# Offshore Windturbines in Areas with Strong Currents

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*Publication date:*
2005

*Document Version*
Publisher's PDF, also known as Version of record

+ VBN

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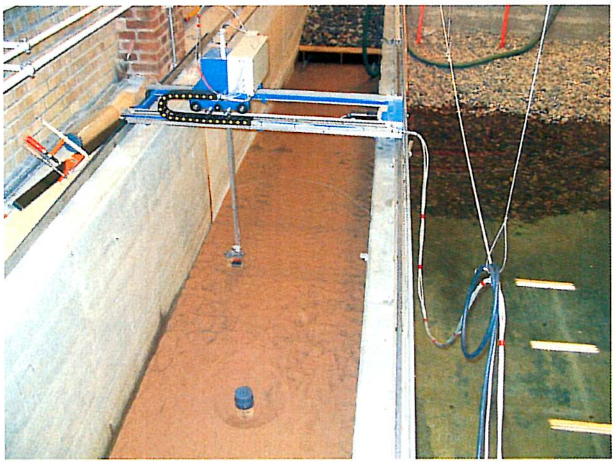

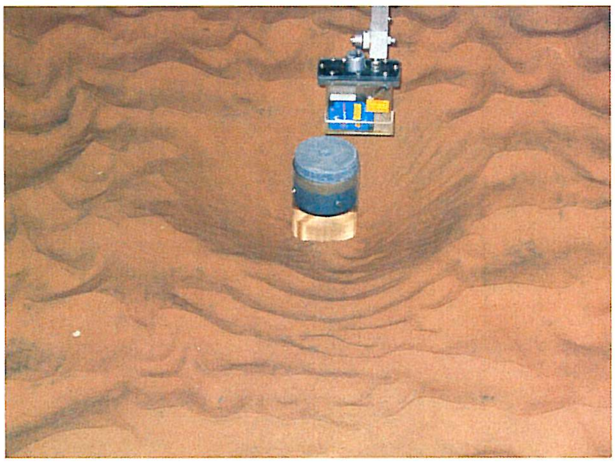

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**Hydraulics and Coastal Engineering No. 19**

**ISSN 1603-9874**

**June 2005**

# Offshore Windturbines in Areas with Strong Currents

by

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# Contents

# Introduction

In connection to the project "Offshore Windturbines in Areas with Strong Currents" a series of model tests have been made at Aalborg University. The project is lead by Offshore Center Denmark and the companies involved are: DHI, Rambøll, Vestas, A2SEA and Aalborg University in Aalborg and Esbjerg.

The overall purpose of the project is to establish a better understanding of the development of scour at circular monopiles of offshore windturbines.

The purpose of the model tests is to illuminate various aspects of scour developed under typical conditions but also to shed light on the influence on scour from various parameters thought to have a significant impact on scour. Furthermore it is the ambition to use the test results in a design situation.

For further information on the conducted test programme contact Brian Juul Larsen (phone: 96 35 72 31, email: i5bjl@civil.aau.dk) or Peter Frigaard (phone: 96 35 84 79, email: peter.frigaard@civil.aau.dk).

# Tests

## Scaling

The tests are performed with a length scale of 1:30. All values are scaled according to Froudes modellaw:

Length: $\lambda_L = 30$
Time: $\lambda_T = \lambda_L^{1/2} = 5.48$

All measures in the following report will be in model scale values.

## Description of Model

The two types of foundation that are being tested are monopiles of 0.1 and 0.2 meters in diameter.

## Description of Set-up

The tests are conducted in a wave flume that is 18.7 meters long and 1.2 meters wide, see figure 1.

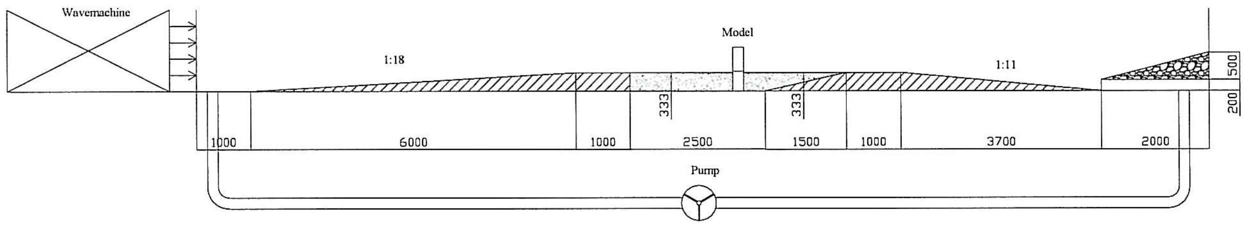



Figure 1. The wave flume. All measures in millimeters.

The top half of the piles can be removed. This feature is used during the profiling of the bed. Sand is spread out in a thin layer across the concrete slopes to reduce the global scour in the sandbox.

## Test programme

The test programme has been designed by Morten Sand Jensen from the consultancy company Rambøll. In relation to the present report on offshore windturbines in areas with strong currents Morten Sand Jensen has also published a review on scour under such conditions.

| Test No | Comments | Diameter of monopile D [m] | Significant wave height $H_s$ [m] | Spectral peak period $T_p$ [s] | Water depth seaward $d_0$ [m] | Water depth at pile $h_t$ [-] | Current induced velocity $U_c$ [m/s] |
|---|---|---|---|---|---|---|---|
| 1.1 | *breaking* | 0.10 | 0.12 | 1.28 | 0.62 | 0.29 | 0.00 |
| 1.2 | *waves, with* | 0.10 | 0.12 | 2.01 | 0.62 | 0.29 | 0.00 |
| 1.3 | *and without* | 0.10 | 0.08 | 1.28 | 0.50 | 0.17 | 0.00 |
| 1.4 | *unidirectional* | 0.10 | 0.08 | 2.01 | 0.50 | 0.17 | 0.00 |
| 1.5 | *current* | 0.10 | 0.12 | 1.28 | 0.62 | 0.29 | 0.30 |
| 1.6 | | 0.10 | 0.12 | 2.01 | 0.62 | 0.29 | 0.30 |

| Test No | Comments | Diameter of monopile D [m] | Wave height H [m] | Period T [s] | Water depth seaward $d_0$ [m] | Water depth at pile $h_t$ [-] | Current induced velocity $U_c$ [m/s] |
|---|---|---|---|---|---|---|---|
| 2.1 | *Only* | 0.10 | | | 0.62 | 0.29 | 0.30 |
| 2.2 | *current* | 0.10 | | | 0.62 | 0.29 | 0.40 |
| 2.3 | - | 0.10 | | | 0.62 | 0.29 | 0.50 |
| 2.4 | *tidal* | 0.10 | | | 0.50 | 0.17 | 0.30 |
| 2.5 | *current* | 0.10 | | | 0.50 | 0.17 | 0.40 |
| 2.6 | | 0.10 | | | 0.50 | 0.17 | 0.50 |
| 2.7 | | 0.10 | | | 0.43 | 0.10 | 0.30 |
| 2.8 | | 0.10 | | | 0.43 | 0.10 | 0.40 |
| 2.9 | | 0.10 | | | 0.43 | 0.10 | 0.50 |
| 2.10 | | 0.20 | | | 0.62 | 0.29 | 0.30 |
| 2.11 | | 0.20 | | | 0.62 | 0.29 | 0.40 |
| 2.12 | | 0.20 | | | 0.62 | 0.29 | 0.50 |
| 2.13 | | 0.20 | | | 0.50 | 0.17 | 0.30 |
| 2.14 | | 0.20 | | | 0.50 | 0.17 | 0.40 |
| 2.15 | | 0.20 | | | 0.50 | 0.17 | 0.50 |
| 2.16 | | 0.20 | | | 0.43 | 0.10 | 0.30 |
| 2.17 | | 0.20 | | | 0.43 | 0.10 | 0.40 |
| 2.18 | | 0.20 | | | 0.43 | 0.10 | 0.50 |
| 3.1 | *Regular* | 0.20 | 0.10 | 1.28 | 0.50 | 0.17 | 0.00 |
| 3.2 | *waves* | 0.20 | 0.10 | 2.01 | 0.50 | 0.17 | 0.00 |
| 3.3 | | 0.20 | 0.10 | 2.50 | 0.50 | 0.17 | 0.00 |
| 4.1 | *Unidir.* | 0.10 | | | 0.62 | 0.29 | 0.30 |
| 4.2 | *current* | 0.10 | | | 0.62 | 0.29 | 0.40 |
| 4.3 | | 0.10 | | | 0.62 | 0.29 | 0.50 |
| 4.4 | | 0.10 | | | 0.50 | 0.17 | 0.30 |
| 4.5 | | 0.10 | | | 0.50 | 0.17 | 0.40 |
| 4.6 | | 0.10 | | | 0.50 | 0.17 | 0.50 |
| 4.7 | | 0.10 | | | 0.43 | 0.10 | 0.30 |
| 4.8 | | 0.10 | | | 0.43 | 0.10 | 0.40 |
| 4.9 | | 0.10 | | | 0.43 | 0.10 | 0.50 |
| 4.10 | | 0.20 | | | 0.62 | 0.29 | 0.30 |
| 4.11 | | 0.20 | | | 0.62 | 0.29 | 0.40 |
| 4.12 | | 0.20 | | | 0.62 | 0.29 | 0.50 |
| 4.13 | | 0.20 | | | 0.50 | 0.17 | 0.30 |
| 4.14 | | 0.20 | | | 0.50 | 0.17 | 0.40 |
| 4.15 | | 0.20 | | | 0.50 | 0.17 | 0.50 |
| 4.16 | | 0.20 | | | 0.43 | 0.10 | 0.30 |
| 4.17 | | 0.20 | | | 0.43 | 0.10 | 0.40 |
| 4.18 | | 0.20 | | | 0.43 | 0.10 | 0.50 |

Table 1. Test programme for the scour tests.

## Measurements

The wave elevation signal is measured beside the model by means of three wave gauges. The wave spectres and the elevation signals are shown in appendix 1. The current velocities are measured with an ultrasonic flowmeter. The scour is measured in a 1.5 cm by 1.5 cm grid with a laser (profiler). The measured grid is 1.5 meter long and 0.93 meters wide. In addition to that the scour holes are measured manually. Figure 2 shows the definitions of stretch and depth (S) of the scour hole.

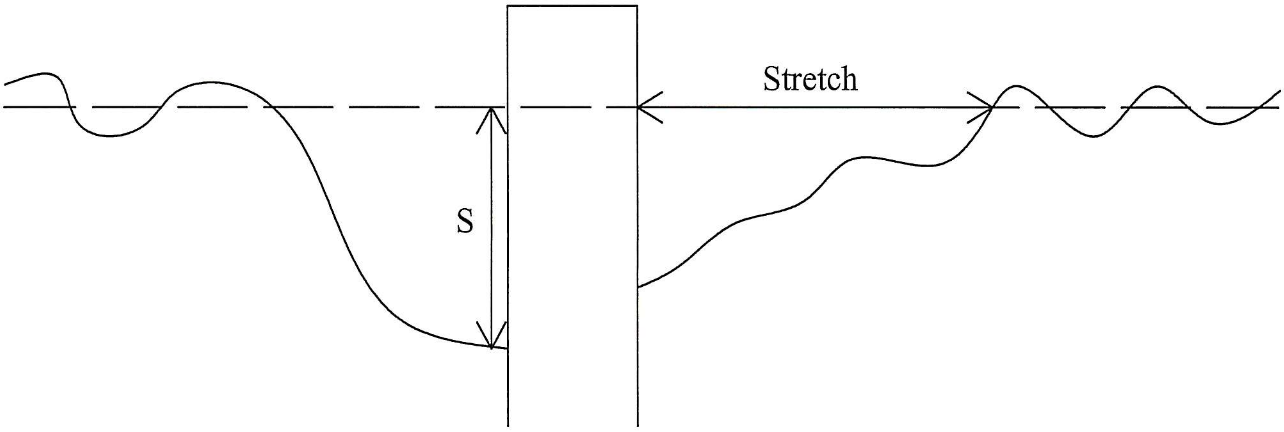



Figure 2. Definitions of stretch and depth (S) of the scour hole.

# Results

Table 2 shows the maximum reached scour depths over the course of the tests. These maxima are the largest depths found from the profiling and / or the manual measurements.

| Test No | Diameter of monopile D [m] | Significant wave height $H_s$ [m] | Spectral peak period $T_p$ [s] | Water depth at pile $h_t$ [-] | Current induced velocity $U_c$ [m/s] | Scour depth S [m] | Relative scour depth S/D [-] |
|---|---|---|---|---|---|---|---|
| 1.1 | 0.10 | 0.11 | 1.31 | 0.29 | 0.00 | 0.012 | 0.120 |
| 1.2 | 0.10 | 0.12 | 1.97 | 0.29 | 0.00 | 0.020 | 0.200 |
| 1.3 | 0.10 | 0.07 | 1.28 | 0.17 | 0.00 | 0.011 | 0.110 |
| 1.4 | 0.10 | 0.08 | 1.97 | 0.17 | 0.00 | 0.014 | 0.140 |
| 1.5 | 0.10 | 0.11 | 1.31 | 0.29 | 0.30 | 0.078 | 0.780 |
| 1.6 | 0.10 | 0.12 | 1.97 | 0.29 | 0.30 | 0.078 | 0.780 |
| 2.1 | 0.10 | | | 0.29 | 0.30 | 0.118 | 1.180 |
| 2.2 | 0.10 | | | 0.29 | 0.40 | 0.154 | 1.540 |
| 2.3 | 0.10 | | | 0.29 | 0.50 | 0.140 | 1.400 |
| 2.4 | 0.10 | | | 0.17 | 0.30 | 0.129 | 1.290 |
| 2.5 | 0.10 | | | 0.17 | 0.40 | 0.155 | 1.550 |
| 2.6 | 0.10 | | | 0.17 | 0.50 | 0.170 | 1.700 |
| 2.7 | 0.10 | | | 0.10 | 0.30 | 0.120 | 1.200 |
| 2.8 | 0.10 | | | 0.10 | 0.40 | 0.145 | 1.450 |
| 2.9 | 0.10 | | | 0.10 | 0.50 | 0.175 | 1.750 |
| 2.10 | 0.20 | | | 0.29 | 0.30 | 0.150 | 0.750 |
| 2.11 | 0.20 | | | 0.29 | 0.40 | 0.270 | 1.350 |
| 2.12 | 0.20 | | | 0.29 | 0.50 | 0.240 | 1.200 |
| 2.13 | 0.20 | | | 0.17 | 0.30 | 0.160 | 0.800 |
| 2.14 | 0.20 | | | 0.17 | 0.40 | 0.245 | 1.225 |
| 2.15 | 0.20 | | | 0.17 | 0.50 | 0.227 | 1.135 |
| 2.16 | 0.20 | | | 0.10 | 0.30 | 0.150 | 0.750 |
| 2.17 | 0.20 | | | 0.10 | 0.40 | 0.220 | 1.100 |
| 2.18 | 0.20 | | | 0.10 | 0.50 | 0.250 | 1.250 |

| Test No | Diameter of monopile D [m] | Wave height H [m] | Period T [s] | Water depth at pile $h_t$ [-] | Current induced velocity $U_c$ [m/s] | Scour depth S [m] | Relative scour depth S/D [-] |
|---|---|---|---|---|---|---|---|
| 3.1 | 0.20 | 0.10 | 1.28 | 0.17 | 0.00 | 0.019 | 0.095 |
| 3.2 | 0.20 | 0.11 | 2.01 | 0.17 | 0.00 | 0.032 | 0.160 |
| 3.3 | 0.20 | 0.09 | 2.50 | 0.17 | 0.00 | 0.026 | 0.260 |
| 4.1 | 0.10 | | | 0.29 | 0.30 | 0.085 | 0.850 |
| 4.2 | 0.10 | | | 0.29 | 0.40 | 0.118 | 1.180 |
| 4.3 | 0.10 | | | 0.29 | 0.50 | 0.118 | 1.180 |
| 4.4 | 0.10 | | | 0.17 | 0.30 | 0.138 | 1.380 |
| 4.5 | 0.10 | | | 0.17 | 0.40 | 0.131 | 1.310 |
| 4.6 | 0.10 | | | 0.17 | 0.50 | 0.165 | 1.650 |
| 4.7 | 0.10 | | | 0.10 | 0.30 | 0.105 | 1.050 |
| 4.8 | 0.10 | | | 0.10 | 0.40 | 0.085 | 0.850 |
| 4.9 | 0.10 | | | 0.10 | 0.50 | 0.160 | 1.600 |
| 4.10 | 0.20 | | | 0.29 | 0.30 | 0.055 | 0.275 |
| 4.11 | 0.20 | | | 0.29 | 0.40 | 0.240 | 1.200 |
| 4.12 | 0.20 | | | 0.29 | 0.50 | 0.240 | 1.200 |
| 4.13 | 0.20 | | | 0.17 | 0.30 | 0.095 | 0.475 |
| 4.14 | 0.20 | | | 0.17 | 0.40 | 0.225 | 1.125 |
| 4.15 | 0.20 | | | 0.17 | 0.50 | 0.150 | 0.750 |
| 4.16 | 0.20 | | | 0.10 | 0.30 | 0.070 | 0.350 |
| 4.17 | 0.20 | | | 0.10 | 0.40 | 0.225 | 1.125 |
| 4.18 | 0.20 | | | 0.10 | 0.50 | 0.230 | 1.150 |

Table 2. Maximum reached scour depths over the course of the tests.

Due to global scour in the sand box the scour depths in table 2 can be slightly uncertain if they are regarded purely as local scour. The global scour has been estimated and subtracted but it can be difficult to quantify and separate from the local scour.

For tests 2.* and 4.* the average S/D values are:

| | |
|---|---|
| Tidal current | 1.26 |
| Unidirectional current | 1.04 |

| | |
|---|---|
| Ø = 0.1 m | 1.34 |
| Ø = 0.2 m | 0.96 |

| | |
|---|---|
| U = 0.3 m/s | 0.86 |
| U = 0.4 m/s | 1.25 |
| U = 0.5 m/s | 1.33 |

Table 3. Average S/D values.

Column 7 and 8 of table 2 are presented graphically in figure 3 and 4.

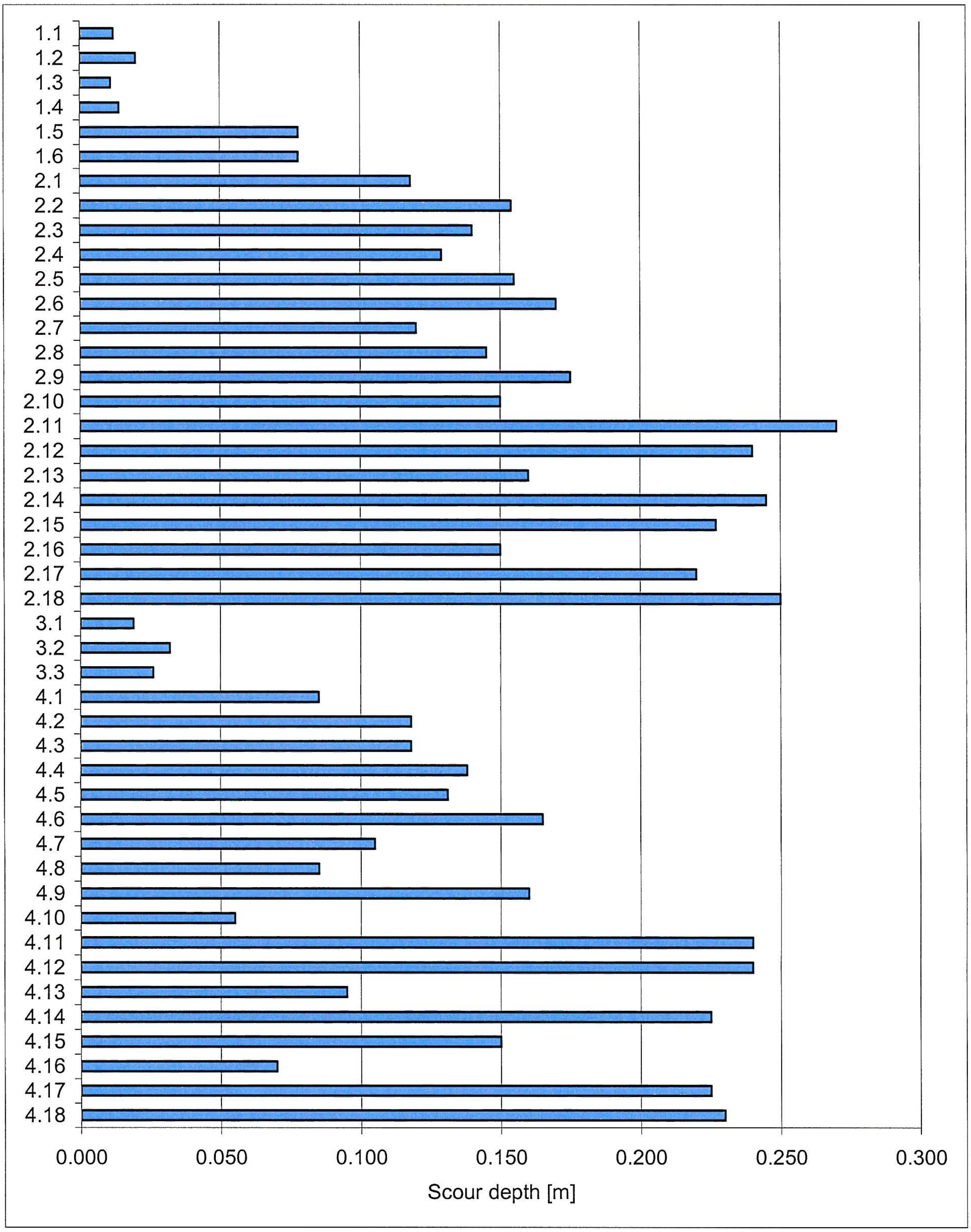



Figure 3. Maximum reached scour depths over the course of the tests.

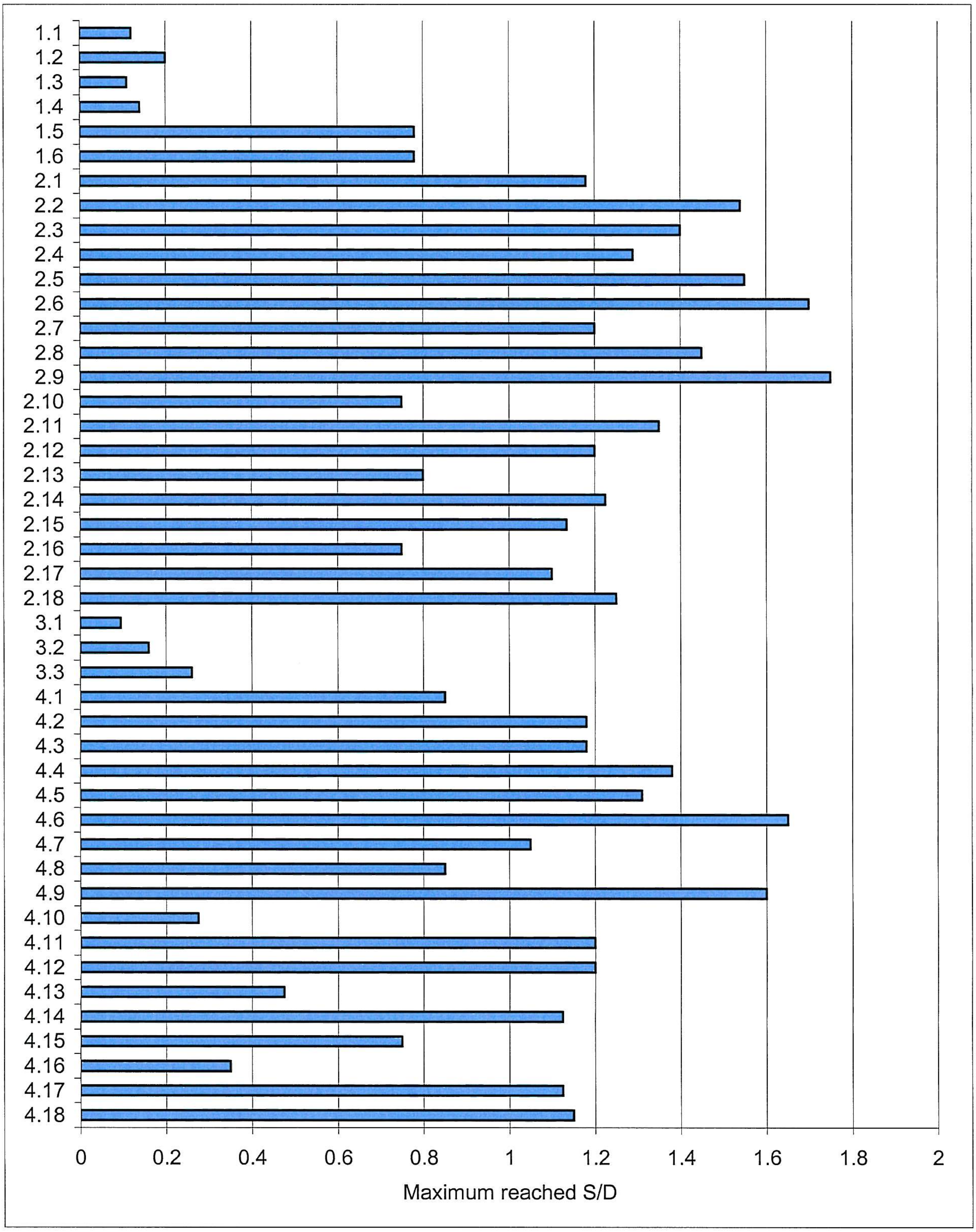



Figure 4. Maximum reached S/D over the course of the tests.

The test duration is not the same for all tests. Figure 5 shows the maximum reached S/D and the test duration of every test in the test programme.

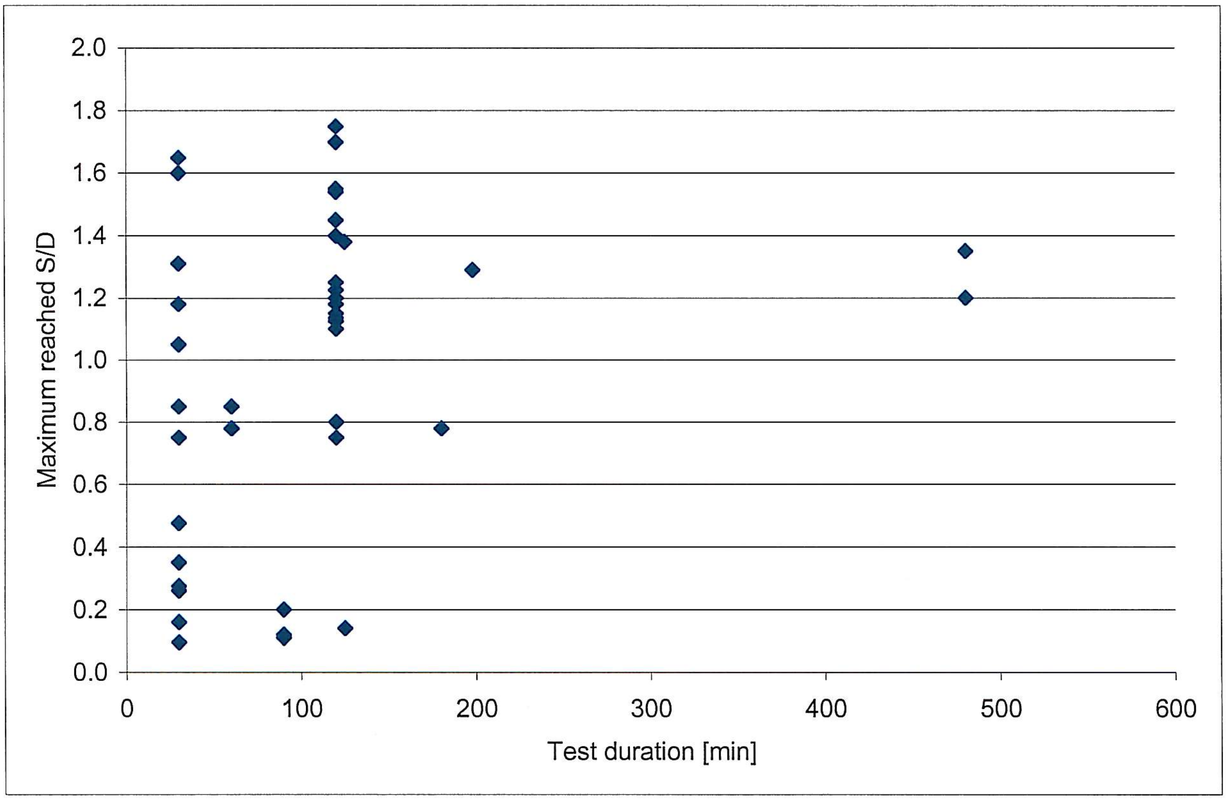



Figure 5. Maximum reached S/D and the test duration of every test in the test programme.

As it can be seen from the test results the cases with waves gives less scour compared with tests where only current is applied. In the following figures focus will be put on part 2 and 4 of the test programme with tidal and unidirectional currents.

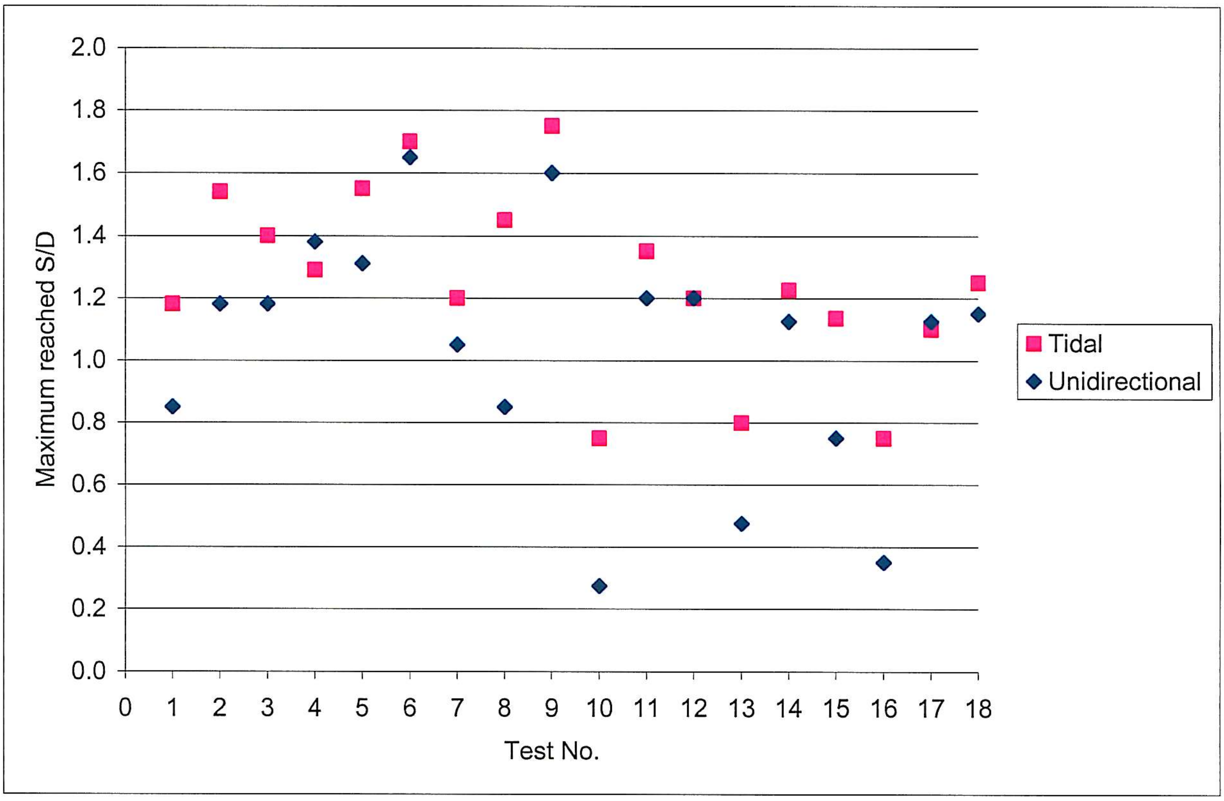



Figure 6. Comparison between test 2.* and 4.*.

With focus on pile size the tests in part 2 and 4 gives the following:

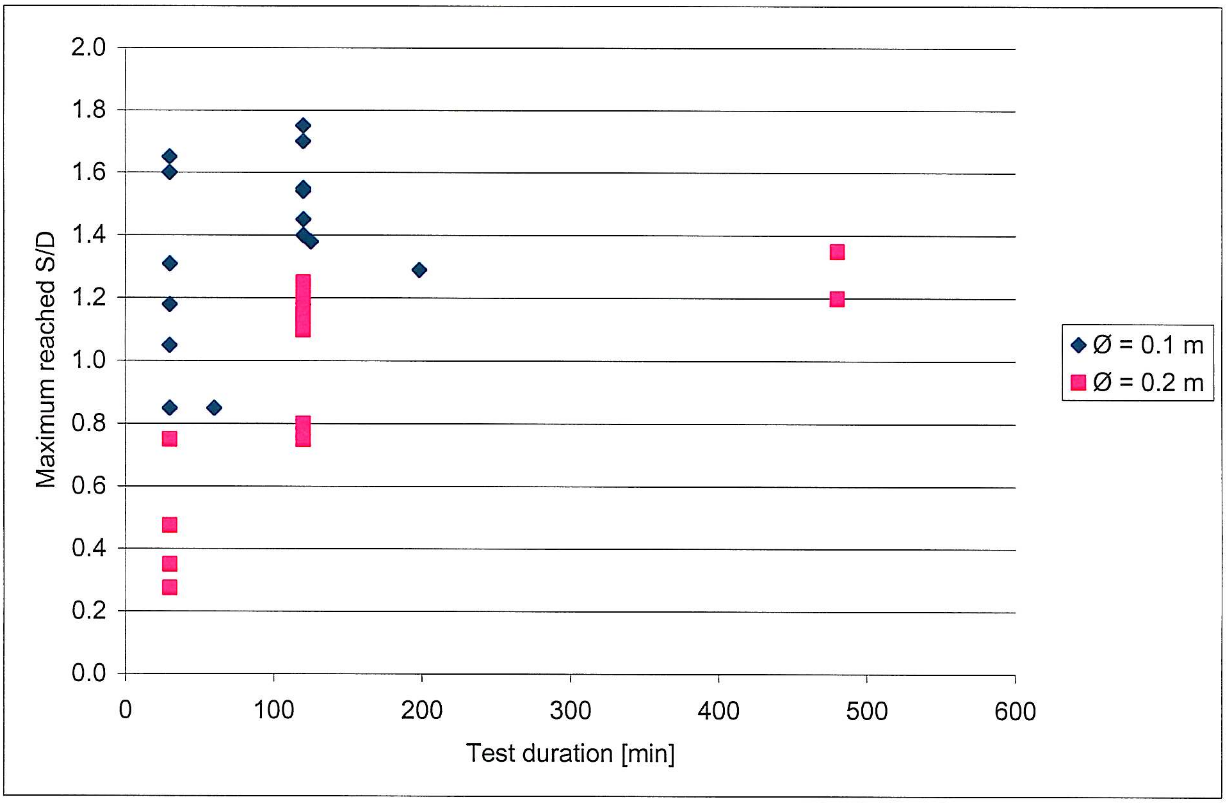



Figure 7. Comparison between pile sizes.

With focus on current velocity the tests in part 2 and 4 gives the following:

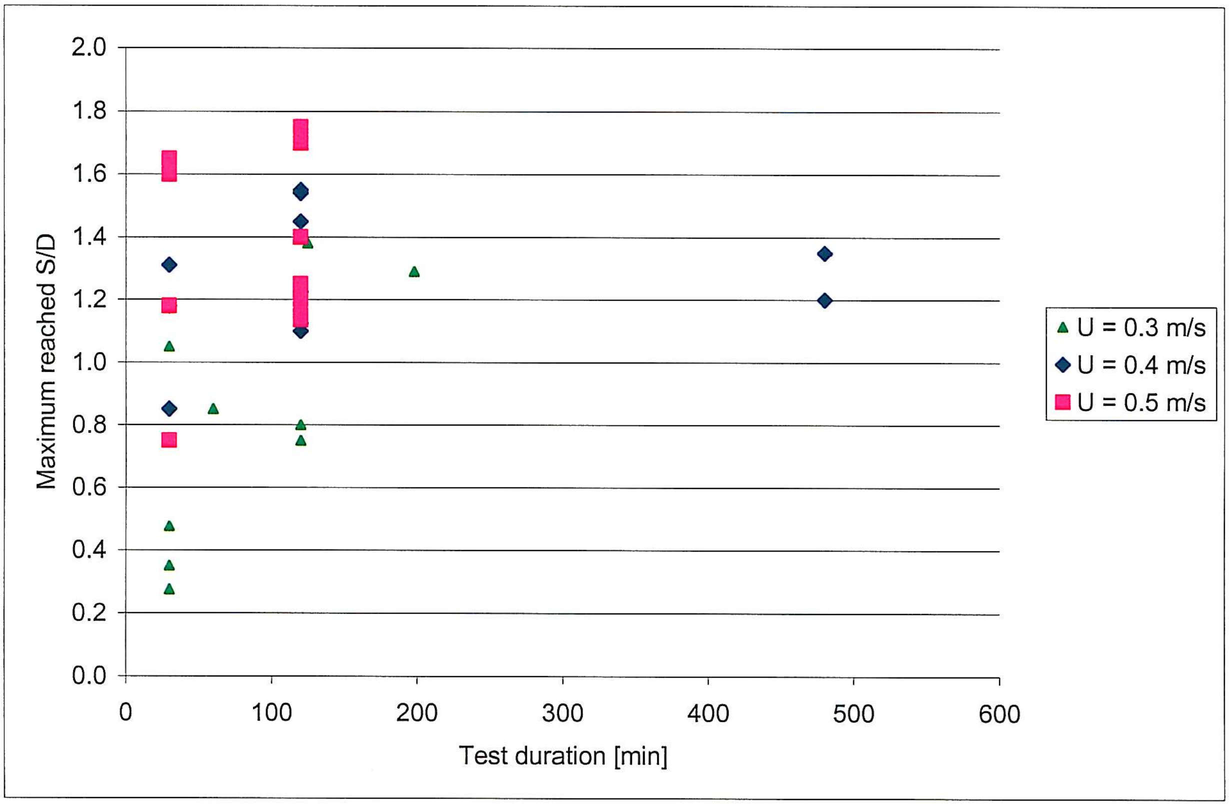



Figure 8. Comparison between current velocities.

A good part of the tests plotted in figure 8 have been measured manually some times over the course of the tests. The result of that can be seen in figure 9.

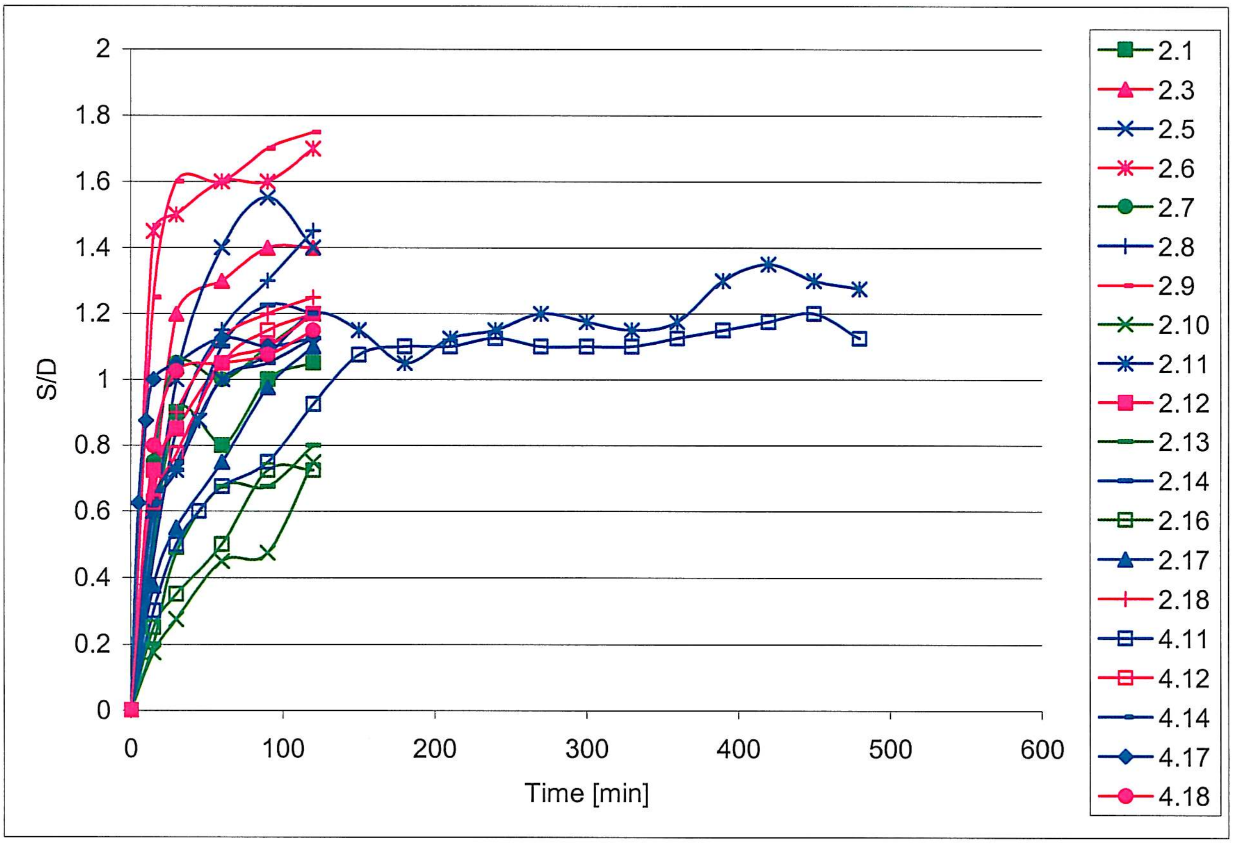



Figure 9. Comparison between current velocities.
Green: U = 0.3 m/s
Blue: U = 0.4 m/s
Pink: U = 0.5 m/s

As it can be seen from figure 9 an eight hour comparative study has been made on test 2.11 and 4.11. Apart from the depth the biggest stretch of the scour holes have been monitored. By use of the biggest depth and the biggest stretch and simple geometric assumptions the following conservative calculations of the volume of the scour holes have been made:

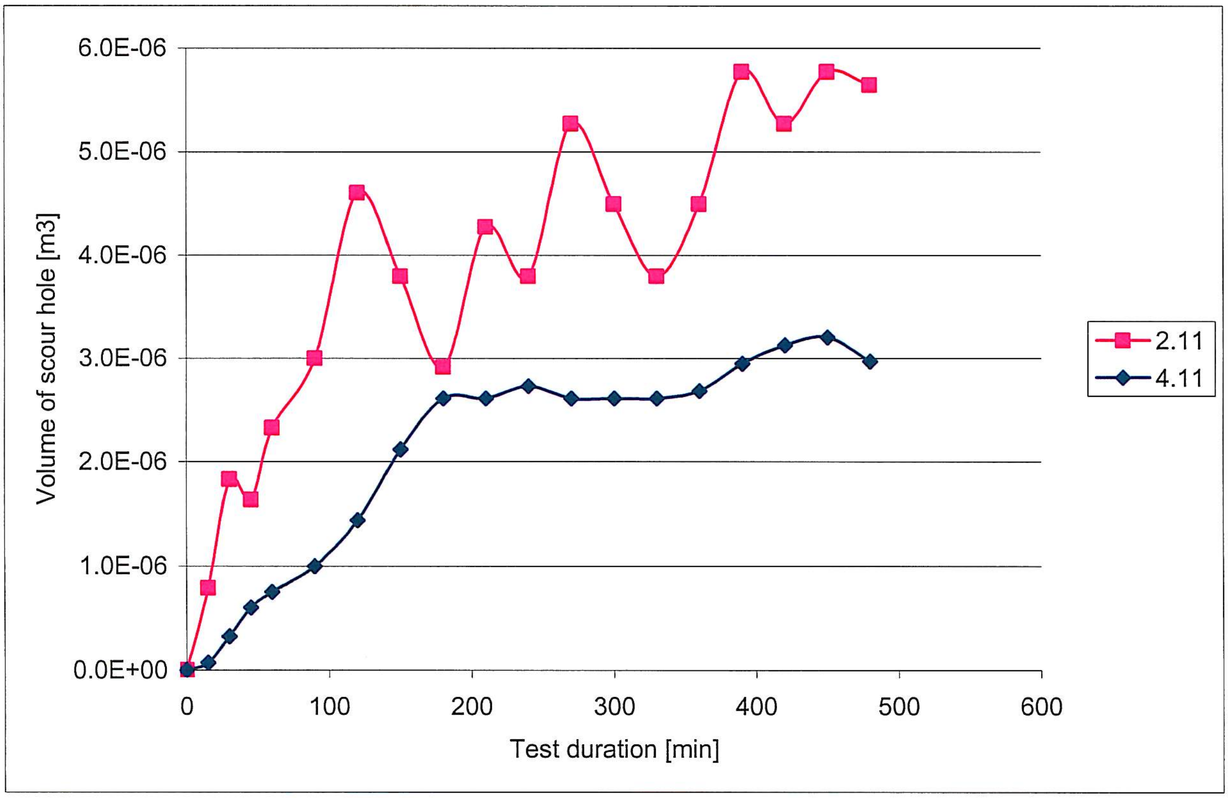



Figure 10. Variation of scour hole volume over time.

## Pictures

Figure 11. The bed has been measured with a profiler. A laser measuring the bed level in a grid.

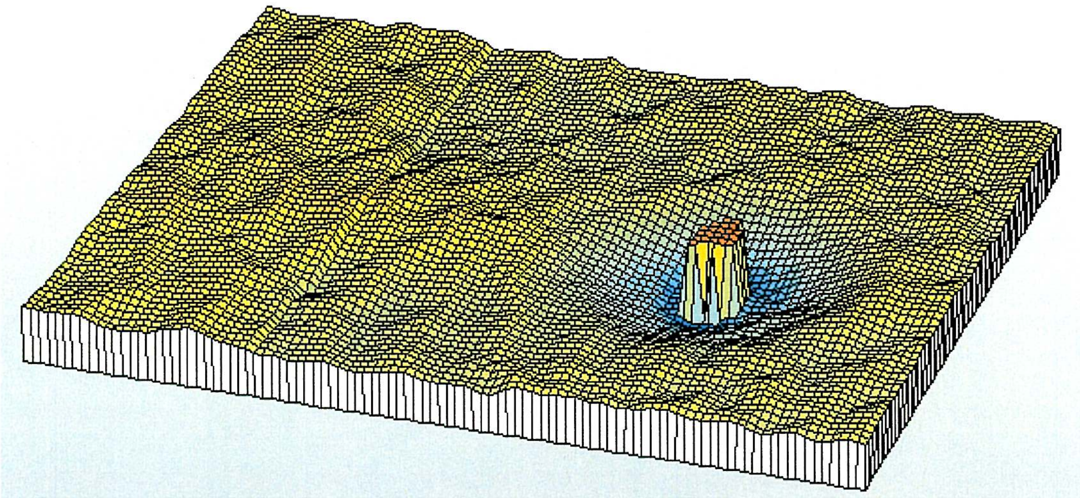


Figure 12. The outcome of a profiler measurement could look this way.

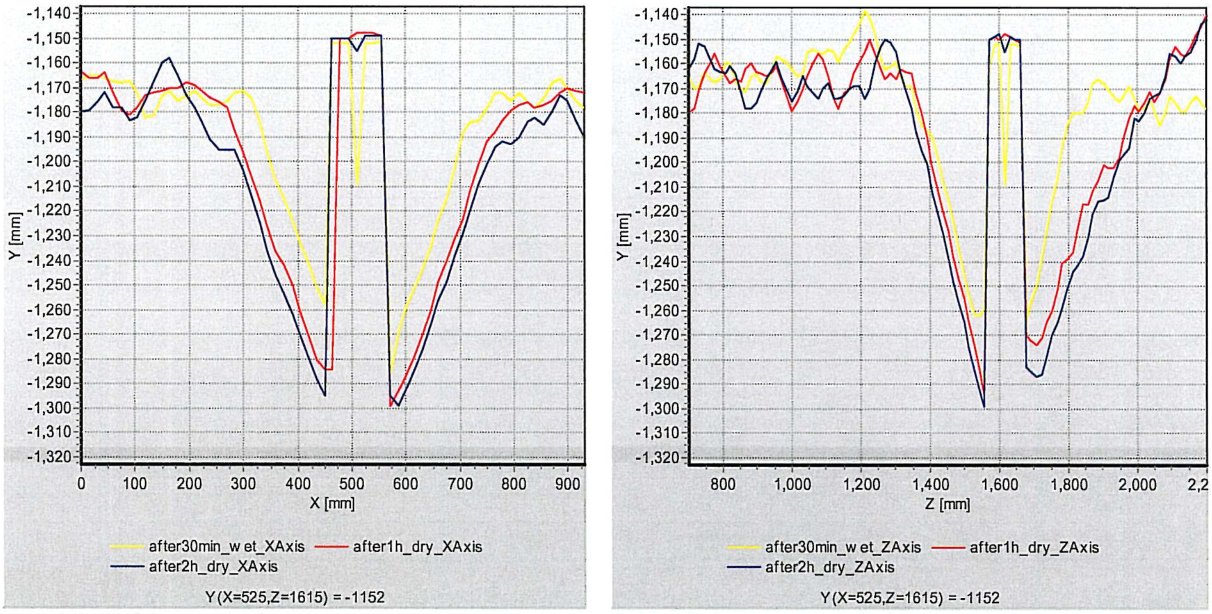



Figure 13. With several measurements over the course of the same test the development of the scour hole has been monitored.

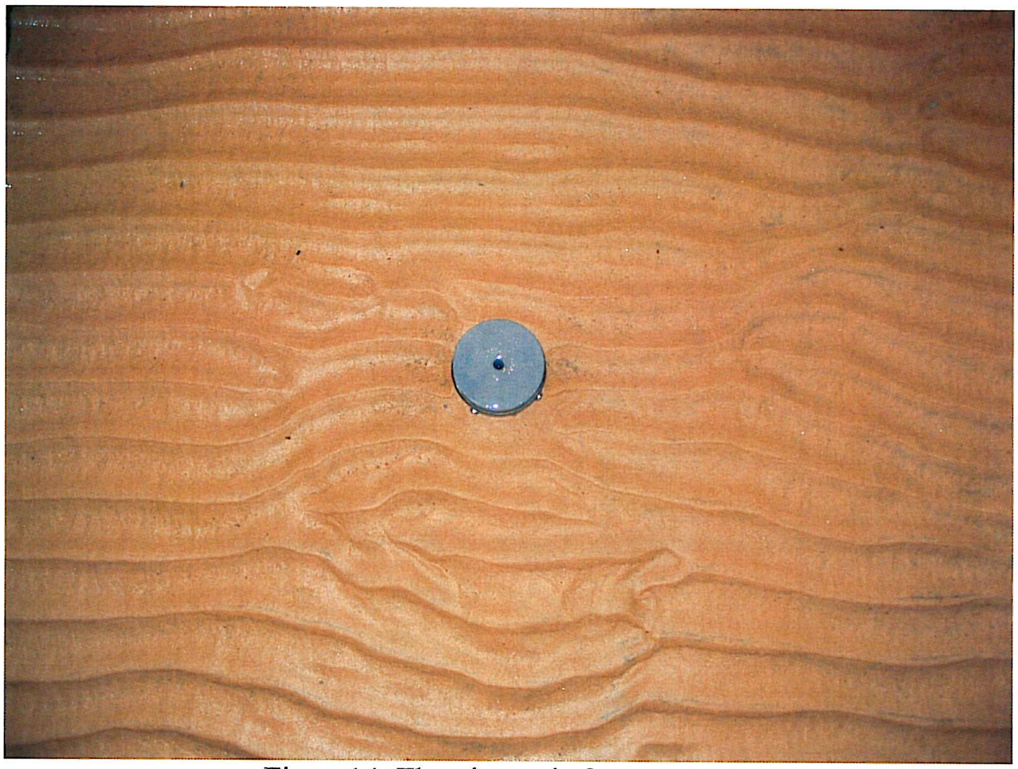


Figure14. The picture is from test 1.1.
In tests 1.1 – 1.4 and 3.1 – 3.3 the scour depths are mainly caused by ripples.

Figure 15. The picture is from test 1.5.
In test 1.5 and 1.6 there was both ripples and a small scour hole.

Figure 16. The picture is from test 2.2.
In tests 2.1 – 2.9 the local scour holes around the pile are of significant magnitude in comparison to the ripples and the global scour.

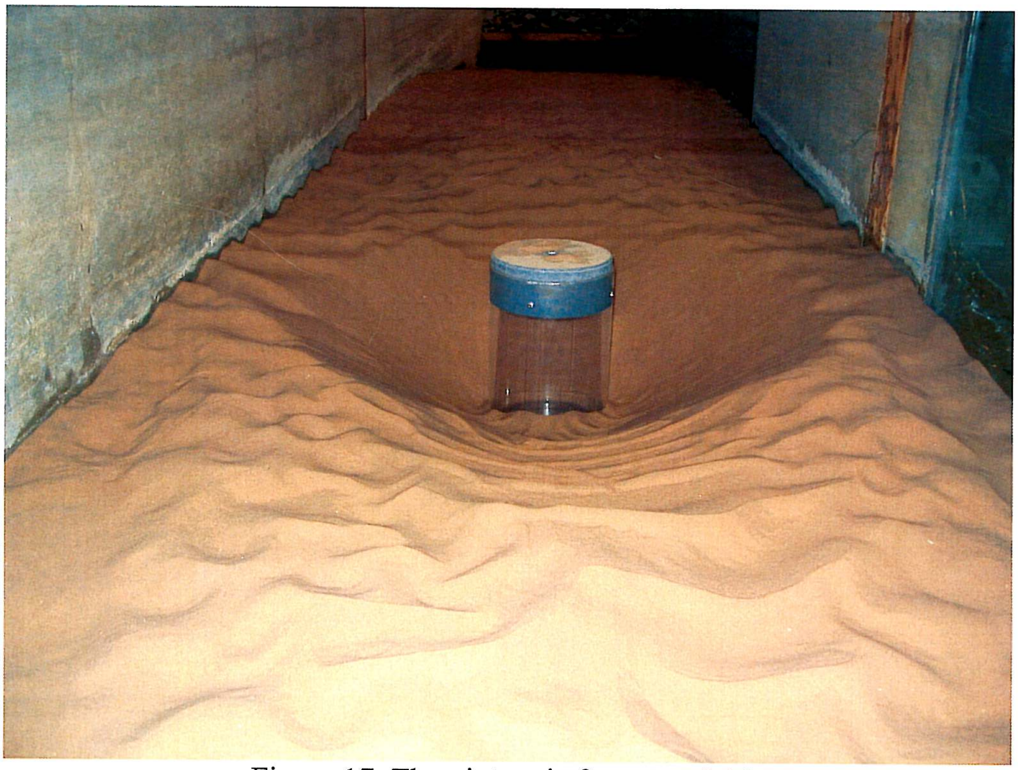


Figure 17. The picture is from test 2.11.
In tests 2.10 – 2.18 the stretch of the scour holes was almost as wide as the width of the flume.

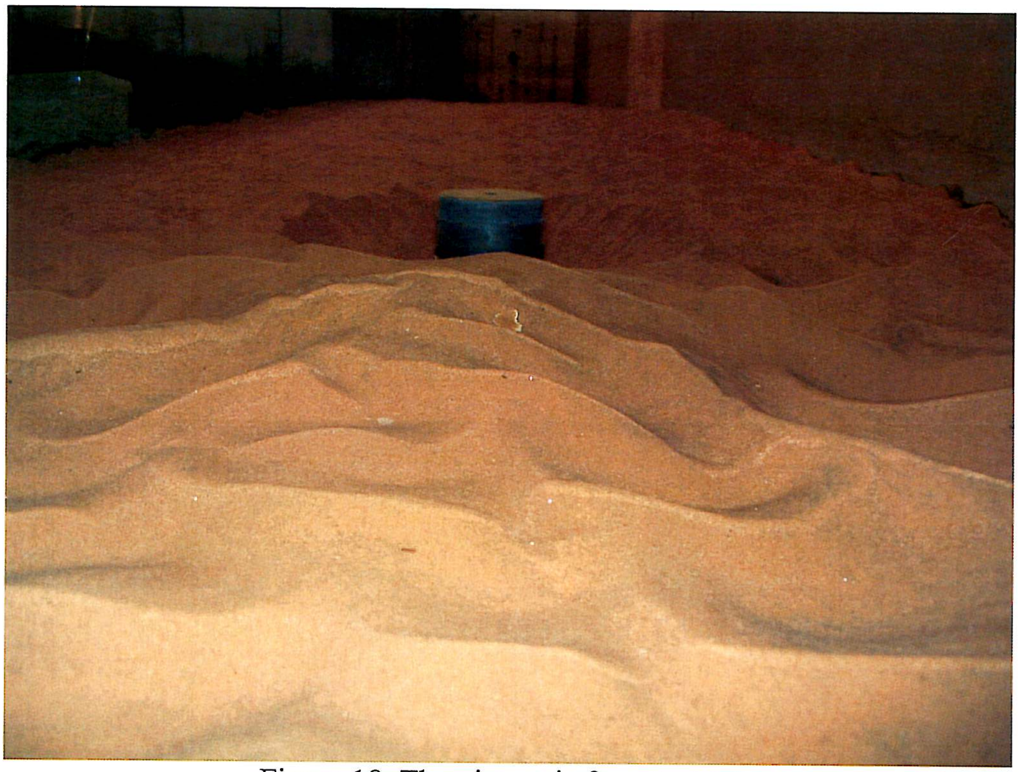
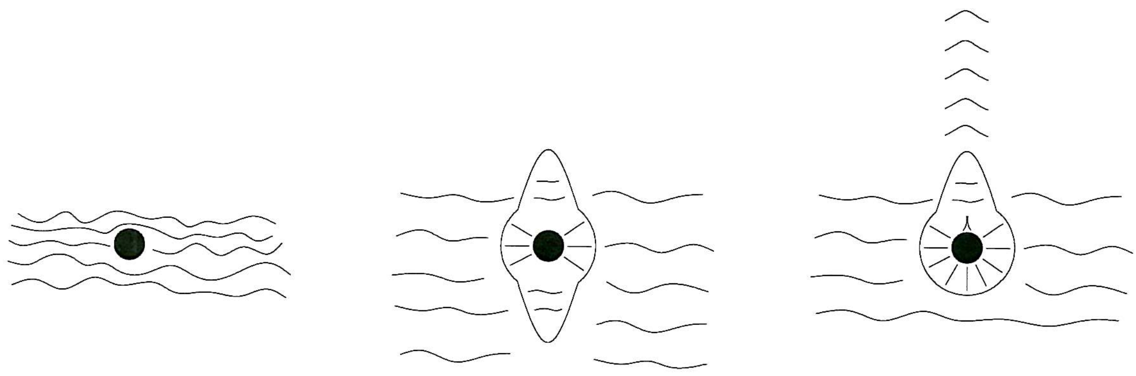


Figure 18. The picture is from test 4.2.
In the tests with unidirectional current there is hump behind the scour hole. The hump on the lee side is the same width as the scour hole and up to 10 times as long.

Figure 19. The pictures are from test 4.11.
The scour holes in part 4 are circular with a tale from ±45° seen from the lee side. Inside the scour hole there is a small hump on the lee side and the circle shape is clearly marked with small ripples "pointing" towards the center of the pile.

As it can be seen from figure 14 – 19 the scour holes have certain characteristics depending on which part of the test programme they come from.



A B C

Figure 20. Typical bed contours from the tests.
A: Part 1 and 3. Waves creating a bed dominated by ripples. Barely any scour.
B: Part 2. Hole created by tidal current creating two tails to make the hole longer than it is wide.
C: Part 4. Unidirectional current creates a hump both inside the hole on the lea side and a long one behind the scour hole.

# Appendix 1 – Irregular Waves

This appendix shows the wave spectres for the tests with irregular waves – 1.1 to 1.6.

## Test 1.1

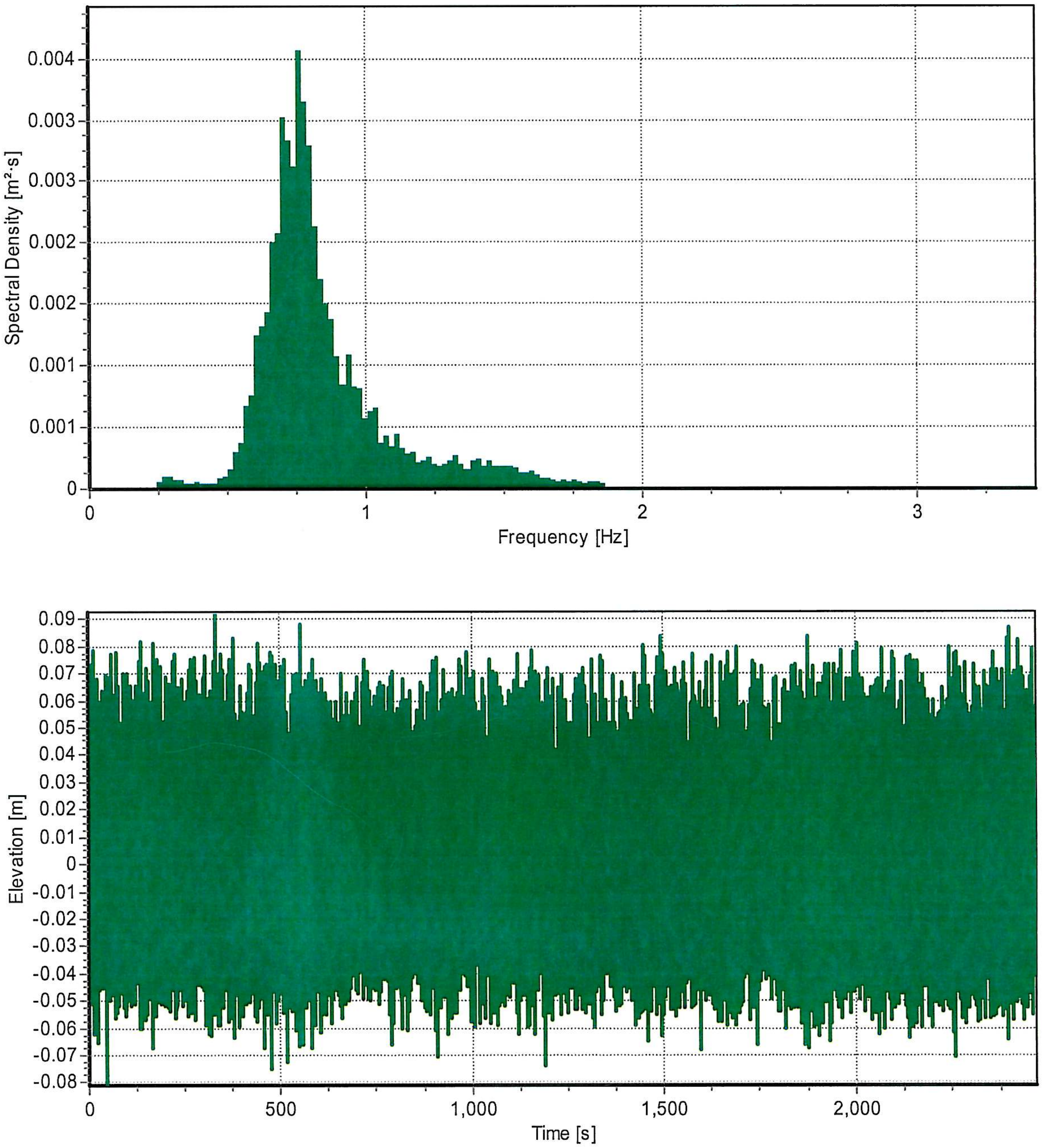
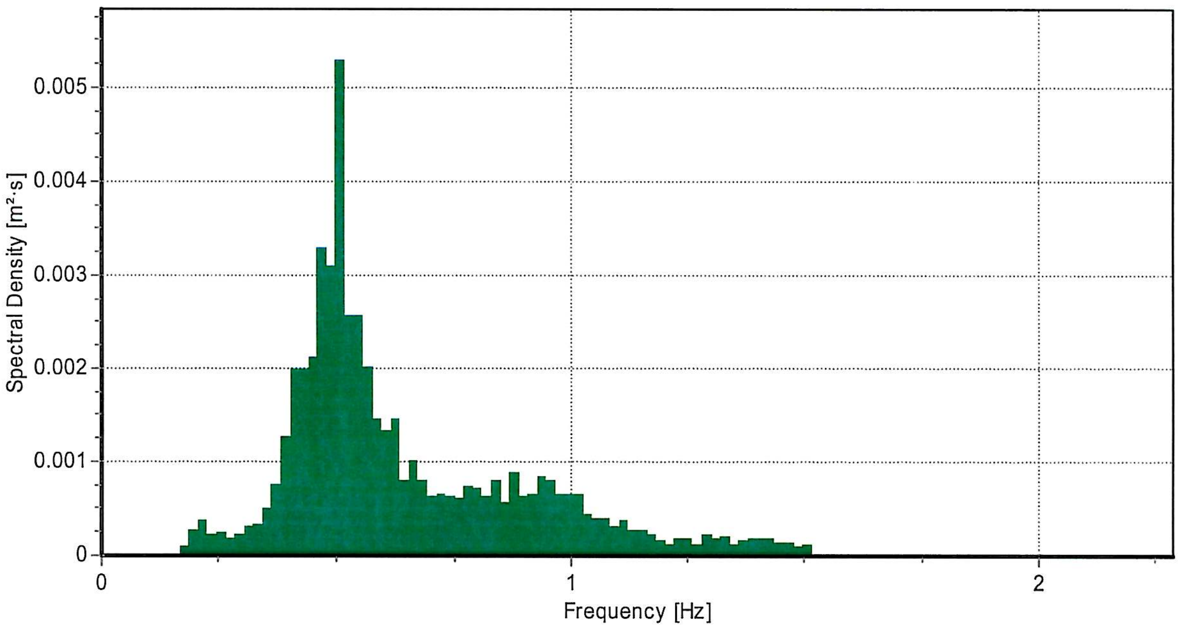



Figure 1.1. Wave spectre and elevation signal for test 1.1.

## Test 1.2



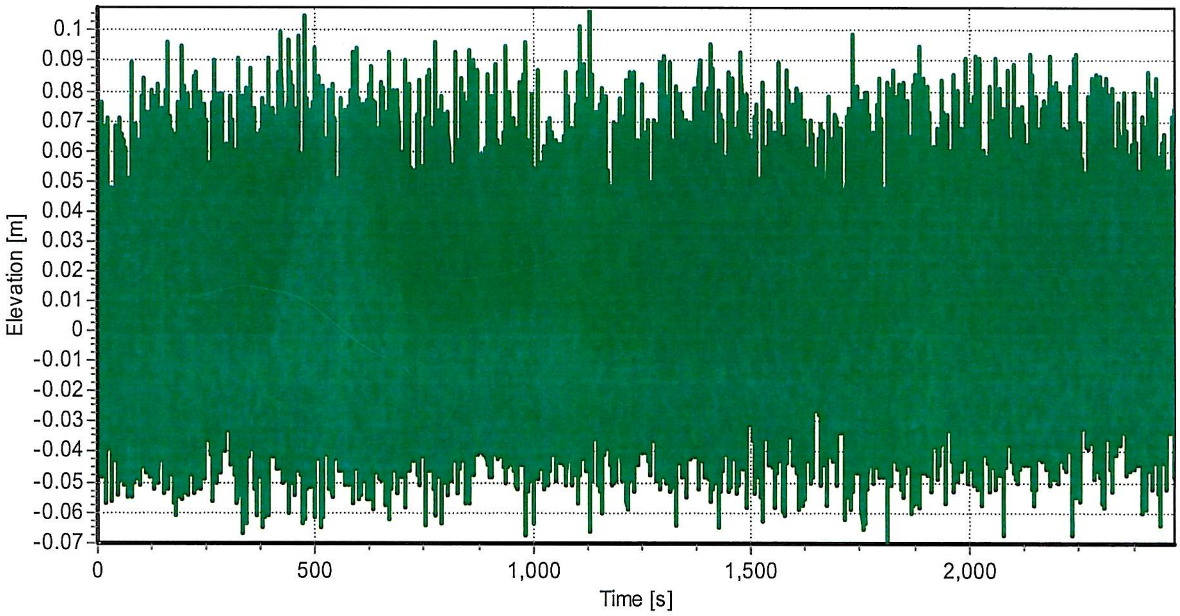
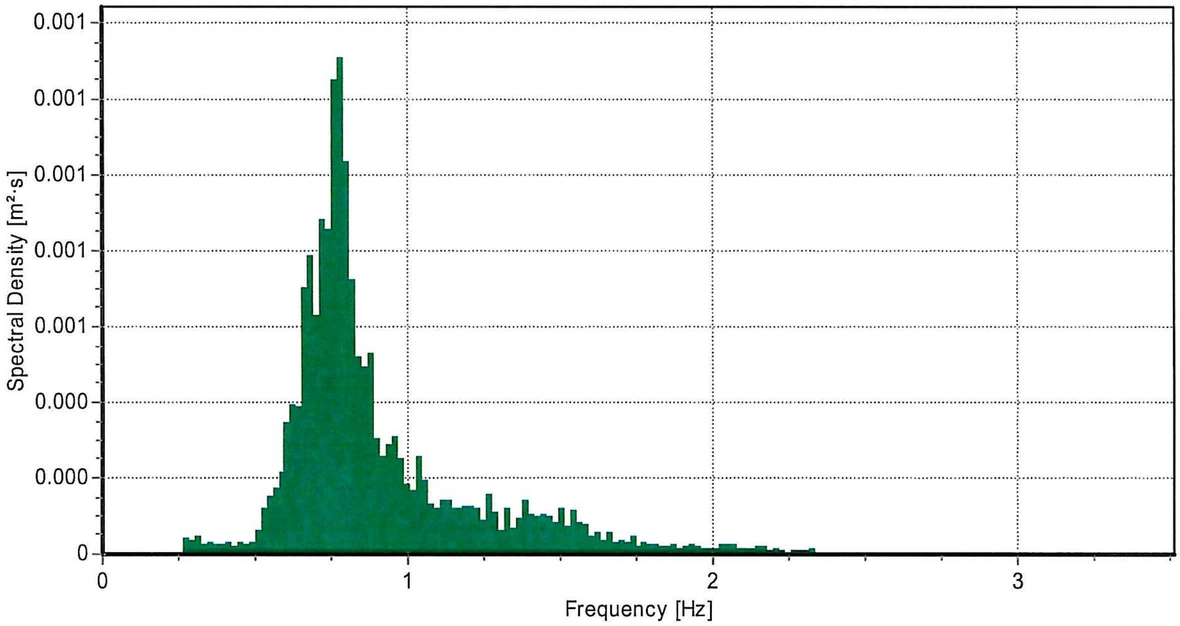




Figure 1.2. Wave spectre and elevation signal for test 1.2.

## Test 1.3



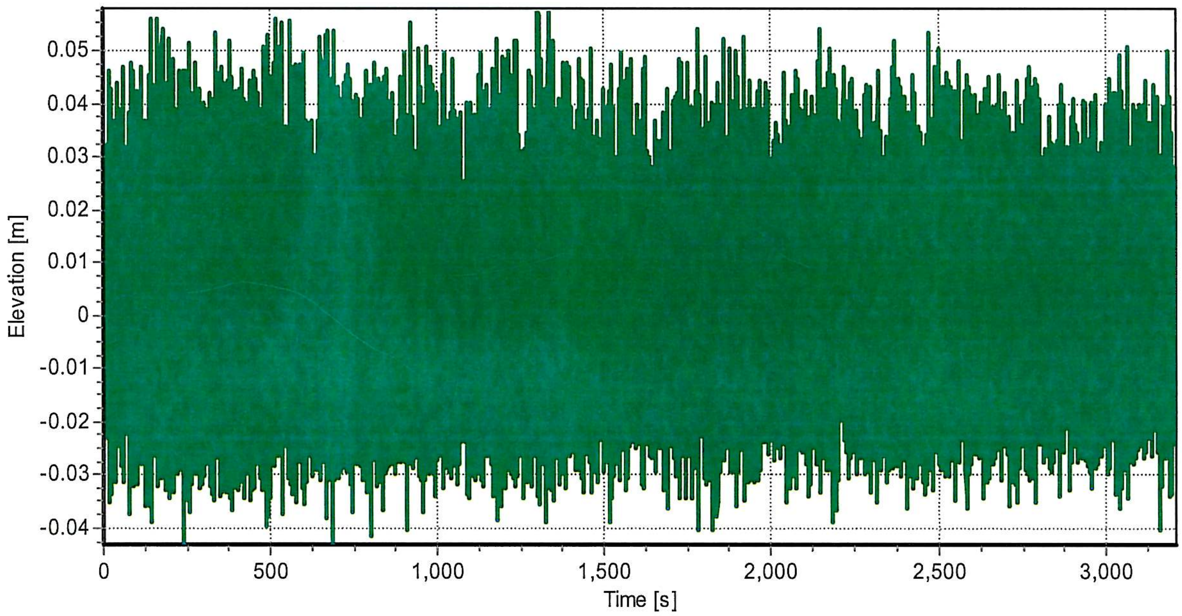




Figure 1.3. Wave spectre and elevation signal for test 1.3.

## Test 1.4

Due to technical problems with the measuring device there are no result plots available for test 1.4.

## Test 1.5

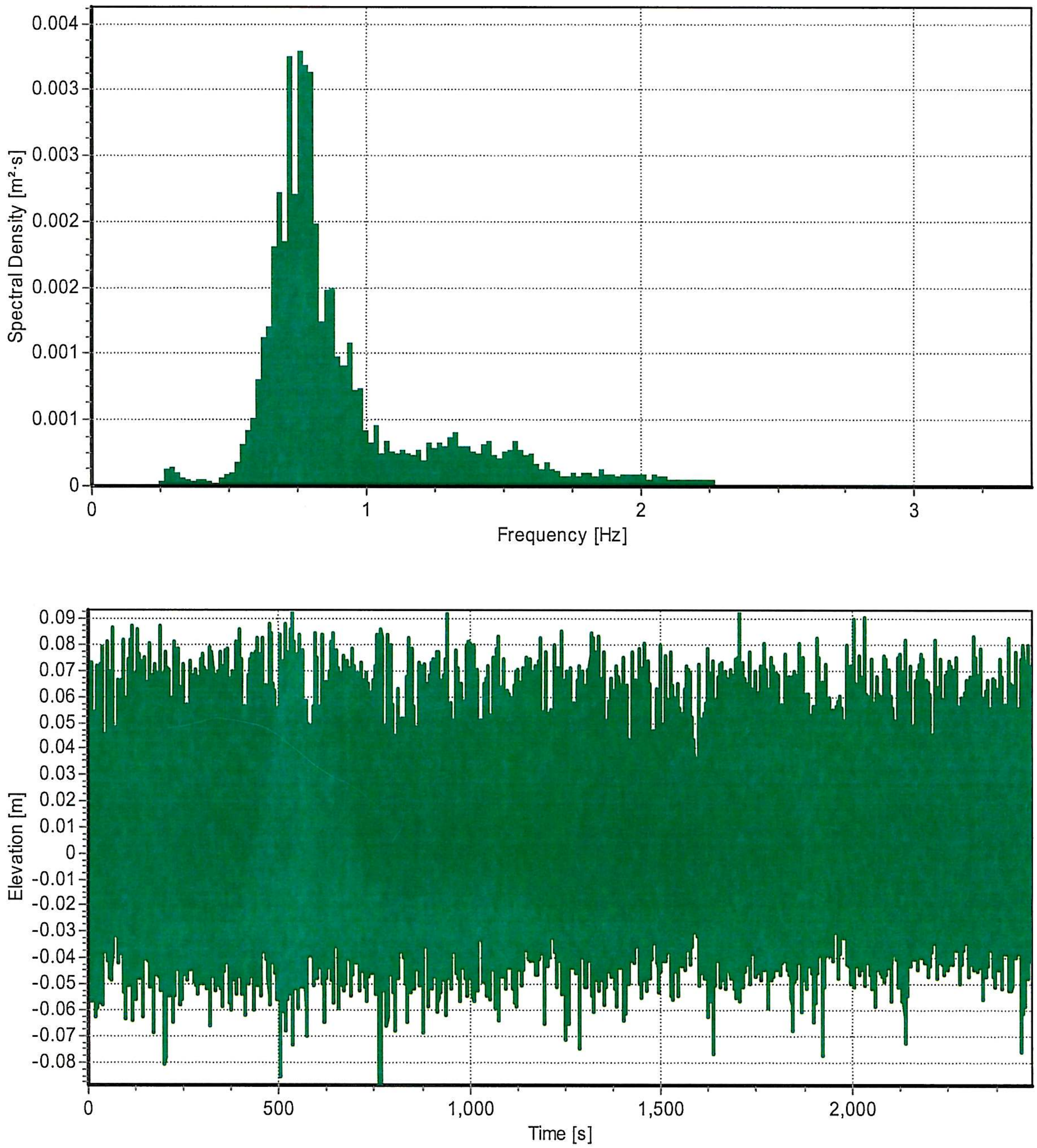



Figure 1.4. Wave spectre and elevation signal for test 1.5.

## Test 1.6

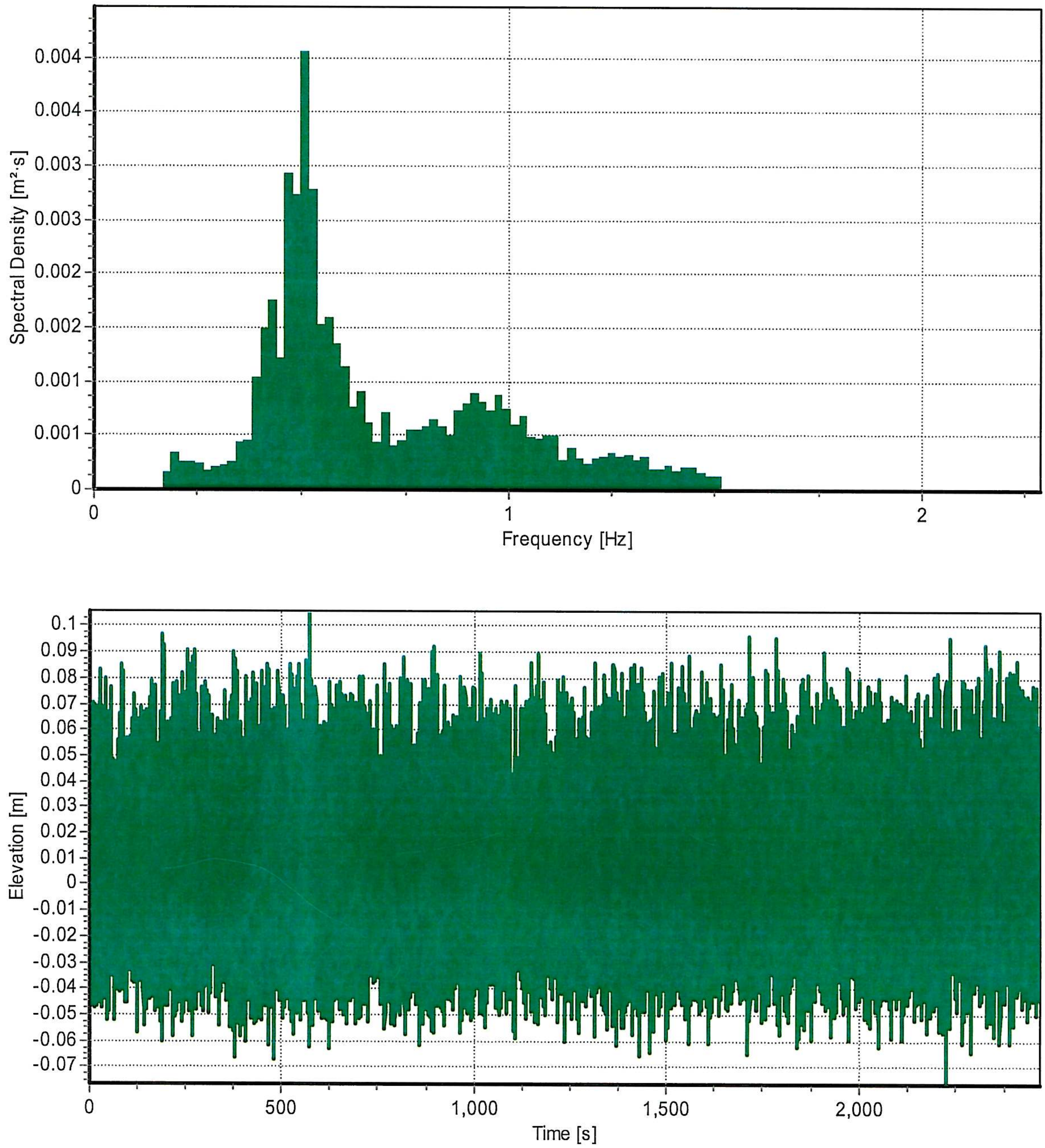



Figure 1.5. Wave spectre and elevation signal for test 1.6.