Infrastructure Access Report

*Infrastructure*: AAU Deep Water Wave Basin

*User-Project*: OpDeDySp

Optimising the design of dynamic scour protection around offshore foundations

IMDC, HR Wallingford, Ghent University and FEUP

Status: Final
Version: 1.0
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EC FP7 “Capacities” Specific Programme
Research Infrastructure Action
ABOUT MARINET

MARINET (Marine Renewable Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC’s Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

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<thead>
<tr>
<th>Ireland</th>
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</tr>
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<tbody>
<tr>
<td>University College Cork, HMRC (UCC_HMRC) Coordinator</td>
<td>Sustainable Energy Authority of Ireland (SEAI_OEDU)</td>
<td>Stichting Tidal Testing Centre (TTC)</td>
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<td>Wave Energy Centre – Centro de Energia das Ondas (WaveEC)</td>
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Source: www.fp7-marinet.eu
# DOCUMENT INFORMATION

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<tr>
<th>User-Group Leader, Lead Author</th>
<th>Piet Haerens, IMDC nv.</th>
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<tr>
<th>User-Group Members, Contributing Authors</th>
<th>R. Whitehouse and A. Brown HR Wallingford</th>
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<tr>
<td></td>
<td>P. Troch and L. Baelus University Ghent, Dept. of Civil Engineering</td>
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<td></td>
<td>F. Taveira Pinto, L. das Neves and FEUP - Departamento de Engenharia Civil</td>
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<td></td>
<td>T. Ferradosa IMDC</td>
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<tr>
<td></td>
<td>A. Bolle, S. Audenaert and</td>
</tr>
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<td>P. De Schoesitter</td>
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| Infrastructure Manager (or Main Contact) | Peter Frigaard and Lucia Margheritini |

## REVISION HISTORY

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<td>SUD/PHI/ABO/PIH</td>
<td>P. Frigaard</td>
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ABOUT THIS REPORT
One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

ACKNOWLEDGEMENT
The work described in this publication has received support from MARINET, a European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme.

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EXECUTIVE SUMMARY

Marine structures are often prone to extreme conditions regarding scour processes, which can affect the foundation’s stability. The scour phenomenon around marine structures is a complex process, which needs to be studied in order to avoid structural collapse as well as financial losses.

Furthermore, a deeper understanding of scour behaviour and scour protection mechanisms will avoid oversized foundations and allow an optimization of the foundation design.

An increasing knowledge in this research field also enables the design of more reliable and secure scour protection systems, which will lead to economically viable engineering solutions, without excessive financial costs.

The most commonly applied type of scour protection is a rock armour layer installed over a filter layer. The armour layer is usually designed to be ‘statically stable’ under extreme hydrodynamic conditions. This means that during the design storm events, no or limited movement of individual rocks is allowed in order to guarantee the overall functionality of the scour protection system. Often, such designs result in large stone sizes, especially at shallow or exposed locations, which is not always economically interesting or technically feasible.

Therefore, a dynamically stable design can be an interesting alternative, even if the amount of material becomes larger. Therefore the present study aimed for different series of lab experiments regarding a dynamically stable rock armour layer installed over a filter layer around a monopile foundation, exposed to a combination of currents and waves.

The main purpose of the tests was to find a dynamically stable design, under specified combinations of wave and current loading, with a smaller stone size than the one used in the static system for the same hydrodynamic conditions.
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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

In the framework of the Marinet Project, a study proposal was developed by IMDC in a partnership with HR Wallingford, UGent and FEUP (Marinet proposal 61). This collaboration aimed for a 5 weeks research program regarding to develop a solid study regarding the design optimization of a dynamic scour protection, for structures such as offshore wind turbine foundations.

For this 5 week period, it was agreed that the mentioned partners would get access to the lab facilities at Aalborg University. The research consisted of testing a scour protected monopile foundation exposed to (typical North sea) combinations of currents and waves.

The proposed experiments were focused on the following research questions:

• Can we find a dynamically stable scour protection configuration for a given combination of wave and current loading and a stone size which is smaller than the one for a static scour protection system for these design conditions?
• How thick should this armour layer be, to allow for reshaping, but to maintain full coverage of the filter layer?

The total assignment included three test series with different water depths (shallow, medium and deep water depth). In each series, the armour layer stone size and the armour layer thickness were varied. Still concerning this proposal, it is important to note that along with the scour tests also the data analysis was done as a part of the assignment. However the collected data need further processing which will be done by the partners outside the 5 weeks access period to the facilities provided by Aalborg University.

The present document is the final report relative to Marinet proposal 61. With the purpose of reporting and analyzing the work carried out during the access period of 5 weeks at Aalborg University, reporting the main learning outcomes, and providing further information, the report has been organized into six chapters.

The first chapter is an introductory one and provides information regarding the initial assignment planned during the access period at the facilities of Aalborg University, as well as the aim and overview of the study.

A brief overview of the tasks and tests performed is given in Chapter 2. Furthermore, an evaluation of the work completed during the access period and a comparison between the several initial objectives and the final outcome of the model tests is given as well in the second chapter, together with analysis & conclusions of the study.

The third chapter describes the main learning outcomes, whereas the fourth provides further information. References and appendices are provided in Chapters 5 and 6, respectively.

1.2 DEVELOPMENT SO FAR

1.2.1 Stage Gate Progress

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<td>• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)</td>
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<tr>
<td>• Finite monochromatic waves to include higher order effects (25 –100 waves)</td>
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Previously completed: ✓
Planned for this project: 🔄
### STAGE GATE CRITERIA

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<td>Hull(s) sea worthiness in real seas (scaled duration at 3 hours)</td>
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<tr>
<td>Restricted degrees of freedom (DoF) if required by the early mathematical models</td>
</tr>
<tr>
<td>Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)</td>
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<tr>
<td>Investigate physical process governing device response. May not be well defined theoretically or numerically solvable</td>
</tr>
<tr>
<td>Real seaway productivity (scaled duration at 20-30 minutes)</td>
</tr>
<tr>
<td>Initially 2-D (flume) test programme</td>
</tr>
<tr>
<td>Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them</td>
</tr>
<tr>
<td>Evidence of the device seaworthiness</td>
</tr>
<tr>
<td>Initial indication of the full system load regimes</td>
</tr>
</tbody>
</table>

### Stage 2 – Design Validation

- Accurately simulated PTO characteristics
- Performance in real seaways (long and short crested)
- Survival loading and extreme motion behaviour.
- Active damping control (may be deferred to Stage 3)
- Device design changes and modifications
- Mooring arrangements and effects on motion
- Data for proposed PTO design and bench testing (Stage 3)
- Engineering Design (Prototype), feasibility and costing
- Site Review for Stage 3 and Stage 4 deployments
- Over topping rates

### Stage 3 – Sub-Systems Validation

- To investigate physical properties not well scaled & validate performance figures
- To employ a realistic/actual PTO and generating system & develop control strategies
- To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag
- To validate electrical supply quality and power electronic requirements.
- To quantify survival conditions, mooring behaviour and hull seaworthiness
- Manufacturing, deployment, recovery and O&M (component reliability)
- Project planning and management, including licensing, certification, insurance etc.

### Stage 4 – Solo Device Validation

- Hull seaworthiness and survival strategies
- Mooring and cable connection issues, including failure modes
- PTO performance and reliability
- Component and assembly longevity
- Electricity supply quality (absorbed/pneumatic power-converted/electrical power)
- Application in local wave climate conditions
- Project management, manufacturing, deployment, recovery, etc
- Service, maintenance and operational experience [O&M]
- Accepted EIA

### Stage 5 – Multi-Device Demonstration
### STAGE GATE CRITERIA

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<td>• Power supply interaction &amp; quality</td>
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<td>• Environmental impact issues</td>
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<tr>
<td>• Full technical and economic due diligence</td>
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<td>• Compliance of all operations with existing legal requirements</td>
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#### 1.2.2 Plan For This Access

The following Table 1 offers the information for the test program agreed before the starting date for the access period to the facilities in Aalborg University.

The same information included in this table can be found in IMDC internal Memo with the following Document reference: I/NO/12089/12.191/ABO – v3.0. Note that the distribution of the previously mentioned Memo can only be authorized by IMDC responsible staff.

The opposing currents and wave were later on decided not to be performed, due to very time consuming changes in the lab.

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<th>waves</th>
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Table 1 Initial Test Program

## 2 OUTLINE OF WORK CARRIED OUT

### 2.1 Setup

#### 2.1.1 Introduction

Looking for a dynamically stable scour protection design, three series of tests were agreed to be performed which focus on the following research questions:

- Can we find a dynamically stable scour protection configuration for a given combination of wave and current loading and a stone size which is smaller than the one for a static scour protection system for these design conditions?
How thick should this armour layer be, to allow for the reshaping, but to maintain full coverage of the filter layer?

Within this proposal, a dynamically stable design was defined as:

- A design where the individual stones (characterized by their $D_{50}$ value (coarse material) or $M_{50}$ (light material)) are not stable close to the pile under the design conditions (taking into account the amplification of the wave and current induced velocities by the presence of the pile).
- A design that allows a reshaping of the scour protection (cfr. Icelandic berm breakwaters) and where after deformation a sufficient thick scour protection remains, in order to protect the seabed against scouring.

This type of design is inspired on the Icelandic type Berm Breakwaters, which were introduced in the early 1980’s as an alternative to traditional rubble mound breakwaters. The fundamental principles of the berm design philosophy are that not only the expected wave load is taken into account but also the potential yield from the available armour stone quarry, the available construction equipment and the pursued function of the breakwater.

For the dynamically stable scour protection design, we would like to make a similar design which does not only take into account wave and current loading but also:

- The maximum stone size that typically can be placed with the currently available equipment (fall-pipe vessels).
- The function of the protection layer: prevent scouring of the seabed around the offshore foundations.
- The use of smaller stone sizes allows the use of a (more) closed filter.

Since velocities are only amplified within a limited area around the foundation, one should expect that such a reshaped scour protection could exist: a local depression in the scour protection near the pile, but a thicker circular layer all around, which prevents further loss of stones from nearby the pile.

Most available research results, guidelines and standards are focused on the design of a statically stable scour protection, but do not deal with damage allowance at all. De Vos (2008) found an expression for the damage number of the scour protection, but did not investigate the “dynamic stability” of smaller stone sizes. Additional test with a similar set-up were performed by Loosveldt and Vannieuwenhuyse (2012) who investigated the applicability of this concept for wider ranges for most of the used parameters by De Vos.

To make the test results more useful and scientific important, we agreed to perform them for a monopile foundation (instead of a gravity based foundation or GBF) because:

- More tests results for static scour protections are available: this limits the required number of tests, since we can start from the static design (which can be quite well predicted)
- The comparison with the damage numbers of De Vos (2008) can be made.
- A better scale can be used in the available facility compared to GBFs or jacket foundations.

Therefore the proposed tests will expose a monopile, protected with several scour protection configurations, to combinations of waves and currents with the final aim of:

- Reaching a dynamically stable scour protection configuration for a given combination of wave and current loading and a stone size which is smaller than the one for a static scour protection system for the same design conditions.
- Finding a suitable armour layer thickness which allows for reshaping, but also maintains full coverage of the filter layer.

### 2.1.2 The Facilities In Aalborg

The scour tests were performed at the Fluids laboratory at Aalborg University. For all the experiments, a wave flume was used which was advertised as being 25m long, 1.2m wide and 1.5m deep.
The set-up agreed between the Marinet proposal 61 partners and the mentioned university can be found in Figure 2.1 (see also section 6.2).

2.1.3 State At Arrival

Despite the information provided before arrival from and to Aalborg University, there were several differences between the actual facilities and possibilities to create the desired set-up and the conditions previously announced by the University (see also section 6.2).

The first thing to be noted regarding the facilities is that a combined wave and current loading could not be performed in the flume. The existing system with a pipeline for the returning flow, installed underneath the flume, was out of use and no tests with combined waves and currents had been performed in several years. A lot of time was lost in the search for a new test set-up. This caused considerable time delays before the calibration and actual tests could be started. Furthermore, the calibration only gave acceptable results with a water depth of 0.50m. For the water depth of 0.36m, it was not possible to create a steady, symmetrical and laminar current. For the water depth of 0.24m, it was not possible to create any current at all. It is also important to mention that the bathymetry of the flume differed from the expected one. Instead of an upward slope followed by a horizontal part (at the monopile section) and a downward slope (see Figure 2.1: Expected test set up) the flume had a constant upward slope of 1:75 (see Figure 2.2: Final test set-up).

The test area was covered with a layer of sand (thickness of minimum 0.35m). In order to minimize the 1:75 slope of the bathymetry, the thickness of the sand was increased in the upstream direction resulting in a milder slope of (approximately) 1:90 along the sand area meaning that the monopile was on a mild sloping bed.

The length of the flume was 21.4m instead of the advertised 25m and it was not possible to regulate the flow with the 4 submersion pumps that could only be switched on or off. Due to the constant upward slope, the pumps were at the highest point of the flume causing them to suck dry at low water levels. Hereby and because of the minimum amount of water needed for them to work properly, it was not possible to create a current with a water depth of 0.24m.

Furthermore, two new and two old pumps installed asymmetrically across the flume’s cross section (2 new ones on one side and 2 old ones on the other side), were being used for the experiments (with different capacities between the old and the new ones). This caused an undesired, asymmetric current regime for a water depth of 0.36m.

In an attempt to create a more symmetrical, stable flow and in order to diminish turbulence, a ‘current distribution box’ was built in front of the wave paddle and the pipe outlets near the wall of the flume were separated from the flow with curved metal panels (see Figure 3.3). However the current distribution box caused the waves to break in
front of the wave paddle for low water depths (0.24m). Furthermore, the pipe outlets and the curved metal panels interfered with the waves increasing the waves asymmetry.

The here above mentioned problems led to the impossibility of performing the first and the second test series which can be consulted in Table 4. Therefore only the third series with 0.50m water depth was tested.

Still concerning the working conditions and set-up at arrival, it is important to mention that no specific information was available regarding the density and $D_{50}$ value of the provided stones. Therefore, quartz and gravel/coarse sand with a specific/desired sieving curve and known density were ordered in large amounts. The delivery took a couple of days.

The profiler device caused a lot of problems and time delays because of the lack of use, bugs in the profiler software and lubrication problems. Several interruptions occurred while the profiles were being taken.

The set-up at the arrival date also presented some reflection problems (higher reflection than the acceptable values). The modification made to account for this situation consisted in placing absorbing foam at the rear end of the flume in order to absorb the waves.

### 2.1.4 Final Test Set-Up

After the evaluation of the set-up present at arrival and the modifications made in order to resolve several (but not all) problems, a final test set-up was achieved. Due to some remaining issues (the configuration of the pumps, the constant upward slope,...) the calibration of the waves and currents only gave acceptable results for a water depth of 0.50m meaning that only the third test series could be performed.

The proposed model scale was 1:50 and the proposed monopile had a diameter of 5.0m in prototype. The scaled hydrodynamic storm conditions for the 3 test series are presented in the following Table 2.

<table>
<thead>
<tr>
<th>Series</th>
<th>$H$ [m]</th>
<th>$U$ [m/s]</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>$D_p$ [m]</th>
<th>$h/D_p$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^{st}$</td>
<td>0.24</td>
<td>0.18</td>
<td>0.14</td>
<td>1.56</td>
<td>0.1</td>
<td>2.4</td>
</tr>
<tr>
<td>2$^{nd}$</td>
<td>0.36</td>
<td>0.18</td>
<td>0.14</td>
<td>1.56</td>
<td>0.1</td>
<td>3.6</td>
</tr>
<tr>
<td>3$^{rd}$</td>
<td>0.5</td>
<td>0.18</td>
<td>0.14</td>
<td>1.56</td>
<td>0.1</td>
<td>5</td>
</tr>
</tbody>
</table>

*Table 2 Model scale hydrodynamic conditions*

Table 3 provides information about the used stone gradings during the performed tests.

Further, the $D_{50}$ of the filter was equal to 0.99mm and the sand bed was composed of a uniform fine sand with a diameter of 0.100mm.

<table>
<thead>
<tr>
<th>Name</th>
<th>$P$ (kg/m²)</th>
<th>$D_{50}$ (mm)</th>
<th>$D_{n50}$ (mm)</th>
<th>Prototype grading</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dansand no. 2</td>
<td>2632</td>
<td>0.99</td>
<td>0.83</td>
<td>10-80kg</td>
<td>Granular filter</td>
</tr>
<tr>
<td>Dansand no. 5</td>
<td>2604</td>
<td>1.78</td>
<td>1.49</td>
<td>50/150mm</td>
<td>Armour stones</td>
</tr>
<tr>
<td>Dansand no. 6</td>
<td>2567</td>
<td>2.69</td>
<td>2.26</td>
<td>80/200mm</td>
<td></td>
</tr>
<tr>
<td>Dansand no. 7</td>
<td>2597</td>
<td>4.13</td>
<td>3.47</td>
<td>5-40kg</td>
<td></td>
</tr>
<tr>
<td>Dansand no. 8</td>
<td>2564</td>
<td>6.01</td>
<td>5.05</td>
<td>10-60kg</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3 Available stone sizes used for scour tests*

Figure 2.2 provides an AutoCad drawing of the final test set-up. This figure shows the actual bathymetry that can be compared to the one presented in Figure 2.1 which was taken from information given by Aalborg University.
Figure 2.2 Final test set-up used for the third test series
In order to understand the final set-up configuration and the made modifications (see section 2.1.3), a series of photos are presented in the following figures.

**Figure 2.3** Front view of the pump outlet construction plus new current distribution box and metal panels (“throat”) to isolate the pipe outlets from the flow

**Figure 2.4** Pumps and bypass valve to regulate the flow
Figure 2.5 Downstream view of the flume, including the installation of the wave gages and the ADV device, note that the monopile is not placed in this picture.

Figure 2.6 Gravel sand placed at the starting slope on the upstream side of the sand bed in order to add some roughness and thereby minimize the turbulence of the flow at the position of the monopile.
The program roughly consisted of two phases: a phase in which the flume and equipment was prepared and calibrated, and a phase in which the experiments were carried out. First, the current velocity was calibrated by taking current profiles at several positions across the flumes length and width. Then the waves were calibrated (in a combined waves and current environment) by registering the wave heights and comparing them to the input values in the wave generating software. Since we wanted to know the undisturbed wave and current conditions, the monopile was not present in the flume during calibration.
The current velocity was determined by means of an Acoustic Doppler Velocity meter (ADV), the wave heights were measured by 3 wave gauges.

The main goal of the experiments is to determine the position of the bed protection elements in time. Therefore the channel bed will be measured by means of a profiler that can quickly scan the area around the monopile foundation and generate a 3D rendering of this zone. Scans were taken after 0 waves (pre-scan), 1000 waves, 3000 waves and 5000 waves.

Furthermore photographs of the scour protection were taken before the test and after 1000, 3000 and 5000 waves, an underwater camera was used to follow the dynamic behaviour of the scour protection during the model tests and a regular camera continuously filmed from a fixed position above the flume. From these movies, stills can be selected.

Although wave and current conditions are, due to calibration, known a priori, it is still essential to verify them during the experiments and therefore they were also measured continuously.

The following list gives an overview of all the used equipment:

- 3 wave gauges (Aalborg University)
- Profiler (Aalborg University)
- Photo camera to take overhead pictures (HR Wallingford)
- Submersible camera continuously filming the scour protection during the tests (HR Wallingford)
- Video camera continuously filming the scour protection during the tests (HR Wallingford)
- 1 ADV (Ghent University)
- 1 ADV (Aalborg University)

An AutoCAD drawing of the test set-up during calibration and a drawing of the test set-up during the scour protection tests is presented in Figure 2.2.

The monopile is placed 3.39m behind the beginning of the sand bed. The ADV from Aalborg University is placed 2m in front of the monopile. Further, 3 wave gauges are placed in front of the location of the monopile.

A regular video camera and a submersible video camera are placed 1m behind the monopile and are continuously filming the scour protection during testing.

Further details regarding material and equipment can be found in IMDC’s Memo with the following Document reference: I/NO/12089/12.191/ABO – v3.0. Note that the distribution of the previously mentioned Memo can only be authorized by IMDC’s responsible staff.

2.2 Tests

2.2.1 Test Plan

Three test series were defined for this test program, each consisting of a typical North Sea condition, often used for the design of a scour protection around offshore wind turbine foundations (Table 4).

<table>
<thead>
<tr>
<th>Series</th>
<th>H [m]</th>
<th>U [m/s]</th>
<th>Hs [m]</th>
<th>Tp [s]</th>
<th>Dp [m]</th>
<th>h/Dp [-]</th>
<th>Water depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>12</td>
<td>1.3</td>
<td>5-7</td>
<td>11</td>
<td>5</td>
<td>2.4</td>
<td>Shallow water (avoid breaking waves)</td>
</tr>
<tr>
<td>2nd</td>
<td>18</td>
<td>1.3</td>
<td>7</td>
<td>11</td>
<td>5</td>
<td>3.6</td>
<td>Medium water depth</td>
</tr>
<tr>
<td>3rd</td>
<td>25</td>
<td>1.3</td>
<td>7</td>
<td>11</td>
<td>5</td>
<td>5.0</td>
<td>Deeper water</td>
</tr>
</tbody>
</table>

Table 4 Hydrodynamic prototype conditions
Within the above conditions, mainly the water depth will be varied, keeping the other conditions (waves and currents) constant. The wave height of the first series should be adapted in order to avoid breaking waves. Series 1 and 2 are depth limited conditions which will be less the case for the third test series.

The plan was to start with only three storm conditions and always test a combination of waves and currents because of the limited time in the lab. If tests would advance well, more conditions could be selected later on.

Five days were foreseen for each series and as a first assumption one test a day would be performed. During the tests the following parameters could be varied:

- Stone size of the armour layer ($D_{50} = 0.35m – 0.27m – 0.21m$) (with $D_{50}=0.35m$ the current fall pipe maximum, and otherwise according to the standard gradings).
- Layer thickness ($4D_{50} – 6D_{50} – ...$) (we already know $2D_{50}$ will not work with small stones).
- The scour protection extent ($5D – 7D - ...$).

The armour layer was installed on top of a granular filter layer (and not a geotextile) in order to better represent reality. Multiple sets of filter and armour layer material were foreseen, in order to save time. It was initially proposed to work with the standard stone classes as shown in Table 5.

<table>
<thead>
<tr>
<th>Prototype grading</th>
<th>Prototype stone diameter $D_{50}$ [m]</th>
<th>Minimum (static) prototype layer thickness [m]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/150mm</td>
<td>0.100</td>
<td>0.50</td>
<td>Can be installed with a fall pipe</td>
</tr>
<tr>
<td>80/200mm</td>
<td>0.150</td>
<td>0.50</td>
<td>Can be installed with a fall pipe</td>
</tr>
<tr>
<td>5-40kg</td>
<td>0.210</td>
<td>0.50</td>
<td>Can be installed with a fall pipe</td>
</tr>
<tr>
<td>10-60kg</td>
<td>0.270</td>
<td>0.54</td>
<td>Can be installed with a fall pipe</td>
</tr>
<tr>
<td>40-200kg</td>
<td>0.400</td>
<td>0.80</td>
<td>(Slightly) too big for the fall pipe</td>
</tr>
<tr>
<td>60-300kg</td>
<td>0.470</td>
<td>0.94</td>
<td>Too big for the fall pipe</td>
</tr>
</tbody>
</table>

Table 5 Prototype stone gradings

During the tests, ‘smart choices’ had to be made in order to get the most out of the test program. For example: start the tests with a stone grading which is one class smaller than the “static” scour protection stone size, and install twice the layer thickness of a classic scour protection design. Depending on the failure mechanism, the next test could consist of:

- A thicker armour layer if the filter became exposed
- A wider scour protection if failure started at the edges of the scour protection
- A smaller stone size if no failure occurred at all

For each stable design (both static and dynamic), the test was continued for a longer period to investigate the role of the storm duration (cfr. the idea as used previously by de Vos (2008) of 1000 waves + 2000 waves + 2000 waves). This is feasible since the flume didn’t need to be drained for measuring: the profiler probe could be lowered just below the water level for the measurements.

The initial test program agreed before the arrival date can be checked in paragraph 1.2.2.

2.2.2 Activities During This Access Period

This paragraph summarizes the activities which took place during the access period week by week and additional information is provided namely regarding the present staff.

The information contained here can also be consulted in the weekly reports made up by the staff working at the laboratory during this period.
2.2.2.1 WEEK 1

Staff at facility during this period:
Andrew Brown (HRW); Lucia Margeritini (AAU); Niels (Technician AAU); Nikolai Holk (Technician AAU); Philippe de Schoesitter (IMDC)

Other assistance provided by:
Francesco Ferri; Thomas Lykke Andersen; Morten Kramer; Morten Møller Jakobsen

General comments:
Identification of quite some issues regarding the available infrastructure which will delay the test program by at least 2 days.

Work completed:
- Installation of the monopile, wave gauges, ADV and underwater camera.
- Lower the pump outlets + placement of the current distribution box and the porous screen (0.30m high, to avoid disturbance of the waves).
- Cover the flume bathymetry with sand to a level of 35mm above the current bathymetry level.
- Testing of the pumps and wave paddle, introduction to the software (data acquisition, paddle set-up).

2.2.2.2 WEEK 2

Staff at facility during this period:
Andrew Brown (HRW); Niels (Technician AAU); Nikolai Holk (Technician AAU); Philippe de Schoesitter (IMDC)

Other assistance provided by:
Emanuel Stroescu (master student - Universal Foundation); Francesco Ferri; Morten Møller Jakobsen

General comments:
Test case with 0.24m water depth: not achievable (pumps run dry)

Work completed:
- Modification of the current distribution box: smoother box, pipe outlets parallel to the flume walls, ‘throat’. Installation of the second bypass valve.
- General introduction to the Epro software (profiler).
- The test area has been covered with a layer of sand a minimum of 35mm thick. In order to minimise the ~1:75 slope of the bathymetry the thickness of the sand was increased in the upstream direction resulting in a ~1:90 slope along the sand area, meaning the monopile is on a flat bed (or very mildly sloping).
- Determination of the right pump configurations for the target current at different water depths.
- Sieving of the ordered sand to confirm D_{50} values provided by the manufacturer, first try out for painting the sand.
- Spatial and temporal current distribution measurements for 0.50m water depth.
- Calibration of the waves (+ current) for 1000 and 2000 waves at 0.50m water depth.

2.2.2.3 WEEK 3

Staff at facility during this period:
Andrew Brown (HRW); Nikolai Holk (Technician AAU); Philippe de Schoesitter (IMDC); Sarah Audenaert (IMDC); Leen Baelus (UGent); Tiago Ferradosa (FEUP)

Other assistance provided by:
Morten Møller Jakobsen; Palle Meinert
General comments:
Test set-up completed and execution of the first scour test.

Work completed:

- Finishing of the calibration of the currents and waves for the water depth of 0.50m.
- Spatial and temporal current distribution for the water depth of 0.36m. Calibration of the waves for the water depth of 0.36m.
- Some granular material has been placed in front of the wooden ramp to add some roughness. This roughness is meant to slow down the velocity a little bit, in order to prevent the existence of scour holes at the beginning of the sand bed (see Figure 2.6).
- Some foam is added to the wall behind the pumps to decrease the reflection (see Figure 2.7).
- Detailed explanation on the use of the Epro software (profiler).
- The data acquisition cable from the profiler was fixed and reinstalled. Installation and first try out of the profiler.
- After a lot of testing, it was decided to paint all the stones with the spray paint. Also for the smallest stone sizes this method works on the condition that the paint is sprayed in very thin layers.
- A model diary has been finalized along with a checklist that is used before every test.
- Execution of the first test (replica of test no. 46 of De Vos (2008)).
- During the first test, it was noticed that the monopile was vibrating a little bit and that it was quite difficult to position it perfectly vertical. A special construction was made to be sure that during every test set-up the monopile is placed exactly the same. The construction also reduces the vibrations (see Figure 2.8).
- Execution of the second test.

2.2.2.4 WEEK 4

Staff at facility during this period:
Andrew Brown (HRW); Nikolai Holk (Technician AAU); Sarah Audenaert (IMDC); Leen Baelus (UGent); Tiago Ferradosa (FEUP)

Senior Engineers at facility during this period:
Richard Whitehouse (HRW)

Other assistance provided by:
Morten Møller Jakobsen; Palle Meinert

General comments:
Execution of the third test series, note that the other two series were not possible to execute.

Work completed:

- The switch of the pump system is fixed.
- Sort out all of the steps that have to be taken to analyze the results.
- Previously, it took almost 3 hours to drain the flume. This problem is solved by using a removable pump. The flume can now be drained in 30 minutes which saves a lot of time.
- Clean up of the sand on the base of the monopile before scanning the profile so that the vertical offset on the profiles can be corrected in the Epro software.
- A user manual is written for most of the used software (WaveLab, Away6, Epro).
- During the analysis, it was noticed that there is a horizontal offset on the different scanned profiles. This is due to the fact that the profiler cannot be positioned on the exact same point before each scan and due to slip of the motor. To solve this problem a Matlab script was developed.
- Set up of a shift system (2 persons in each shift) to make work more efficient.
- Execution of test s3_002_D50_4x135_2D50
- Execution of test s3_003_D50_4x135_4D50
• Execution of test s3_004_D50_4x135_3D50
• Execution of test s3_005_D50_2x686_8D50
• Execution of test s3_006_D50_2x686_4D50
• Everyone installed the Epro software on his/her computer.
• Aalborg University provided a WaveLab license (till end of December).

2.2.2.5 WEEK 5

Staff at facilities during this period:
Tiago Ferradosa (FEUP); Sarah Audenaert (IMDC); Andrew Brown (HRW)

Other assistance provided by:
Nicolai Holk (Technician); Emanuel (MSc Student)

General comments:
Finish the third test series (0.50m water depth). Preparation and start of the modifications to adapt the flume for lower water depths.

Work completed:
• Execution of test s3_006_D50_2x686_4D50
• Execution of test s3_007_D50_2x686_6D50
• Execution of test s3_008_D50_4x135_3D50
• All the plans and drawings for the modifications have been made and communicated to the technicians.
• Start the modifications at the back end of the flume.
• Digging the pit and removal of the absorbing beach and pipes.
• Also the current distribution box at the paddle end of the flume is removed.
• All the ‘basic’ analysis (waves, currents, profiles) is finished.
• Removal of all the equipment from the flume and storage of everything in a save place.
• Start of the sieving of the desired (larger) stone gradings which will be used during the tests with the smaller water depths.

2.3 RESULTS

2.3.1 The Series Performed

At the beginning of proposal 61 it was agreed that three series of scour protection tests would be performed according to the plan stated in paragraph 1.2.2. However, due to major delays and the impossibility of performing scour tests with lower water depths (0.24m and 0.36m) the working plan was changed.

Nevertheless, considerable efforts allowed the finishing of the third series, which corresponded to a water depth of 0.50m.

This test series represents a typical North Sea, deep water situation. The applied hydrodynamic conditions during this test series (in prototype and model values) are summarised in Table 6.

<table>
<thead>
<tr>
<th>Series 3</th>
<th>H [m]</th>
<th>U [m/s]</th>
<th>Hs [m]</th>
<th>Tp [s]</th>
<th>Dp [m]</th>
<th>h/Dp [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>25</td>
<td>1.3</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>0.5</td>
<td>0.18</td>
<td>0.14</td>
<td>1.56</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6 Prototype and model values for third series’ hydrodynamic conditions
In order to better represent reality, the armour layer was installed on top of a granular filter (Figure 2.9). The used filter material has a $D_{50}$ value of 0.99 mm. The filter layer is, for each test, placed with a thickness of 0.01m.

The armour layer is placed in four concentric rings (width equal to the pile radius) in different colors. In this way it is possible to visually observe where the stones have moved during the test. For each test the same color code is used: the orange stones are placed in the ring closest to the monopile, the uncolored stones are placed in the second ring; the yellow stones are placed in the third ring and the white stones are placed in the outer ring.

The last ring (white ring) is extended under a slope of 1:3 in order to prevent/minimize edge scour. Figure 2.10 gives an example of a test set-up.

The laboratorial work performed during the access period is briefly summarized in the following Table 7. Note that for this series there were no tests left to do.
### 2.3.2 The Remaining Tests

Due to the earlier mentioned reasons it was impossible to finish the initial test program. The problems encountered during the access period, especially in the first two weeks were explained in paragraph 2.2.2. Nevertheless the major problems encountered can be summarized as follows:

- No waves and current combined loading could be performed in the flume at arrival.
- The flume’s bathymetry differed from the previously announced bathymetry by Aalborg University, the continuous slope (1:75) did not match with the desired profile stated Figure 2.1.
- The length of the flume was 21.4m instead of 25m, this had some implications regarding turbulence, streamlines and flow constriction at the monopole section.
- It was impossible to regulate the flow for a water depth of 0.36m, due to the fact that the 4 submersion pumps could only be switched on or off.
- The pumps position was too high (due to the continuous slope) for a water depth of 0.24m. Therefore, it was not possible to generate a current for this water depth.
- The profiler equipment had several working problems, which led to interruptions during test and delays.
- The profiler’s laser could only be used for the third series water depth. A change of the laser probe is needed for the first and the second test series in order to increase the accuracy of the measurements for the lower water depths.
- No specific information was provided regarding the density and $D_{50}$ value of the available stones.
- The available sieves were too small for a quick and effective sieving process.
- There were no facilities for determining the density of the stones or to crush them in order to get the desired $D_{50}$ values.
- The absorbing beach could not do its job successfully and presented high levels of reflection.
- The throat at the wave paddle (curved metal plates around the outlets of the pipes) is moving during the tests and affects the waves.
- For lower water depths (0.36m) the current velocity profiles are asymmetric.
- The wave field proved to be asymmetric as well.

Taking into account the initial test programs the remaining tests still to be performed are the ones foreseen for the medium (0.36m) and shallow (0.24m) water depths. The estimated time here for is about 3 to 4 weeks.

Aalborg University accepted that the situation was not ideal for anyone and they would make time to modify the flume so the other partners could come back for 3 to 4 weeks additional access (end of November/ beginning of December).

It was agreed that Aalborg would make the desired modifications while keeping the long low gradient bed profile so at least that is not changed from what was used for 0.50m depth tests. In this way, all tests done so far don’t have to be repeated entirely.

<table>
<thead>
<tr>
<th>Dansand no. 8</th>
<th>Dansand no. 7</th>
<th>Dansand no. 6</th>
<th>Dansand no. 5</th>
<th>Dansand no. 2 (filter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{50}$</td>
<td>$D_{50}$</td>
<td>$D_{50}$</td>
<td>$D_{50}$</td>
<td>$D_{50}$</td>
</tr>
<tr>
<td>$D_{50} = 6.015\text{mm}$</td>
<td>$D_{50} = 4.135\text{mm}$</td>
<td>$D_{50} = 2.686\text{mm}$</td>
<td>$D_{50} = 1.779\text{mm}$</td>
<td>$D_{50} = 0.99\text{mm}$</td>
</tr>
</tbody>
</table>

**Table 7 Overview test matrix for deep water situation ($h=0.50\text{m}$)**
The following modifications to the flume have been agreed (summary):

- Dig a pit and lower the pumps.
- Place extra valves on the pumps so that the current can be regulated.
- Create a new absorbing beach with lower reflection levels.
- Remove the current distribution box.
- Place the hoses over the wave paddle and let the current come from behind the wave paddle.
- Drill (symmetrical) holes in the wave paddle in order to create a steady, symmetrical, laminar current.
- Replace the laser of the profiler.

Availability of the stones:

- Stones are available at the lab and we agreed on sieving out the desired gradings ourselves with the help of some of the technicians or Emanuel.
- Lucia agreed on determining the density of the provided stones.
- Staff needed in the lab during the extra weeks of access.
- It was agreed in principle that both IMDC and HR Wallingford will provide staff during 2 weeks each. Additional staff will be looked for, since two people are needed in the lab in order to make the tests a success.
- Further discussion is required but HR Wallingford may possibly be able to provide a placement student to assist during the tests.
- Emanuel Stroescu is a master student at Aalborg University who will continue using the test set up. Aalborg agreed that he could help during the extra access time.

The agreement achieved between Aalborg University and the several partners led to the opportunity of performing the remaining tests, i.e. shallow and medium water depths (0.24m and 0.36m respectively).

### 2.4 Analysis & Conclusions

Due to some problems which were encountered in the lab, it was not possible to execute the entire test program as planned. Out of the three test series, only the third one, for the deeper water depth could be performed. Although flow and wave conditions were not perfect, it was considered that the results obtained for the third test series were satisfactory. However the initial main purpose of the test program was not totally achieved due to the major delays that occurred. The shallow and medium water depth series have not been tested yet. Therefore initial objectives were not accomplished.

Despite the problems faced during the 5 week access period the partners managed to overcome the difficulties and showed a remarkable capacity of creating successful solutions. The decisions taken focussed not only on accomplishing the third test series but also to improve the facilities to provide a suitable set-up for future laboratorial work. This was only possible by the good work and collaboration off all people involved (the laboratory technicians, the lab team, the Marinet partners and Aalborg University).

We are also grateful that Aalborg University offered us the possibility of an extended access period to complete the full test program. This consensus implied several flume modifications which were started by the partners working team and are being further implemented by the technicians of Aalborg University. The estimated time to complete this process was 2 to 3 weeks. After the confirmation of the desired set-up and working conditions, the partners will go back to the laboratory for an expected 4 weeks period. During this amount of time the first and the second series shall be completed.
3 MAIN LEARNING OUTCOMES

3.1 PROGRESS MADE

3.1.1 Progress Made: For This User-Group or Technology

Due to the problems encountered during the five week access period, especially in the first two weeks as explained in paragraph 2.2.2 and further summarized in paragraph 2.3.2, it was impossible to finish the initial test program, as described in paragraph 1.2.2. The partners in this user-group have however managed to overcome the difficulties and showed a remarkable capacity of creating successful solutions, in collaboration with Aalborg University which offered us the possibility of an extended access period to complete the full test program.

The final objective is to make a first attempt in the formulation of practical guidelines for the design of a dynamically stable scour protection design, for which the tested conditions provide preliminary assessment. Possible following steps for the research include:

- Comparing results with available datasets from both, experimental and field measurements.
- Increase own dataset of results with new experimental modelling, with varying scour protection characteristics and/or hydrodynamic conditions.

3.1.2 Progress Made: For Marine Renewable Energy Industry

The most commonly applied type of scour protection system around offshore wind foundations is a “statically stable” design, typically consisting of a rock armour layer installed upon a filter layer. Under design conditions no or limited movement of the rocks is allowed in order to guarantee the overall functionality of the scour protection system. In shallow water, such designs often result in large stone sizes which are not always economical due to complicated and time-consuming installation methods.

Alternatively a dynamically stable design allowing some reshaping of the scour protection system can be investigated. However guidelines or standards today do not provide any guidance on the design of a dynamic, reshaping scour protection and therefore physical model results are needed. The preliminary test results of Marinet proposal 61 reveal that the application of a dynamic scour protection system in shallower water conditions looks promising, although more research and detailed analysis of the results is needed.

3.2 KEY LESSONS LEARNED

- Finding a reliable test set up proved to be a real challenge. A lot of difficulties were encountered and overcome in order to find a good and reliable test set up. The most difficult part was obtaining a steady, laminar and symmetrical flow in the flume whilst keeping the wave field undisturbed. The best results were obtained by cutting of a few centimetre from the wave paddle and generate the flow from underneath this paddle.
- A lot of other technical difficulties were encountered under which the colouring of the very small stones of the filter material grading. The best solution is to use a small amount of spray paint, let the stones dry and then rub them. This process is repeated 4 to 5 times in order to get all the sides of the stones painted.
- An important lesson learned is that it is important to know a lot regarding the test facilities when very specific things are required (what is the condition of the flume, what are the exact dimensions, what is the pump capacity, what is the wave paddle capacity, which measurement equipment is available, which modifications are possible, which modifications are not possible,...). A good contact and open communication with the lab is therefore very important.
- It proved to be very instructive to work together with different people with different professional backgrounds.
4 FURTHER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

Following is the list of scientific publications made (published and planned) as a result of this work:

- [published] Sousa, Tiago (2013). Avaliação e verificação dos níveis de segurança de proteções de fundações de estruturas offshore do tipo monopilar, MSc Thesis University of Porto, Portugal. - Thesis -
- [published] Armour stone conference: HR Wallingford - Oral presentation -
- [planned] Publication in a peer-reviewed international scientific journal
- [planned]Paper & presentation at the OMAE conference 2014
- [planned]Paper & presentation at CoastLab 2014

In all of the previous, acknowledgement is given, as requested by the infrastructure access conditions.

4.2 WEBSITE & SOCIAL MEDIA

A reference to the project has been included in the following Web-site & Social Media:

- Announcement on the IMDC website.
- E-newsletter of offshore-wind: http://www.offshorewind.biz/2013/02/12/innovative-scour-protection-system-put-to-test-in-denmark/ (exact copy of the text that was in the announcement on the IMDC website) - access date April.2013 -

5 REFERENCES


Loosveldt, N.; Vannieuwenhuyse, K. (2012). Experimental validation of empirical design of a scour protection around monopiles under combined wave and current loading, MSc Thesis Gent University, Belgium.

6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The main objective of the testing done at the University of Aalborg was to try to find a proof of concept for the idea of a dynamically stable scour projection. A prototype model was thus tested. When, after analysis of the obtained results it shows that this idea might work, more research will be required in order to further validate this concept.
6.2 NOTE ON THE FACILITIES AAU

Note on Deep Flume - AAU-
Prepared by Lucia Margheritini, PostDoc. (lm@civil.aau.dk)
for Marinet project number 01 (first round).
Date 14/06/2012

The flume

The flume is 25 m long, 1.2 m wide, and 1.5 m deep. The wave generator is controlled by a pc-controlled DHI Servo Amplifier. The standard generation software is AWASYS, which is an active absorption system that can be used to generate both regular and irregular waves (typical wave heights are in the range 0.03 m < x < 0.18 m). The AWASYS system is developed by the laboratory. The flume is also equipped with a pump system for producing currents and waves simultaneously. The capacity of the pump is up to 0.2 m/s. If strictly necessary, it should be possible to rent another pump to increase overall capacity. Previous tests on scour ranged between the 1:100 to 1:30 scale.

Scour is monitored with the PROFILER (Fig 1), tool to profile structures – surfaces. The data are handled by EPro, designed at AAU. The data from the profiler can be exported in matlab or similar for further analysis. EPro is anyways already able to calculate eroded volumes scour depth (find here further info: http://vbn.aau.dk/files/4268661/EPro_user_manual).

Typical set up can be seen in Fig. 3.

![Figure 1](image1.jpg)

Test setup for scour experiments

![Figure 2](image2.jpg)
Usually the model of the foundation is made up of two parts: one that is rigidly connected to the very bottom of the flume and an upper part, that is screwed to the lower one and removed before the measurements with the profiler. In Fig. 3 you can see the lower part of a model of a monopile foundation with the profiler measuring the area around it; on the right side there is a result of the profile measurement. It takes around 20 minutes to measure the area around a scour hole. Sometimes measurements must be repeated. Dry measurements are better, but then time to fill in and out the flume becomes very prohibitive and waste of water is something we would like to avoid.

**Figure 3**

**Model – construction - instruments**

It would be of great help if you could come with your own model/s. Nevertheless, if strictly necessary, we can also build them. Different materials are available at AAU for the scour protection and if after scaling we realize we don’t have the right size, we can order them and because they will then stay at AAU, Marinet will cover the costs. In any case, I am now asking if Marinet can cover also construction of models outside AAU and belonging then to the applicant. I will let you know as soon as I get an answer.

We do have wave gauges to measure wave heights. Data acquisition and Analysis is done usually through Wavelab. To measure the current velocity we have different propellers or ultrasonic flowmeters. Those are not the best. If you have instruments that you prefer to use, you can always bring them along.

**Personnel and access**

You have been granted access from the 1st of October to the 16th of November 2012. During this time you can stay in the laboratory as much as you want, but you always must be at least two people for security reasons. I will myself be in the laboratory with you for most of the normal working hours. In addition you will have initial supervision from the EPro developer Palle Meinert and maybe also Anastasia Nezhentseva, PhD on scour around bucket foundations – waiting for confirmation.

**Deadlines**

It is important we respect this time frame for the access, while for the Marinet report we have until the end of January 2013.