Den numeriske model af samspillet mellem havvindmølleparker og sandbanker vil gøre det muligt at forbedre placeringen af parkerne og undgå negative effekter fra parkerne.

1.3 Executive summary

The overall aim for the project was to improve long-term management of scour around offshore wind turbines. This improved scour management will lead to the implementation of LCOE (Leverised Costs Of Energy).

The project consisted of three parts: (1) an improved method for predicting long-term scour around monopiles, (2) improved understanding of the mechanics of scour protections, and (3) better modelling of the interaction between offshore wind farms and large-scale morphology.

The prediction of long-term development scour (weeks, months, years) is important when the scour mitigation strategy has to be decided. Scour in the marine environment is a highly complex process, where cycles of scouring and back-filling of the scour hole appear with the ever-changing sea state. Extreme scour found in physical model tests are often highly conservative, but more realistic scour depth cannot be deducted from usual extreme design conditions due to the cyclic behaviour of the process and the fact that extreme wave conditions may result in little scour, while dayly tides may eventually cause the maximum scour. To overcome this, a time-dependent method is needed. A standard CFD (Computation Fluid Dynamics) model will be far too time-consuming, so a simple CFD model is used to calculate a number of standard cases then feeded into a simple time-step model. This makes it possible to do fast and accurate calculations of the scour development over time. The method could also be applied to operational conditions like prediction of scour around the legs of an installation vessel over the coming days.

Although considerable efforts have been put into improving the understanding and modelling capabilities of scour development around unprotected foundations, and in turn substantiating the viable option of reducing the installation with scour protection at the seabed, it is still in many cases key to install scour protections. The latter a design choice, which often relies on either reducing the needed driving depth of the monopiles or limiting the effect of the developing scour on the frequency response of the foundation structures.

The design of scour protections is undergoing major changes from massive fully stable and static rock structures to much smaller and more adaptive and dynamic rock structures. The project has provided a substantiate amount of new knowledge on the topic, both in terms of design diagrams and knowledge of the processes stabilising and destabilising a scour protection. This knowledge can be used to generate new designs and optimise traditional scour protections and minimise risk of damage and failure to the scour protection over the lifetime of the structure, and even provide more durable and less costly scour protections.

A numerical model of migration of sand banks and the interaction between offshore wind farms and sand banks have been developed. The numerical model can provide knowledge on the stability of sand banks, e.g. size, shape, migration speed and direction. Knowledge of the stability of the sand banks is important when designing offshore wind farms on a sand bank as large changes in the sand bank within the life time of the wind farm may threaten the integrity of the wind farm. Interaction between the wind farm and the sand bank may also threaten the intregrity of the wind farm and cause undicided effects on the surrounding environment.

1.4 Project objectives

As described in Section 1.2, the project had three focus areas named work scopes A, B and C.

Work scope A focused on computational modelling of scour around piles in waves and combined waves and current. The aim was to develop a simplified method for calculating the time-varying scour around monopiles exposed to waves and combined waves and current. The time variation was calculated using a simple and fast time-step model with input from more advanced CFD (Computational Fluid Dynamic) models.

Work scope B was related to scour protections and involved both physical and numerical model tests as well as studies of field data. The research focused on detailed understanding of the three common dynamic responses of scour protection:

1. Armour stone stability
2. Sinking/winnowing failure
3. Edge scour

and incorporating this knowldge and results into concrete design diagrams. The planned physical model tests included tests of the sinking of scour protections around monopiles in the case of waves, and combined waves and current as well as the model tests quantifing the onset of this sinking.

Based on the response from the advisory board, some additional physical model tests were added:

- Stability of cover stones around a monopile
- Stability of a single-graded scour protection

Stability of cover stones in scour protections has long been an issue for discussion. It is – at a first glance – an easy task to determine the stability of the rocks with known hydrodynamic conditions, but the effect of the sudden change in roughness from the surrounding seabed to the scour protection and the amplification of the flow primarily due to the pile make the task difficult; often ending up in loops leading to far too large or small stones. The study provides guideline diagrams for the design of scour protections based on new results and results from the literature.

The study of single-layered scour protections was a response to the ongoing trend of installing scour protections consisting of only one stone material through the entire thickness of the scour protection rather than the traditional scour protection of two layers – filter and cover layer. The study provided in-depth knowledge on the mechanisms and dynamic behaviour of the single-layered scour protections. During the execution of these tests, a photogrammetry method for high-resolution and 3D (three-dimensional) monitoring (time and space) of changes in the scour protection and surrounding bed level was developed and validated.

As part of work scope B, numerical simulations of scour protections have been carried out. The work has resulted in very detailed models of the flow in scour protections. The CFD models provided detailed knowledge on the pattern in the scour protection that has not been resolved before. These phenomena related to removal of sediment have previously been observed in physical model tests, but not fully explained. The developed methods are very computational demanding and cannot be directly used for design and verification purpose, but they can be an important tool to understand detailed processes in the scour protection; knowledge that can be used to optimise in the design process.

Work scope C was related to large bed forms and their interaction with offshore wind farms. The scope was to develop a numerical model to correctly simulate the migration of large bedforms.

1.4.1 Implementation of the project

The project has overall reached its objective. However, there have been some delays and changes during the implementation. The completion of the project was delayed by one year, mainly due to malfunctioning wavemaker during model testing, the high effort of getting access to suitable filed surveys of scour protections, and the fact that it was more difficult to find relevant candidates for the Ph.D.-positions than first expected.

In relation to the individual work scopes, the delays and issues can be detailed as described below.

During the implementation of work scope A, some unexpected problems in relation to setting up the CFD models and programs were to solved. This caused delays of the milestones related to this work scope. However, at the end of the project, CFD models are working, and current and waves results are ready.

Work scope B experienced a number of delays and a change in the objectives. The physical model tests were delayed a year due to delay of renovation of the facility. This did not influence the outcome of the project.

It was originally planed to develop a database of field survey data of scour protections as part of work scope B. This would have been a great support in the effort of improving scour protections, but scour protection design is seen more and more as a key component in the competition of the offshore wind market, and it is therefore extremely difficult to get access to under conditions suitable for the project. DHI have put a lot of effort in achieving field data during the project and some have been obtained. However, most of the data was of too poor quality or provided with restrictions that made it impossible to follow the original plan. Nevertheless, data from Horns Rev 1 Offshore Wind Farm has been available for the project and used as a reference case, but it does not contain enough data to develop a meaningfull database.

The work related to this work scope C was carried out by a Ph.D.-student, who was employed later than originally expected. This caused a general delay of the entire work scope, but it did not cause problems related to the execution and quality of the work. After the employment of the Ph.D.-student Jonatan Magalit and following start of the work, the progress has overall followed the plan. The main supervisior associated professor Jacob Hjelmager resigned from DTU during the project and associated professor David Fuhrmann took over as main supervisor. This change has not impacted the outcome of the workscope.

1.5 Project results and dissemination of results

One of the key points in the project has been to improve the knowledge on the dynamic behaviour of scour protections. A better understanding of the mechanisms is a necessity for a systematic improvement of the design. The project has focused on scour protections made of rock dump – the most common type. Three different failure modes are observed for these scour protections when applied in the marine environment:

(1) instability of cover stones due to hydrodynamic loading

(2) subsidence of the scour protection into the seabed due to suction removal of the base sediment through the voids of the stone material

(3) the loss of stones at the periphery of the scour protection caused by formation of edge scour.

This project has focused on the first and the second of these failure modes.

Scour protections based on rock dump have been used extensively over decades, and given this fact, surprisingly little published research has been done on this topic. The first attempts to describe the mechanisms of scour protections were related to river hydraulics, primarily bridge piers in rivers. These studies include Chiew (1995), Hoffmans and Verheij (1997), and May et al. (2012). Other studies have included the effects of the marine environment: Chiew and Lim (2000), Lauchlan and Melville (2001), De Vos et al. (2011 and 2012), Nielsen et al. (2011, 2013), Sumer and Nielsen (2013), Petersen et al. (2014) and Petersen et al. (2015). These studies describe many of the mechanisms causing damage to the scour protections, but some mechanisms – especially in relation to the flow in the scour protection – were not fully described in the before-mentioned studies.

This project has added important knowledge about the mechanisms of scour protections, which has not been publicly available before:

- Description of the mechanism of sinking of the scour protection adjacent to a monopile exposed to waves
- Description of the stability of the sediment beneath a scour protection around a monopile exposed to waves and combined waves and current
- Description of the removal of cover stones and an easy-to-use method to determine a minimum stable size
- Description of the mechanisms related to a single-graded scour protection

These results, together with data from the literature, have been used to:

- Explain the sinking of the scour protections installed at Horns Rev 1 Offshore Wind Farm
- Develop a stochastic model for predicting the stability of a scour protection around a monopile with respect to the three before-mentioned failure modes.

Furthermore, a photogrammetry system for measuring changes in the scour protections and surrounding seabed with a high spatial and temporal resolution has been tested as part of the project. The system has been proved very useful during the tests related to the single-graded scour protections.

1.4.2 Scour Calculator

The scour protection model is based on the lookup of tables populate with rates of scour for various depths of a scour hole, under various flow conditions (boundary layer thickness, Shields parameter and KC number). The tables can be utilised to provide long-term prediction of the evolution of a scour hole, helping to determine the need for scour protection at a particular site offshore. The scour rates are calculated by CFD calculation of the bed and suspended load sediment transport on fixed bed geometries around a monopile structure. The shapes of the hole vary in size and are idealised by a frustrum shape, with the sides angled at the angle of internal friction of the sediment. The method was implemented in the open-source CFD code OpenFOAM. Calculations were conducted on current and waves to demonstrate the feasibility of the method.

Further to this, a novel method to iterate to an equilibrium scour hole was explored. The method formulates the scour problem as an optimisation problem and iterates to an equilibrium hole. This method is complementary to the scour protection calculator as it can be applied to make better estimations of the shape of a scour hole, as opposed to using a simple frustum. The method could be applied to structures placed on a sandy bed, which have not been studied by experiments or resource-intensive fully-morphological CFD calculations. Details of this work can be found in Mandviwalla (2018).

1.4.3 Detailed Numerical Modelling of Protection Layers

This work explored the use of Large Eddy Simulation (LES) modelling coupled with the Discrete Element Method (DEM) to model the dynamics of turbulent eddies and their interaction with sediment particles. The work highlighted the mechanisms of sediment suspension from a flatbed as well as between armour layers in turbulent flows. Such detailed models showed potential in highlighting physical mechanisms as well as helping to build more practically less detailed engineering models. Details can be found in Mandviwalla (2018).

1.4.4 Sinking of a scour protection adjacent to a monopile exposed to waves and current

Previously, Nielsen et al. (2011 and 2013) described the mechanisms of sinking of scour protections around monopiles exposed to a current. A similar description in the case of waves and combined waves and current was on the other hand not available. This topic was investigated as part of the project in an attempt to improve the knowledge. A series of physical model tests was initiated, and both mechanisms were studied both qualitatively and quantitatively. The results were surprising as they unveiled that a larger scour protection was likely to cause larger sinking compared to a smaller scour protection. The reason for this phenomenon was found to be closely linked to the two basic scour mechanisms:

- Scour/removal of sediment from the scour hole
- Infilling and backfilling of sediment from the surrounding seabed to the scour hole

Both phenomena will practically take place at the same time. The relative magnitude of the two processes will then determine whether the scour hole will grow, shrink or remain stable, see Sumer et al. (2013). A similar process will take place when a scour protection is installed, but the tests showed that the scour protection – at least at the initial state – prevented the infilling of sediment better than the scouring of sediment. The reason for this is that the flow inside the scour protection is controlled by the pressure gradient, which is increased by the presence of the pile allowing mobilisation of sediment adjacent to the pile. Opposite, at the edge of the scour protection, away from the pile, there is no amplification of the flow, and consequently the flow in the scour protection is weaker. This made it possible to have a significant suction of sediment through the scour protection adjacent to the pile, while sediment transported into the scour protection is trapped at the edge; however, after a while, the pores at the edge of the scour protection filled and inflow of sediment could again reach the pile. An illustration of the erosion and deposition of sediment adjacent to the pile over time is shown in Figure 1. The effect is clearly seen; the maximum erosion level – and consequently maximum sinking – is reached already around 120 s. After this, in-filling of sediment dominates and can even reach the top of the cover stones at some locations.

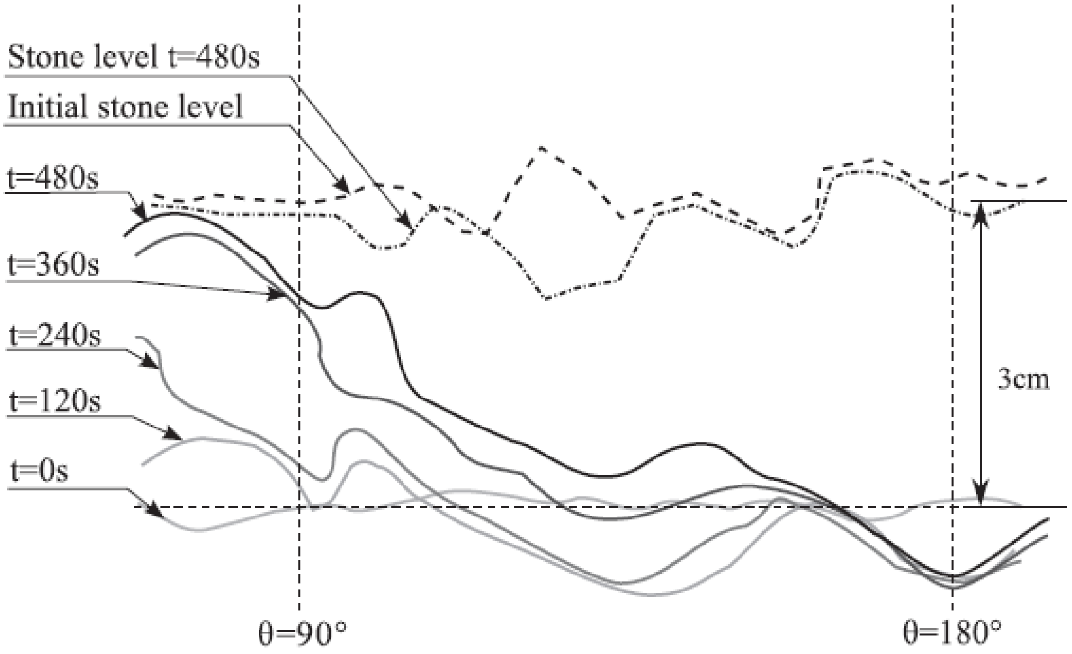

Figure 1 The development of the sediment level adjacent to the pile inside the scour protection, Nielsen et al. (2015).

The study also produced two design diagrams for estimation of the sinking of scour protections in waves and combined waves and current.

Figure 2 shows the situation in the case of waves alone. The diagram looks confusing at the first sight, but can be explained based on the mechanisms described above. Firstly, a thin scour protection marked by small circles causes the smallest sinking at least for KC (Keulegan-Carpenter) numbers less than 15. For thicker scour protections, the sinking is independent of the thickness in the tested intervals, but as observed in the figure, there is a strong dependency on the KC-number. This sudden decrease in the sinking is found to be associated with the horizontal extension of the scour protection relative to the pile diameter. In the present experiments, this ratio was kept constant at 4, and for this ratio, a pile KC-number of around 6 corresponds to a nearbed horizontal wave motion amplitude of the distance from the edge of the scour protection to the edge of the pile. In other words, the decrease in sinking for thicker scour protections is related to the KC-number, and the ratio between the horizontal extension of the scour protection and the pile diameter and the position of the decrease may for this reason change position depending on the pile to scour protection ratio. It is, however, not in any case recommended to take this decrease into account for design purpose.

It should also be noted that an increase in the sinking in the case of a thin scour protection will take place for KC-numbers larger than 15. A single point at around KC=17 indicates that this increase will take place for a KC-number around 15 to 20.

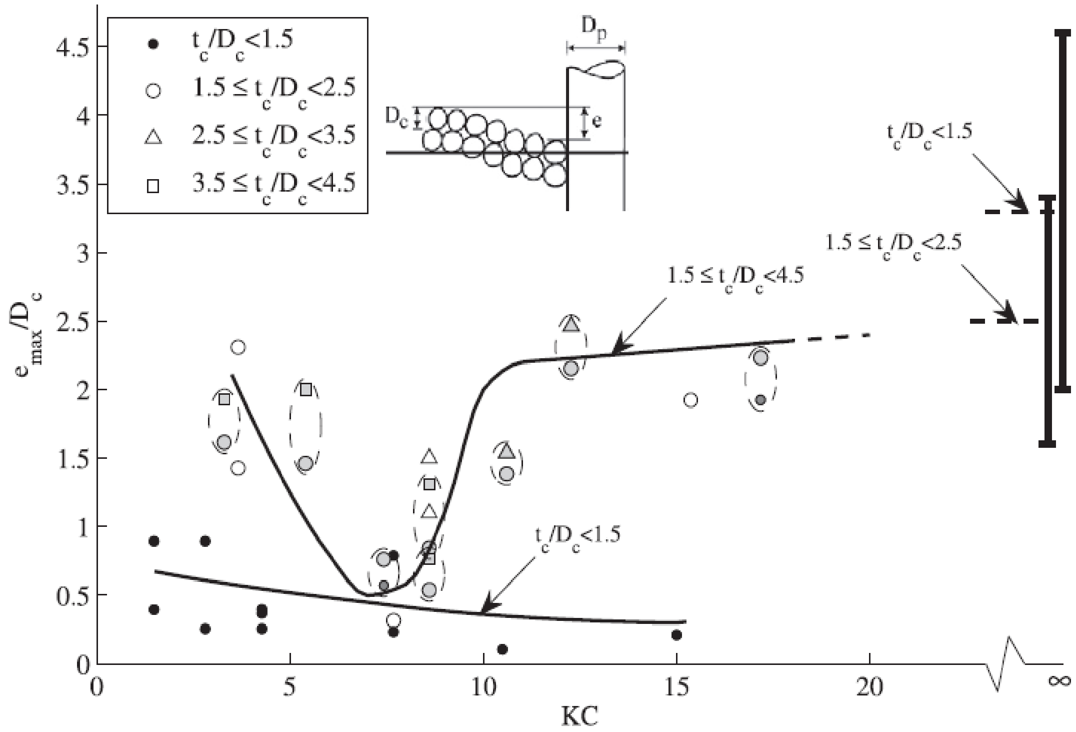

Figure 2 Equilibrium sinking of the scour protection exposed to waves as a function of the KC-number and the relative thickness of the scour protection. Figure from Nielsen et al. (2015).

Figure 3 shows a similar plot, but for the current-wave ratio u_{cw}. In this case, thick scour protections (more than two (2) layers of stones have a constant sinking in the tested interval and more or less independent of the KC-number (tested from 4 to 11). On the other hand, the thin scour protections with only one layer of stones has very little sinking in the wave-dominated region ($u_{cw} \approx 0$), while it experienced the largest sinking in case of current alone ($u_{cw}=1$). In the case of an intermediate thickness (2 layers), the sinking ends up as a combination of the thin and thick scour protection.

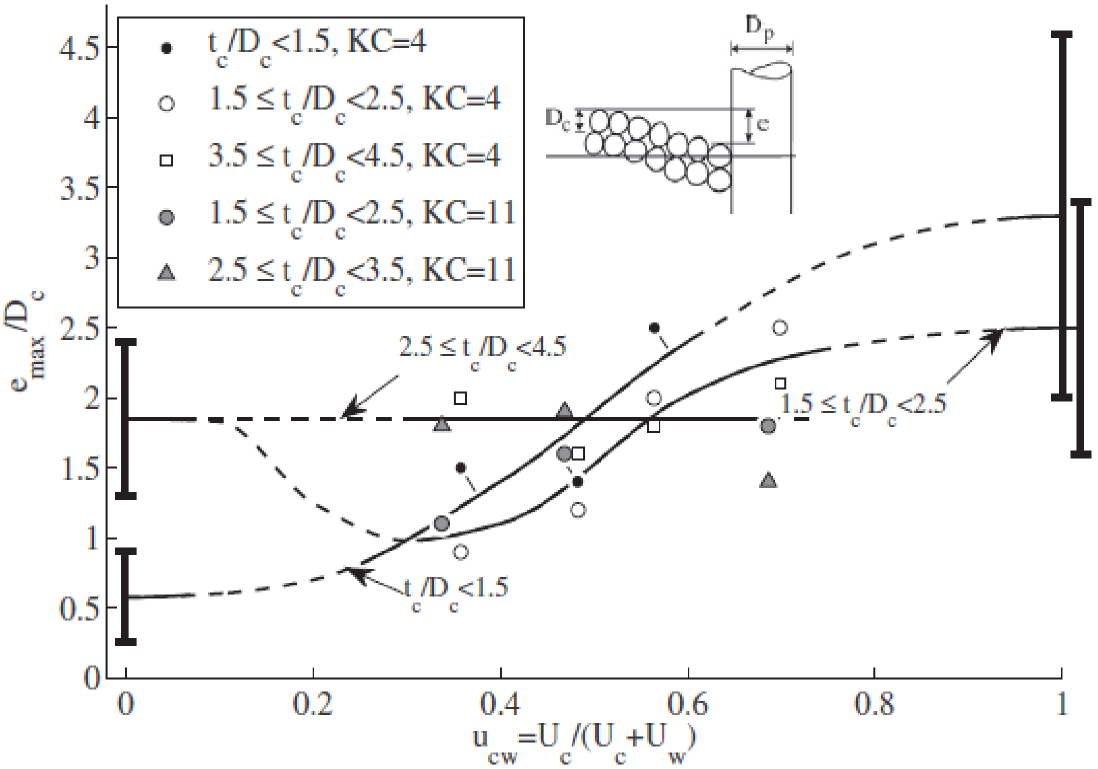

Figure 3 Equilibrium sinking of the scour protection exposed to combined waves and current as a function of the ucw-number and the relative thickness of the scour protection. From Nielsen et al. (2015).

More detailed descriptions of these mechanisms as well as the design diagrams are reported Nielsen et al. (2015).

The results of this study were furthermore used to explain the sinking of the scour protections observed at the Horns Rev 1 Offshore Wind Farm. The wind farm was installed in 2002 at Horns Rev in the North Sea approximately 15 km off the Danish West Coast. The turbines were founded on monopile with a traditional scour protection: a 0.5 m thick filter layer (5 to 20 cm stones) with a two-rock (35 to 55 cm) thick cover layer on top. This design was tested in a physical model test and was found to be fully stable; nevertheless, in 2005 a control survey showed that the scour protections had sunk around 1.5 m adjacent to the monopile, and in some cases more, see Hansen et al. (2007). The sinking could not readily be explained based on the available knowledge, and it was clear that a better understanding of the mechanisms was needed. The first attempt to explain the sinking was based on physical model tests with current as this is known to be the most severe effect in case of scour. The current caused sinking equivalent to the observations at Horns Rev 1 OWF, but stability tests showed that the current at Horns Rev was too weak to cause any sinking. The results of the tests were reported in Nielsen et al. (2011 and 2013). However, the results for waves and combined waves and current obtained in the present project showed that sinking in the same order of magnitude could happen for waves as for current, as detailed earlier in this report. Based on this knowledge, the surveys of the scour protections at Horns Rev 1 OWF were analysed, and it was found that the relative largest damages occurred:

- in the shallow parts of the wind farm; areas with highest near-bed wave activities
- for the initially largest scour protections

This was a clear indication that waves played a key role in the sinking of the scour protections, and that the relatively large scour protections applied could have increased the damage. The results of the analysis of the Horns Rev 1 OWF data were reported in Nielsen et al. (2014); Figure 4 shows the main result of the analysis.

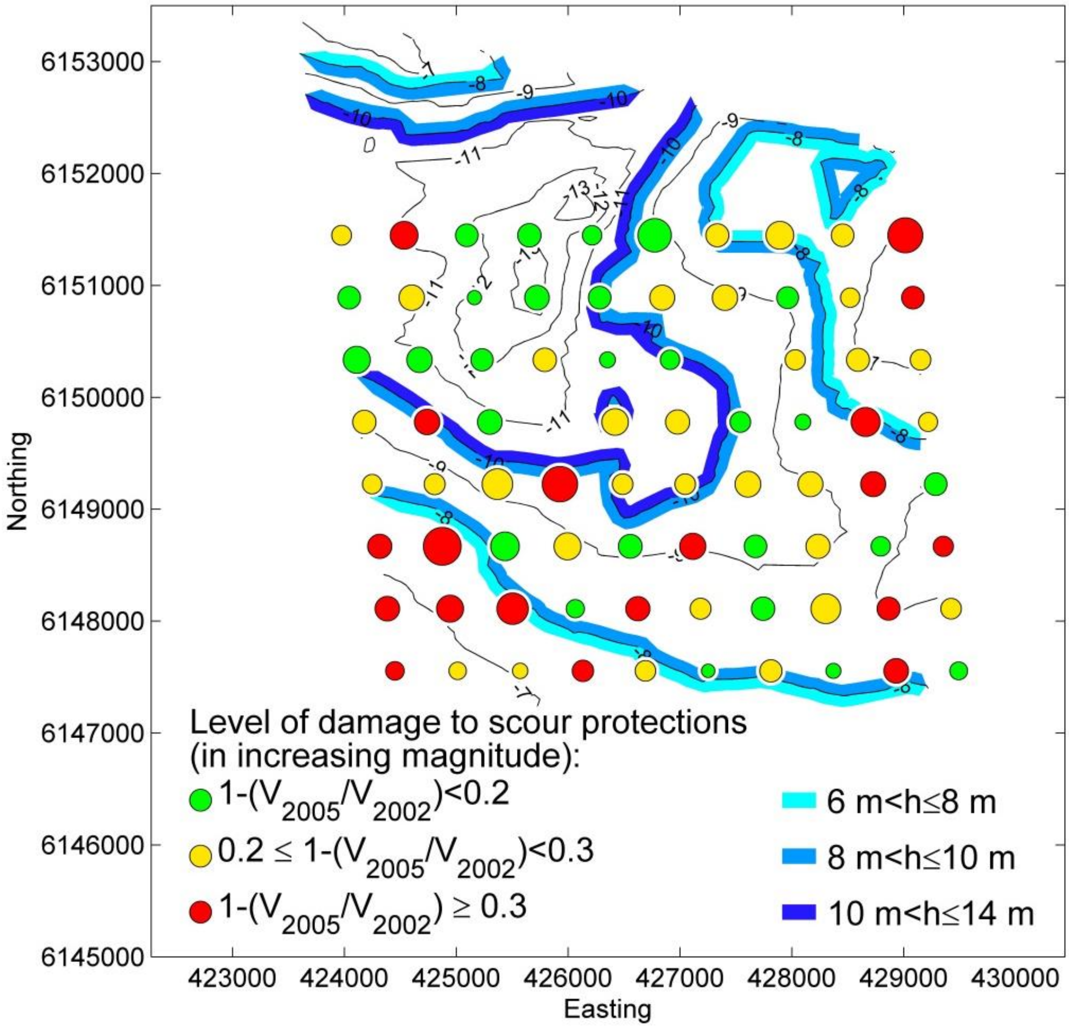

Figure 4 Relative damage to the scour protection at Horns Rev 1 OWF in the period 2002 to 2005. Each foundation is represented by a circle; the colour of the circle represents the level of damage, while the size represents the initial volume of the scour protection. From Nielsen et al. (2014).

1.4.5 Stability of sediment underneath a scour protection around a monopile exposed to waves and current

The other important parameter when it comes to sinking of the scour protection is the mobility of the sediment underneath a scour protection. Nielsen et al. (2013) presented results of the mobility in case of a current and a monopile, but nothing was available for waves and combined waves and current. To unveil this issue, a physical model test campaign was initiated.

The test campaign gave a number of useful results. The results from Nielsen et al. (2013) giving the stability of sediment underneath a scour protection exposed to current were reproduced with a slightly different method than the method originally applied by Nielsen et al. (2013). The main results consisted of waves, and combined waves and current tests.

Figure 5 shows the results from the present study together with results from previous studies. The plot has been modified compared to the plot presented in Nielsen et al. (2013), where the critical mobility, Ω_c, was plotted as function of the grain Reynolds number. In the present study, the critical mobility is plotted as function of the relative thickness of the scour protection, t_{sp}/d_b, where t_{sp} is the total thickness of the scour protection and d_b is a characteristic dimension of the base sediment, typically the median size, but in the case of Wörman (1989) the 85% fractile was reported and, consequently, applied. The plot shows some dependency on the thickness of the scour protection; however, the trend indicates that it will be neglectable for thicknesses relevant for practical applications, $t_{sp}/d_b>2000$. The plot shows that waves – especially waves with low KC-numbers – have a much lower critical mobility compared to current. This effect decreases for higher KC-numbers and tends to be very small for KC-numbers larger than 17, at least for relative thin scour protections. On the other hand, sediment under a scour protection exposed to combined waves and current are found to be more stable than both the current and the wave case, but in this case no effect of the KC-number is seen in the case of combined waves and current. Further details can be found in Nielsen and Petersen (2018).

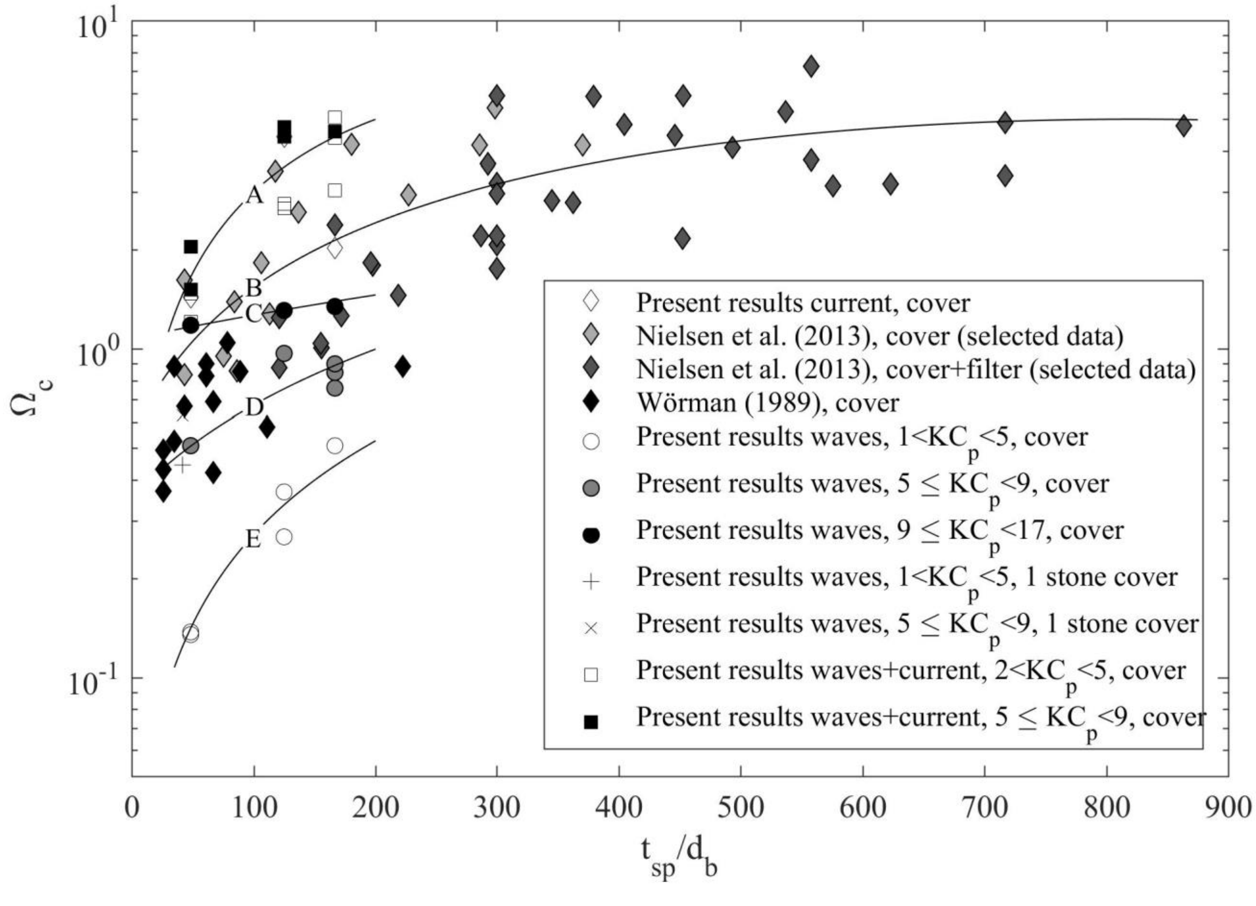

Figure 5 Critical mobility number as function of the t_{sp}/d_b. The trend lines are: A) combined waves and current, B) current, C) waves $KC_p<5$, D) waves $5<KC_p<9$, and waves $9<KC_p<17$. Note, the Wörman (1989) results are based on 15% and 85% fractiles for the cover stone size and base sediment, respectively, and can for this reason be expected to have slightly lower mobility numbers. Data from Nielsen et al. (2013) for very large stones in the scour protection have been omitted.

1.4.6 Stability of cover stones around a monopile

During the project, a need of a better understanding of the stability of the cover stones around a monopile was uncovered during meetings with advisory board. As an opportunity of having an intern, Cyrielle Morlet, doing a major part of the needed physical model tests, it was decided to include this topic in the project.

The study is a supplement to the studies by De Vos et al. (2011 and 2012). Where De Vos et al. focused on developing a design method based on imperical equations, the present study aimed at a more detailed description of the processes causing the damage to the scour protection and to develop a simplified design method based on design diagrams. Where imperical equations are easy to use and fast method within the valid ranges, the design diagram-based method combined with detailed knowledge of the ongoing processes is a very strong method in broader ranges, where a direct use of the imperical equations might provide misleading results.

Figure 6 shows one of the main design diagrams made from the results of the study. It presents the critical Shields number calculated for undisturbed seabed covered by the armour stones as function of the ratio between stone size and pile diameter in the case of a current. The shown critical Shields number is valid in the horse shoe vortex at the upstream side of the pile. The critical Shields number was found to be smaller in the lee-wake vorticies downstream of the pile, but this damage due to the lee-wake vorticies was, on the other hand, found to be very small as most of the movements of the stones were relocations of stones within a small area.

Figure 6 shows that for cover stones to pile diameter, ratii smaller than approximately 0.1, the critical Shields number is almost constant and rather low around 0.004, or around one tenth of the critical Shields number for an undisturbed case. For higher values of the cover stone size to pile diameter ratio, the critical Shields number starts to increase rapidly: Already at D_c/D_p around 0.3, the critical Shields number has increased to 0.03 or approximately the same as the undisturbed case. Nevertheless, scour protection designs applied to present offshore wind farm projects will at present typically range from 0.03 to 0.06; so for most practical applications, the lower value of the critical Shields number must be applied.

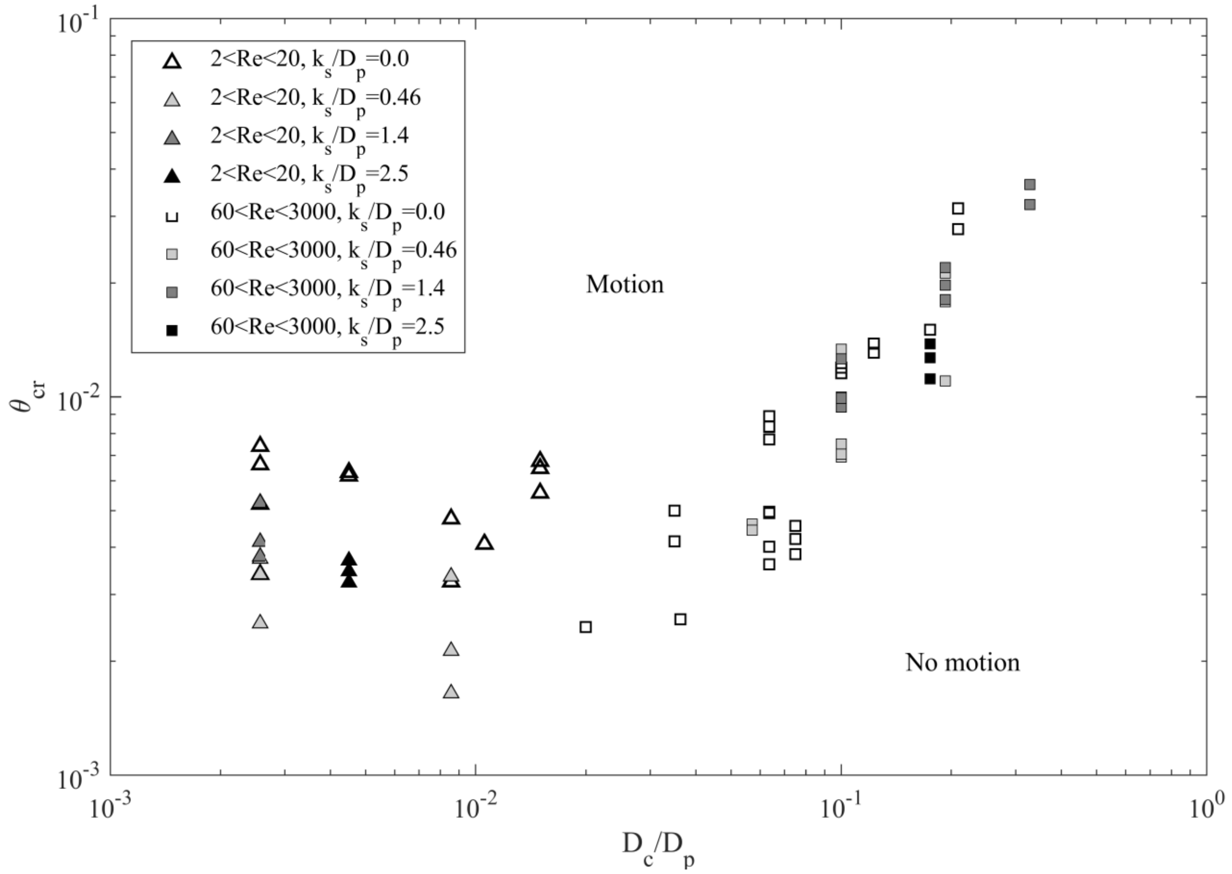

Figure 6 The relation between the critical Shields parameter and the non-dimensional stone size, D_c/D_p, in the horse shoe vortex in case of current. The results are valid for $h/D_p>4$.

Figure 7 shows the critical Shields number as well, but in this case as function of the wave-current ratio, ucw=$u_c/(u_c+u_w)$. This plot shows that the critical Shields number is larger of the pure wave case, $u_{cw}=0$, and decreases for increasing effect of current. The two different criticalities, in the lee-wake and the horse shoe vortex, are also seen, but they were only observed in the current-dominated regimes. The exact trend of the horse shoe criticality is unknown as no combined wave-current tests have been conducted in the present studies, and De Vos (2011) only reported first motion (lee-wake).

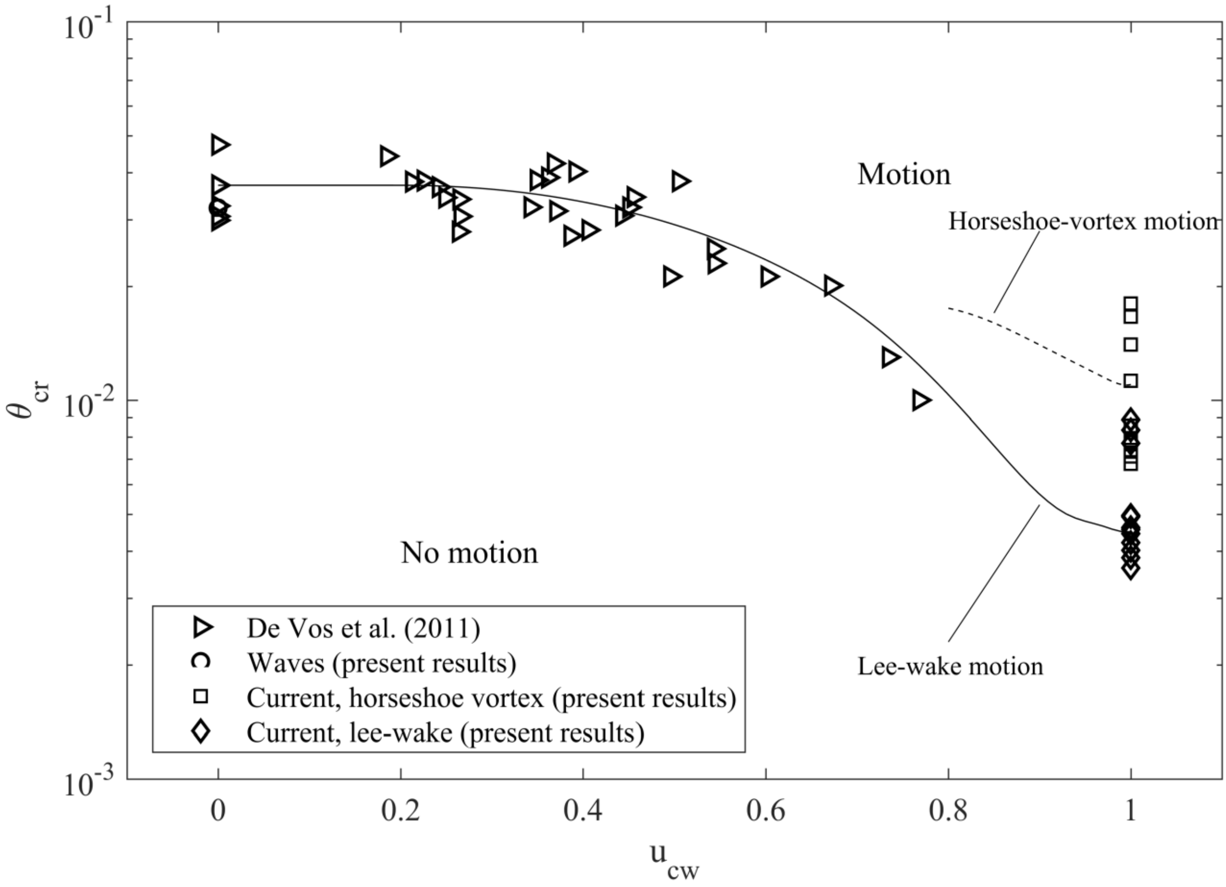

Figure 7 The effect of combined waves and current. The KC-numbers for waves and combined waves and current cases are in the range 1 to 10.

1.4.7 Scour Protection Calculator

As part of the project, DHI has developed a tool called "Scour Protection Calculator" (SPC). SPC is a simple tool to assist the design and verification of scour protections around monopiles. The inputs for the SPC are time series of environmental conditions like sea states (significant wave heights and peak periods), current velocity, tide, etc., structural dimensions of the monopile, seabed material parameters, and dimensions of the scour protection.

The output are the risk of failure for the three most common failure modes (lose of cover stones, sinking of scour protection adjacent to the pile, and edge scour) based on the input time series. The calculation process is illustrated in Figure 8; for details see Petersen and Nielsen (2015).

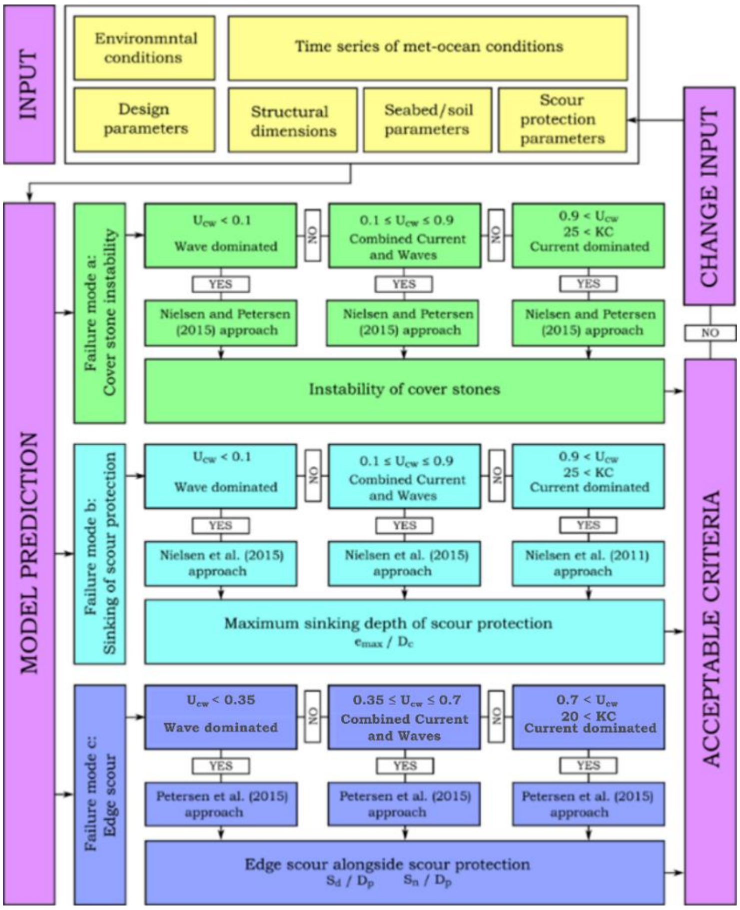

Figure 8 Flow diagram for the SPC.

1.4.8 Stability of single-layered broad-graded scour protection

During the latest years, single-layered broad-graded scour protections have become more and more common. Opposite the traditional scour protection, which consists of two or more narrow graded layers, usually a filter layer to prevent erosion of the bed and a cover layer to protect the filter layer, the broad-graded scour protection consists of only one layer. This single layer must then be so broad-graded that it can work as both filter and cover layer. The main benefit appling this kind of scour protection is the reduced number of offshore operations. The traditional narrow-graded scour protection is usually installed in three steps:

1. Filter layer
2. Monopile driven through the filter layer into the seabed
3. Cover layer

while a single-layered scour protection is installed in only two operations:

1. Scour protection
2. Monopile driven through the scour protection into the seabed.

There are two clear benefits: The single-layered scour protection requires one offshore operation less than the traditional, and the risk of damage to the filter layer – especially after installation of the monopile, but before the cover layer installation – is eliminated. The traditional scour protection is often designed to be fully stable so no loss or movements of material are accepted or it is designed as a dynamic scour protection allowing some movements of material during severe conditions. Opposite, some fine material from the top of the scour protection can be anticipated to be lost in the case of the single-layered scour protection, where this material is more or less fully exposed. During the design of a scour protection, it is important to have a clear knowledge of the amount of material to be lost, and how thick the affected layer will be in order to design and install an optimal size of scour protection.

To give some answers to this, a number of physical model tests in current were carried out. The main focus was to quantify the development of the scour protection, but some effort was also put into getting some insight in the mechanisms driving the development of the scour protection in current. The tests were carried out at MEK-DTU in a 4 m wide current flume. The width of the flume allowed to test two monopiles: -5 and 11 cm in diameter – at the same time without interference between the piles. The water depth was kept at 0.5 m and the bed was fixed. The development of the scour protections was monitored via a dynamic underwater measurements system described in Section 1.4.9.

The procedure for the model tests was to place the scour protection around the monopiles with horizontal extension of 4 to 5 times the diameter of the monopile; an example of this is seen in Figure 9. After installing the scour protections in dry condition, the flume was gently filled just to cover the scour protections, in order to let the scour protection settle. After this water was drained again and the set-up photographed by the dynamic measuring system in dry condition before the flume was filled gently again to the specified water depth. The flume was filled gently enough to prevent damages to the scour protections by the inflow of water. Once the flume was filled, the test was started at the specified current speed, which was kept throughout the test. The test lasted until equilibrium was reached and no further development happened. The development was monitored via the dynamic underwater measuring system.

Figure 9 Example of scour protection before testing.

The key component in these tests was the material applied for the scour protections. These were made by mixing various narrow-graded stone material; in total nine different stone compositions were used for the tests, see Figure 10. The compositions consisted of materials in the interval from 0.1 to 20 mm, and the geometrical standard deviations of the composition were 3.0 to 4.9 mm.

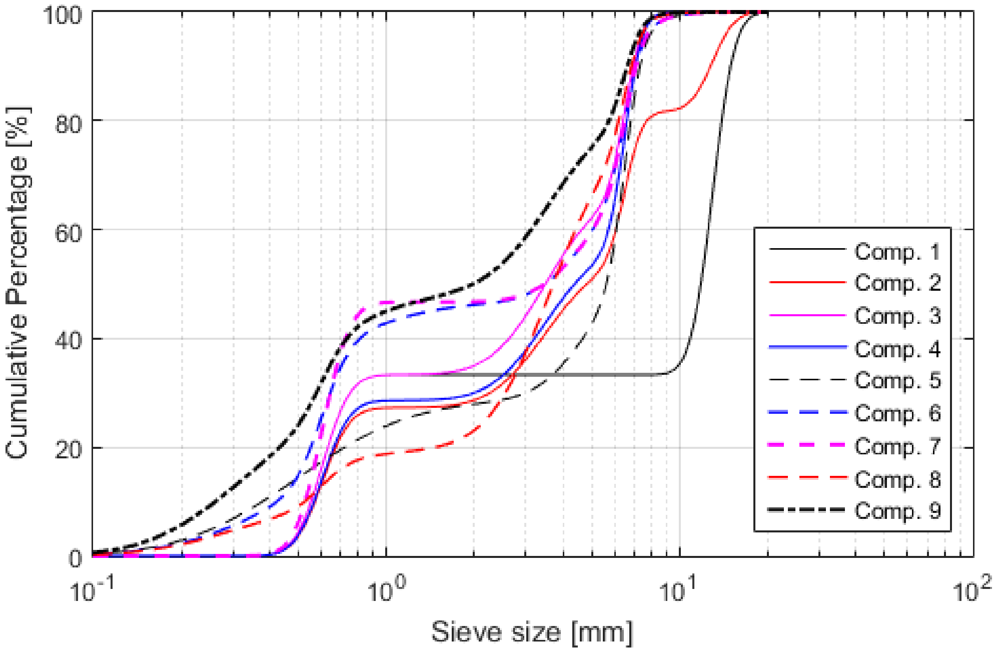

Figure 10 Gradation curves for the nine different stone compositions applied.

Beside the overall development measured by the dynamic underwater measuring system, the development of the gradation of the materials was measured. This included measurements of the stone sizes at different distances to the pile, different angular sections around the pile ("cake pieces"), and different vertical levels. These analyses were not made for all tests as they were heavily time consuming.

Two important parameters have to be introduced to describe the results: the level of settlement and the level of erosion. The situation is seen in Figure 11; the settlement is the change in the level of the surface of the scour protection, while the level of erosion is the interface between the intact scour protection and the part of the scour protection, where fine material has been washed away. This new system can be seen as a traditional scour protection with a cover layer above the level of erosion and filter layer below. A contour plot of the level of erosion after removing the loose cover stones is shown in Figure 12.

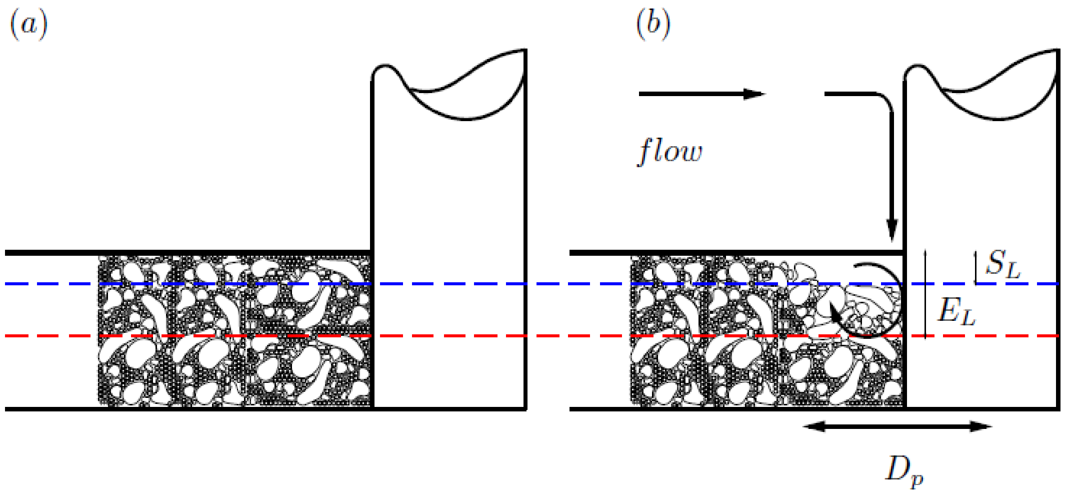

Figure 11 Definition sketch of level of settlements and level of erosion, respectively S_L and E_L, on the upstream side of the pile - (a) Initial state, (b) Equilibrium state.

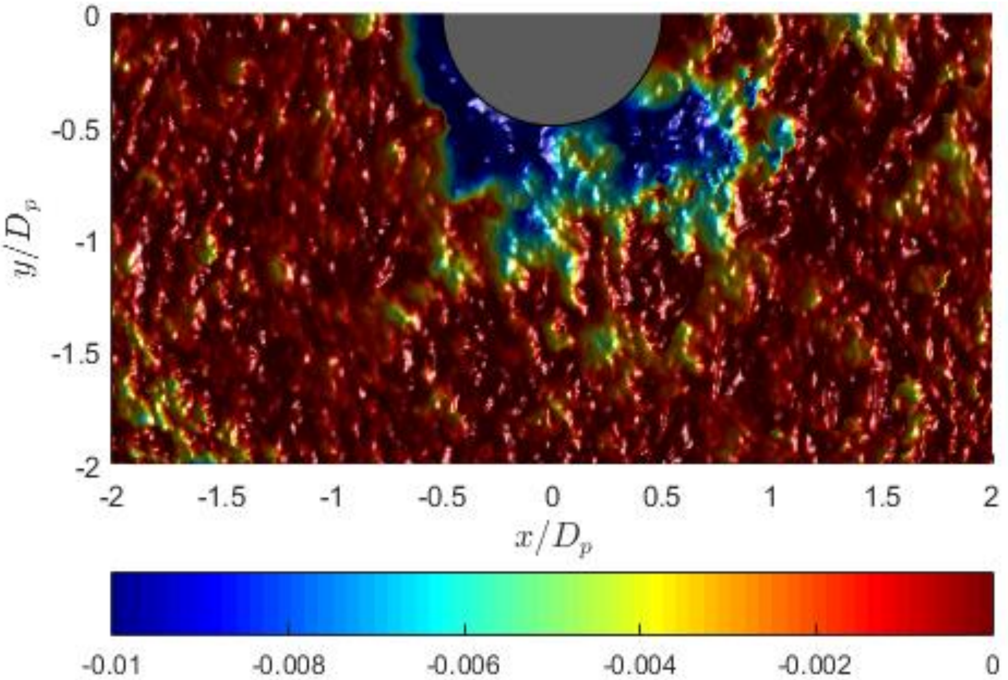

Figure 12 Example of contour plot of erosion level. Current is going in the x-direction from negative to positive.

If the level of erosion can be seen as the interface between cover and filer layer, representative values should coincide with results presented in Sections 1.4.5 and 1.4.6. The stability of the layer above the level of erosion ("cover layer") has been plotted as in Figure 6, where the single-layer scour protection data points are based on the median stone size of the material above the level of erosion. Figure 13 shows that the results for the broad-graded scour protection coincide with the results for a traditional scour protection. This indicates that the results found in Figure 6 can be applied to estimate the median size of the remaining fraction of the stones above the level of erosion in the case of a broad-graded scour protection. Then, the characteristic sediment size for the undisturbed scour protection can be found as the median of the fraction not involved in the stable top layer.

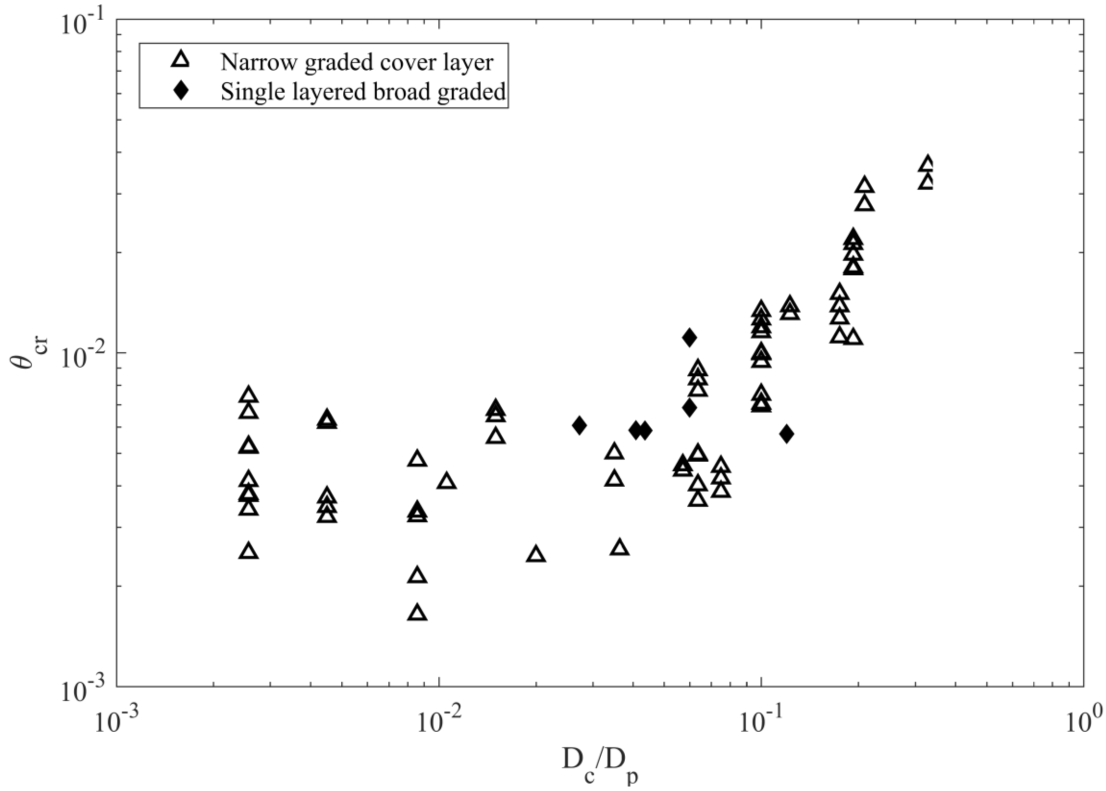

Figure 13 Stability of top layer for narrow and broad-graded scour protections. The narrow-graded results are from Figure 6.

Figure 14 shows the critical values of the mobility number, Ω, for the interface between cover/filter layer and the erodible bed (seabed or undisturbed broad-graded scour protection) underneath. The critical mobility number seems to be higher, around five times, for the broad-graded scour protection compared to the narrow-graded; however, it is conservative to apply the curve valid for the narrow-graded scour protections. The figure can mainly be used to estimate the thickness of the remaining part of the material that has been subject to erosion and thereby to have an indication how thick the initial layer has to be.

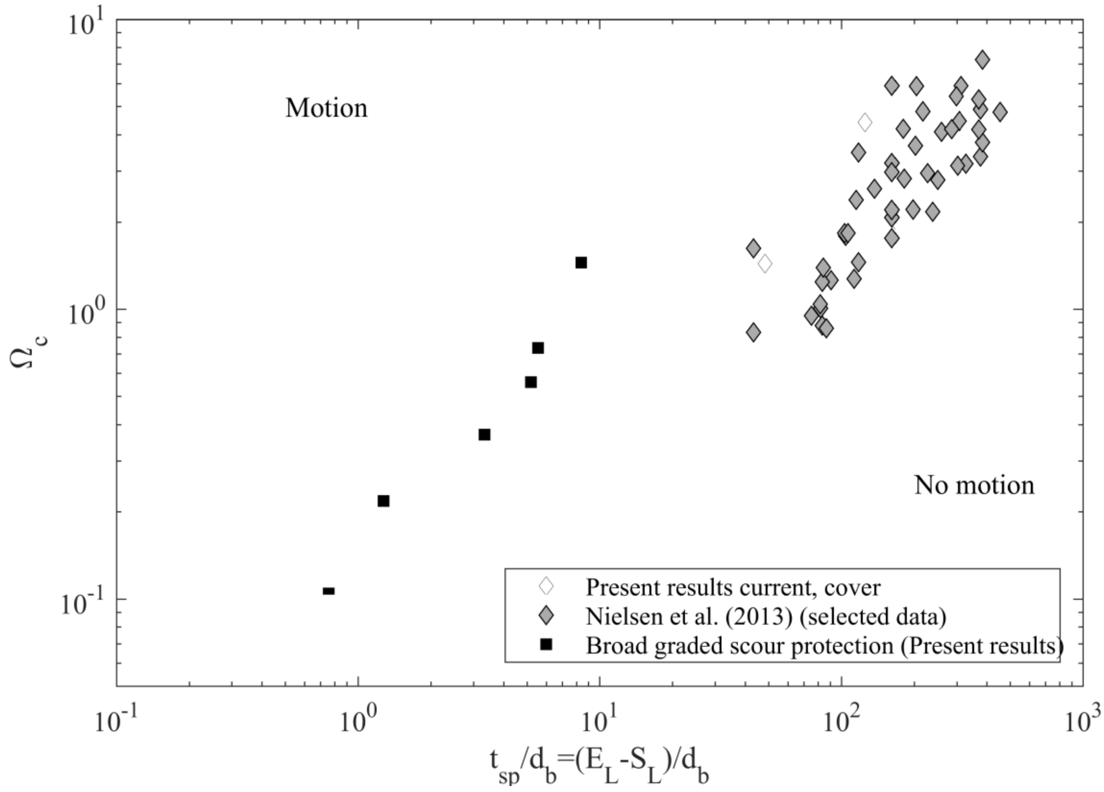

Figure 14 Stability of the interface between cover/filter layer and erodible bed.

1.4.9 Dynamic underwater measurements of scour protection settelments

One of the major issues for conducting physical model tests with scour and scour protection is to obtain a sufficient high resolution in the measurements. Traditionally, measurements have been made manually using a point gauge or manual readings from video recordings of small sticks placed in the seabed. These methods are very time consuming and have some huge limitations to the resolution both in time and space, as well as the accuracy was limited specially for non-skilled experimentalists. As part of the tests of the stability of single-layered broad-graded scour protections, Section 1.4.8, an opportunity of testing another method, based on photogrammetry, was opened. The method is based on synchronized video recordings of the area of interest by a number of cameras (typically 2 to 3). The applied method is based on RaspberryPi computers and cameras built-in to custom-made watertight casings, and the videos are processed using Agisoft’s Photoscan.

The method provides a high resolution in time (30 Hz full spatial resolution and up to 90 Hz reduced spatial resolution) and in space (<1 mm often <0.2 mm) and with a spatial accuracy better than 0.5 mm. The method can be applied during the model tests, eventhough some sediment is suspended in the water column or it can be used to provide “before and after” pictures. Overall the method is a significant improvement of the measuring techniques needed for physical model tests of scour and scour protections.

Figure 15 shows an example of measurements of the development of ripple formations at a sandy bed. The plots have a high degree of details that would be impossible to obtain using the traditional methods described above.

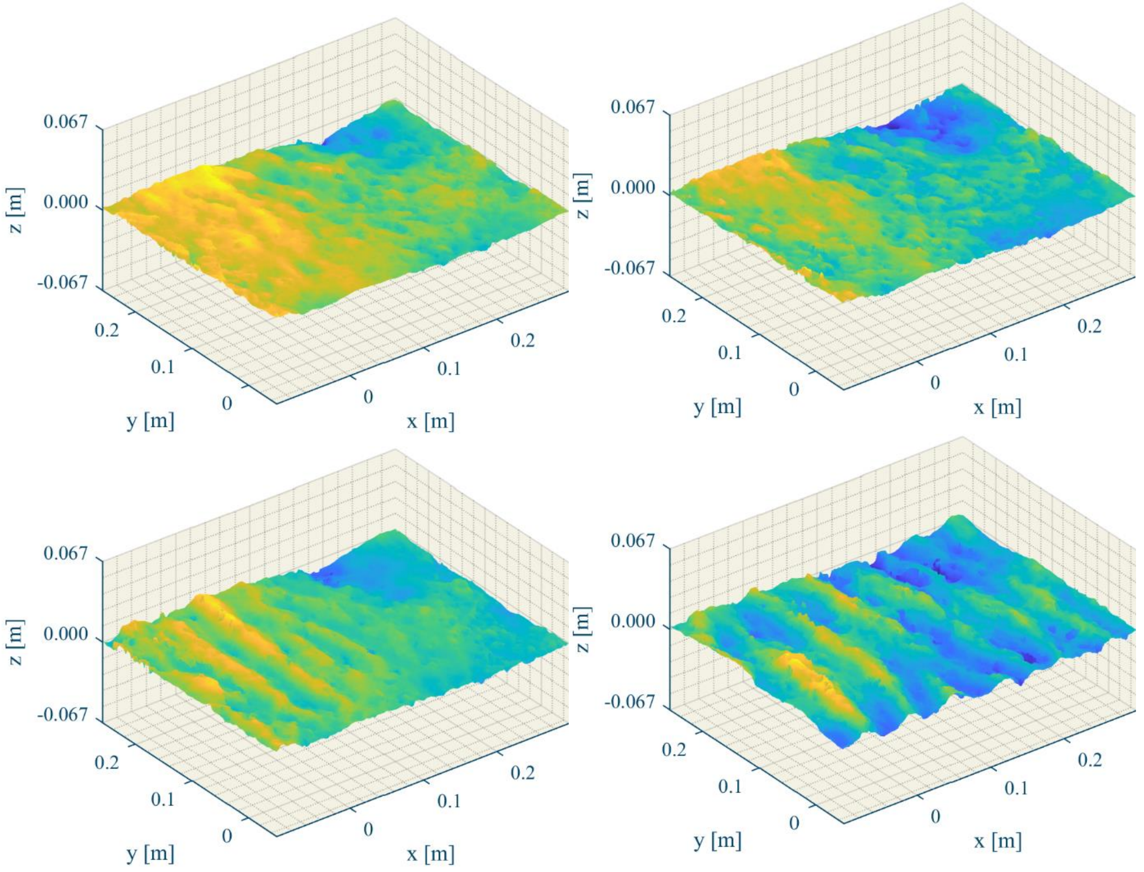

Figure 15 Illustration of measurements of ripple formation on sandy bed in four different time steps

1.4.10 Stability of large-scale bed forms in the sea and their interaction with offshore wind farms

In coastal and offshore areas, there is an ongoing interaction between the sandy seabed and the motion of the seawater due to currents and waves. At some of these locations, large-scale sand banks and sand-waves, spanning over hundreds of meters to several kilometers, can be observed. The dynamic behaviour of these large-scale bed forms makes their monitoring extremely important for offshore activities, including dredging, construction of offshore wind farms, laying of pipelines and cables, as well as vessel navigation. This project has looked into the following three aspects: 1) What causes large-scale bed forms to emerge in the first place? 2) What processes are important for maintaining a fully-developed "stable" bed form? and 3) How will the introduction of structures such as wind farms affect the long-term dynamics and stability of existing bed forms? The above questions have been addressed with various computational models, which incorporate the water motion and the morphodynamics of the seabed. The study has demonstrated how the large-scale bed forms can emerge due to the instability of a plane bed, and has also emphasized the importance of incorporating suspended sediments. The temporal bed form development has been simulated from their initial emergence until reaching a stable form. With the introduction of wind farms, the results suggest that their interaction is largely dependent on the water depth and velocity as well as the distance between the wind turbines. For kilometer-sized bed forms, the effects were limited and took place over century-long time scales, but bed forms of shorter lengths such as sand-waves have shown to be affected over annual time scales. Results from the project are presented in Margalit (2018), Margalit and Fuhrman (2017) and Margalit et al. (2018).

1.4.11 Recommendations for scour and scour protections around monopiles

The project has produced a lot of new knowledge in relation to scour and scour protections. Some of this knowledge will lead to new ways of designing especially scour protections. In the following, recommendations for scour and scour protections based on this and previous projects are outlined. The recommendations are – for the most part – based on physical model tests that may not cover all possible effects and conditions at actual offshore project. The recommendation should therefore be used as a minimum check of a scour strategy rather than full solution covering every relevant issue. No one of the partners in this project can be held responsible for any consequences of the use of these recommendations or other data provided or referenced in this report.

The first thing to consider for a scour strategy is the need of a scour protection. When the need of a scour protection is considered, the following should be included as a minimum:

- The integrity of the structure. Specially important for gravity-based structures placed directly on the seabed.
- Needs for protection of secondary item e.g. export cables.

As scour is a dynamic process with continuous cycles of scour and back-filling of the scour hole, and the most extreme sea states are not necessarily the worst in relation to scour, it is always recommended to base this consideration on simulated time series of the scour process based on as long time series (hindcasts) as possible. This will provide data on extreme scour, but also accumulated periods of different scour depths, which can be relevant for accessing fatigue damage.

The simulated time series of the scour should as a minimum include effects of:

- Pile size
- Sediment (representative)
- Wave conditions (time series 1 to 3 hours resolution)
- Current conditions (time series 1 to 3 hours resolution)
- Tide (time series 1 to 3 hours resolution)

The model could also include effects as stratified sediment and self-armouring due to coarse non-erodible sediment.

During the scour assessment, the impact of possible bed forms (sand-waves and banks) should also be considered. Migrating bed forms might change the general local seabed level by several meters. Both migration speed and the height of the bed form should be considered. It is recommended to place foundations in the trough of the bed forms if the migration speed (wave period) is in the order of or smaller than the design life of the foundation. Note, scour protections will in general not prevent reduction in seabed level due to migrating bed forms.

If a scour protection – based on the above considerations – is found to be necessary, the following should be taken into account. As seen in Nielsen et al. (2014), a scour protection should in general be as small a possible. This can in general be obtained by applying single-layer broad-graded scour protections; however, under some conditions this is not possible, e.g. if very large stones (preventing the driving of the pile) are needed for stability. Independent of the scour protection system, the resilience to the three failure modes should be demonstrated:

- Overall stability of the system
- Stability for suction of sediment through the system
- Edge scour

This recommendation is based on scour protections made of rocks, which is recommended as this method has been proven and is resiliened towards common failure modes. Other systems exist, but have in general not been proven for typical conditions. For a rock scour protection, the overall stability is related to the stability of the top layer, which should remain fully intact (static design) or with tolerable damages (dynamic design) under extreme conditions. The top layer will in general experience the largest forces under extreme events and can for this reason be designed for relevant extreme events with relevant return periods. Relevant design criteria could be those outlined in Nielsen and Petersen (2018a) or if single-graded scour protection is applied, see Section 1.4.8.

The scour protection must be checked for possible sinking or suction of sediment adjacent to the pile. Some sinking may be acceptable for the design: in that case, the expected maximum sinking should be quantified. Note, the maximum sinking is not necessarily associated with extreme sea states, and analyses based on time series are recommended. If no sinking is acceptable, it should be demonstrated that this is fulfilled. Note, physical model tests cannot readily assess sinking of the scour protection due to scaling problems with the sediment. For this reason, results from model tests can only be used to prove sinking if the model set-up is designed specifically for this purpose. Relevant literature is Nielsen et al. (2011, 2013, 2014, 2015), Nielsen and Petersen (2018a, 2018b), Sumer and Nielsen (2013).

Edge scour takes place at the boundary between the scour protection and the surrounding seabed. Edge scour cannot be fully prevented, but it can be reduced by minimising the height of the scour protection, i.e applying a single-graded scour protection. Some of the stones from the scour protection will slide into the hole formed by the edge scour and thereby stop the scour process. For this reason, it is important to have enough material to supply this falling apron. To ensure this, it is recommended to apply a scour protection with an overall horizontal extension of around four times the diameter of the monopile. The scour protection should also be sufficiently thick at the edge to contain the needed material. Relevant literature is Petersen et al. (2015).

1.4.12 Dissemination of the project

The project has resulted in a number of peer-reviewed and conference. The peer-reviewed papers are:

- Nielsen, A. W., Probst, T., Petersen, T. U. and Sumer, B. M. (2015): Sinking of armour layer around a vertical cylinder exposed to waves and current, Coastal Engineering, Vol. 100, pp 58-66.
- Nielsen, A. W. and Petersen, T. U.: Stability of sediment and cover stones around a vertical cylinder under the influence of waves and current, under preparation .
- Nielsen, A. W. and Petersen, T. U.: Onset of Motion of Sediment underneath Scour Protection around a Monopile, submitted for publication.

- Petersen, T. U., Pedersen, A. V., Nielsen, A. W., Hansen, D. A. and Fredsøe, J.: Stability of single graded scour protection around a cylinder in a current, under preparation.
- Margalit, J., Fuhrman, D.R. and Jensen, J.H. (2018): The morphing of sand banks: a numerical linear stability analysis. Submitted to Coastal Engineering.

The conference papers are:

- Nielsen, A. W., Sumer, B. M. and Petersen, T. U. (2014): Sinking of scour protections at Horns Rev 1 Offshore Wind Farm. In proceedings of International Conference on Coastal Engineering (ICCE), Seoul, Korea, pp 1-14, https://journals.tdl.org/icce/index.php/icce/article/view/7700/pdf_865.
- Petersen, T. U. and Nielsen, A. W. (2015): Model prediction of the dynamics of scour protections around monopiles, in proceedings of EWEA Offshore, Copenhagen, Denmark.
- Margalit, J. and Fuhrman, D.R. (2017): Development of large scale bed forms in the sea: 2DH numerical modeling. In Proceedings of: Coastal Dynamics 2017, pp. 1120–1130, Helsingør, Denmark.
- Hansen, D. A., Petersen, T. U., Nielsen, A. W., Pedersen, A. V. and Fredsøe, J. (2018): Dynamic underwater measurements of scour protection settelments, Accepted for publication.
- Petersen, T. U. (2018) International Conference on Scour and Erosion 2018, Taipei, Taiwan (abstract submitted).

PhD Theses that resulted from the project are:

- Margalit, J. (2018): Development of natural seabed forms and their interaction with off shore wind farms. PhD Thesis, Technical University of Denmark.
- Mandviwalla, X. (2018): Fast Methods for the Analysis of Scour Development and Armour Layers, PhD Thesis, Technical University of Denmark.

In addition to the publications listed above, results from the project have been or will be presented orally at:

- Vind dag I Fredericia 2012
- The International Conference on Coastal Engineering 2014, Seoul, Korea.
- EWEA Offshore 2015, Copenhagen, Denmark.
- Hydralab+ Assembly May 2017, Santander, Spain.
- Coastal Dynamics 2017, Helsingør, Denmark.
- Coast Lab 2018, Santander, Spain.
- DANCORE Young Professionals Day 2018, Copenhagen
- ICSE (International Conference on Scour and Erosion) 2018, Taipei, Taiwan (abstract submitted).

Parts of the results have also been included in the course material for the DHI course "Scour around marine structures". The course was held in 2014 and 2015 at DHI Hørsholm with participants from universities and industry primarily in Europe, but also other contries.

The results of the project have also been presented at an end-user seminar at DTU Lyngby in January 16, 2018. The seminar was hosted by Dansk Vandbygningsteknisksselskab and had 50 participants primarily from Denmark, but also some from Germany, the Netherlands and UK.

1.4.13 Conclusions

The project has overall succeeded in realising its objectives. It has provided important new knowledge within scour protection, which has made it possible to apply cheaper and more effective designs to offshore wind farm projects.

The project did not fully realised two objectives. The development of a model for time series based scour development has not been fully completed and validated. However, the CFD model is working and the model can easily be applied on various projects.

The development of a database with survey data of scour protections of offshore wind farms was stopped. The increasing competition on the offshore wind market made it impossible to anyone who would provide data for publication.

The project has provided new knowledge especially regarding scour protections, which have strengthened DHI's market position. DHI has had an increasing number of scour-related projects over the last years, both at the Danish and international markets.

DHI expect to continue the growth in the market and plane to develop easy-to-use-tools for short-term and long-term scour development and scour protection stability.

1.4.14 References

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Nielsen, A. W. and Petersen, T. U. (2018a): Stability of sediment and cover stones around a vertical cylinder under the influence of waves and current, under preparation.

Nielsen, A. W. and Petersen, T. U. (2018b): Onset of Motion of Sediment underneath Scour Protection around a Monopile, submitted for publication.

Petersen, T.U., Sumer, B.M. and Fredsøe, J. (2014): "Edge scour at scour protections around offshore wind turbine foundations", Conference Proceedings of the 7th International Conference on Scour and Erosion, ICSE-7, Dec 2014, Perth, Australia.

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1.6 Utilization of project results

The project has provided crucial new knowledge within several aspects of scour and scour protections.

The findings have been incorporated into the methods used by DHI to scour and scour protection problems. The new knowledge on stability of different parts of a scour protection has already been applied in consultancy projects by DHI, including both Danish projects and projects abroad. DHI has experienced an increasing market for scour and scour protection related work and expect this to continue in the coming years. As part of this, DHI has started collaboration with LICengineering A/S in Denmark and NGI in Norway on several Danish and international projects.

DHI will continue working on the Scour Protection Calculator (SPC) and aim at bringing it to a level, where it can be provided as a commercial tool in the MIKE Powered by DHI software. DHI will also use the results of the project to improve the existing Scour Calculator already available in the MIKE Powered by DHI software.

The project has provided knowledge that has helped decreasing the costs of scour management and therefore offshore wind power. The biggest gains are in relation to scour protections, where the project has provided knowledge – previously not publically available – for safe design of modern small cost effective scour protections.

The two Ph.D.-students have participated in a number of activities related to teaching and other dissemination:

Co-supervised masters projects:

Jesper Roland Kjærgaard Pedersen - ”Optimised estimation of scour holes around marine structures ”

Betina Skovgaard Grysbæk - “Calculation of scour rates for long term scour prediction”

Søren Løgstrup Sørensen – “Influence of Offshore Windfarms on the Morphology of Large Scale Bedforms in the Sea”, 2016.

Andreas Stengel Hansen – “Influence of Offshore Windmill Foundations on the Stability of Large Bedforms”, 2015.

Luca Fianchisti – “Stability of Large-Scale Bedforms in the Sea”, DTU, 2015.

Taught fully or partly the following courses:

Turbulence Theory - 6 Lectures (2016)
Marine Structures II - 1 Lecture (2016)
Marine Structures I - Teaching Assistant (2015)
Hydrodynamics II – Teaching Assistant (2014—2017)

Presented their projects at the following conferences:

- EWEA Offshore 2015, Copenhagen, Denmark.
- Coastal Dynamics 2017, Helsingør, Denmark.
- Coast Lab 2018, Santander, Spain.
- DANCORE Young Professionals Day 2018, Copenhagen

As well as the end-user seminar at DTU.

The students have published the following articles and theses:

- Margalit, J., Fuhrman, D.R. and Jensen, J.H. (2018): The morphing of sand banks: a numerical linear stability analysis. Submitted to Coastal Engineering.
- Margalit, J. and Fuhrman, D.R. (2017): Development of large scale bed forms in the sea: 2DH numerical modeling. In Proceedings of: Coastal Dynamics 2017, pp. 1120–1130, Helsingør, Denmark.
- Margalit, J. (2018): Development of natural seabed forms and their interaction with off shore wind farms. PhD Thesis, Technical University of Denmark.
- Mandviwalla, X. (2018): Fast Methods for the Analysis of Scour Development and Armour Layers, PhD Thesis, Technical University of Denmark.

1.7 Project conclusion and perspective

The project has provided new key knowledge in the process of reducing the costs of offshore wind development:

- An operational CFD model for simplified calculation of scour has been developed. It has been tested on monopiles, but can be applied to generic structures.
- New knowledge on stability of scour protections including new knowledge on single-layered broad-graded scour protections.
- A working numerical model of the migration of large bed forms and their interaction with offshore wind farms.

The CFD model for simplified calculation of scour can be used to improve the long-term prediction of scour around structures, but it may also be relevant for short-term scour, e.g. around legs of installation vessels and for installation of export cables at the right depth at unprotected foundations.

The new knowledge on stability of scour protections will be used to reduce the costs of scour protections now and in the future. Data to make a safe design of single-graded scour protections has not been publically available before and has a high potential in reducing the costs of scour protections and improve the quality and functionality of the protections at the same time.

The numerical modelling of migration of large bed forms provides knowledge useful for design of wind farms in areas with large bed forms. The migration speed and possible interaction between the sand bank and wind farm is a key knowledge in the design of offshore wind farms at sand banks. The model can calculate the migration as well as the interaction with wind farms.