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Wave height from pressure
measurements

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Preface

This report is written as interim report for a bachelor thesis for the study Civil Engineering of the Delft University of Technology.

I would like to thank Associate Professor ir. H.J. Verhagen for serving as my supervisor. I also would like to thank the staff members of the Fluid Mechanics Laboratory for the help during the experiments. Special thanks go out to prof. dr. G. Masselink of the Plymouth University and his team of the BARDEX II project for giving us the opportunity to test the pressure meter in the Delta Flume. The pressure meters are provided by Environment Mapping & Surveying (EMS) from South Africa and the data of the test in the Delta Flume is provided by Deltares.

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Summary

For this project, Environment Mapping & Surveying (EMS) from South Africa has provided two pressure meters for wave measuring. These pressure meters give a value for the pressure, which must be converted to pressure and after that to a Rayleigh distribution and a wave spectrum. Therefore is the purpose of this report to test the pressure meter and to convert the outcomes of the pressure meter to wave heights, resulting in a Rayleigh distribution and a wave spectrum.

At first, there were calibration tests in still water to measure the hydrostatic pressure. The pressure meter was lowered in the water, with some stops, hanging still. At that moment the water depth could be found in the graph of the measured values in the time, so the relation between the water depth and the measured values is found. With that relation it is possible to find the relation between the measured values and the real pressure. The relation between the measured value V_m and the pressure P is described as:

$$P(V_m) = 254 * V_m - 43250$$

After this, the verification tests are done. These tests are done in the Delta Flume of Deltares, during the Bardex II project. The pressure meter was lowered into the flume, to measure the waves that were made for the Bardex II project. After this, the outcomes were converted by three Matlab-scripts into a Rayleigh distribution, a wave spectrum and some characteristic values, like H_s and H_{m0} . These figures and the values are compared to the measurements of Deltares to find the accuracy of the pressure meter.

The comparison with the measurements of Deltares shows that the pressure meter has an accuracy of five percent. The most important characteristic values are even more accurate, up to one or two percent. The figures of the Rayleigh distribution and the wave spectrum are comparable to the figures of Deltares. These outcomes make the pressure meter a quite accurate instrument to measure waves. Due to the fact that this instrument is inexpensive in comparison to other wave meters, it is a very usable instrument for fieldwork or low-budget projects.

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1. Introduction

There are many different ways to measure wave height and wave length. Most of these ways are expensive or complicated. Therefore, an inexpensive and uncomplicated instrument to make these measurements would be a solution. The pressure meter of Environment Mapping & Surveying (EMS) is such an instrument. It measures the pressure at the bottom of the sea, lake et cetera. With these measured values the wave height and wave period can be found.

The purpose of this thesis is to test the pressure meter and to convert the outcomes of the pressure meter into wave heights, resulting in a Rayleigh distribution and a wave spectrum. The first step is to convert the measured values to pressure values. Therefore the pressure meter has to be calibrated. After that, the pressure is converted to wave height. This is done in two ways. The first way is by way of the frequency analysis. This results in a wave spectrum which shows the distribution of energy over the various wave frequencies. The second way is by way of the period analysis, which results in a Rayleigh-distribution for the wave heights.

In the second chapter of this report, the problem is described. This forms the point of departure for the rest of the thesis. The third chapter, literature, gives the required background information about the linear wave theory. This chapter also shows the expected problems during the experiments and it finishes with background information about other types of instruments to measure waves. The fourth chapter, data processing, is about the converting of the outcomes of the pressure meter to real pressure and after that, to a wave spectrum and a Rayleigh-distribution. Chapter five, experiments, is divided in three parts. The first part, instruments, describes the pressure meter. The second part is a report of the calibration tests and the calibration, while the last part of this chapter describes the verification tests. The results of these tests are analyzed in the next chapter, chapter six. At the end, there is the conclusion in chapter seven.

2. Problem description

2.1 General information

The pressure meter gives a value in Volts for the measured pressure, which must be converted to pressure in Pascal. When the pressure is known, it is possible to get information about the waves. This report deals with two ways to convert the pressure to information about the wave height. The first way is with the frequency analysis and the second way is with the period analysis.

2.2 Frequency analysis

With the help of a MATLAB-script, the pressure is converted to a variance-density spectrum, which shows the distribution of energy over the various wave frequencies. The problem with this type of converting is that the spectrum will give unrealistic values for higher frequencies. A wave with a higher frequency is a shorter wave, which has minimal or none pressure differences at the bottom. Therefore, the output of the pressure meter is just noise. When calculating with that noise, the outcome could be very unrealistic and unreliable. It is necessary to find the frequency where the outcomes become unreliable to get an accurate MATLAB-script for converting the pressure into a wave spectrum.

2.3 Period analysis

The second way is to convert the pressure, also with the help of a MATLAB-script, to a wave distribution, which shows the probability of a certain wave height to occur. For deep water, roughly three times H_s , this distribution is a Rayleigh-distribution with a straight line. In shallow water, the largest waves will break. This causes a curve in the straight line for the distribution, which gives deviations in the outcomes.

3. Literature

3.1 Linear wave theory

The pressure under water depends mainly on two things: the hydrostatic pressure and the pressure caused by waves. According to Schiereck (2003), the subsurface pressure at any water depth can be calculated with:

$$P = -\rho g z + \rho g a \frac{\cosh k(h+z)}{\cosh(kh)} \sin \theta \quad (1a)$$

With:

$$a = \frac{H}{2} \quad k = \frac{2\pi}{L} \quad \theta = \omega t - kx \quad \omega = \frac{2\pi}{T}$$

The first part of this equation represents the hydrostatic pressure, the second part represents the pressure caused by waves. The pressure meter is located at the bottom of the sea, lake et cetera. Therefore, h is equal to $-z$. This means $\cosh(k*0) = 1$. For this project, equation (1a) can be reduced to:

$$P = -\rho g z + \rho g a \frac{1}{\cosh(kh)} \sin \theta \quad (1b)$$

Due to a variety of causes, waves are generally irregular. The best way to describe these irregular waves is with a so-called energy-density spectrum. This spectrum is made on the basis of Fourier analysis and shows the distribution of energy over the various wave frequencies. The total area of the spectrum represents the total energy of the waves, divided by ρg . With this spectrum, a wave height distribution can be derived.

This distribution of wave heights can be described with a Rayleigh-distribution. This Rayleigh-distribution uses the significant wave height, H_s . This significant wave height is equal to the average height of the $1/3$ part of the highest waves, also written as $H_{1/3}$. The Rayleigh-distribution is described as:

$$P\{\underline{H} > H\} = e^{-2\left(\frac{H}{H_s}\right)^2} \quad (2)$$

The Rayleigh-distribution gives a straight line for deep water. In shallow water, the largest waves will break, so there will be a less amount of large waves. The line will bend and the top of the line will be at a lower wave height.

To prevent misunderstandings, it is necessary to get a clear definition about the characteristics of the waves. The period of an individual wave, T , is defined as the time between two downward zero-crossings. The wave height, H , is the highest crest minus the lowest trough between these zero-crossings. The relation between individual wave height and wave period is weak (Schiereck, 2003).

According to Bishop & Donelan (1987) and Kuo & Chiu (1994), the connection between wave pressure and wave height can be written as:

$$H = \frac{H_p}{K_p} \quad (3a)$$

With:

$$K_p = \frac{\cosh k(h+z)}{\cosh kh} \quad H_p = \frac{p'}{\rho g}$$

In this equation, p' is the fluctuation of wave pressure. To compensate the differences between the theory and the outcomes of the tests, an empirical correction factor, N , is added to this equation. The equation is now:

$$H = N \frac{H_p}{K_p} \quad (3b)$$

The Shore Protection Manual (1984) determines: "In general, N decreases with decreasing period, being greater than 1.0 for long-period waves and less than 1.0 for short-period waves." About the accuracy of this equation are different opinions:

- Lee and Wang (1984): "In terms of wave energy spectrum, the linear transfer function is found to be good for intermediate water depth application. The bulk of the spectral components can be faithfully recovered, except in the high frequency range. As water becomes shallower, nonlinearity effect and current influence may also become more prominent. In this case, the linear transfer function should be modified to account these effects"
- Cavaleri (1980): "It was found that waves are more attenuated than it is foreseen by linear theory, the difference being up to 10%."
- Evesta and Harris (1970): "The agreement reported here is much better than most of those cited in the review paper by Grace (1970)."
- Hom-ma, Horikawa and Komori (1966): "The above equation has been recognized for many years to be inaccurate to correlate H_p with H even in the case of regular wave condition."

3.2 Expected problems

The theory is based on sine waves, where each wave has the same wave length and the same wave height. This is in theory, in practice each wave has a different wave length and a different wave height. Usually, waves are combinations of smaller waves and larger waves. Therefore it is difficult to give a clear definition of a wave. When using a spectral analysis, with the definition mentioned in the previous section, where the wave period is defined as the time between two downward zero-crossings, it is possible smaller waves will stay unobserved, because larger waves will dominate the outcomes. Forristall (1982) states: "For random waves, spectral analysis should be used rather than a wave-by-wave analysis. The latter method ignores the fact that individual waves contain energy at frequencies other than that of the inverse of the zero-crossing period." Forristall (1982) names also two other problems. First, the second-order pressure term, due to the kinetic energy of the wave orbital motion, has been neglected. The second point is that nonlinear of higher-order wave effects are not considered.

Another problem is the fact that the pressure meter only works of waves in shallow water. In deep water, the pressure differences are minimal, so the pressure meter is not able to measure pressure

differences. Due to the lack of differences in the measured pressure, the outcome will be a straight line of nearly the same pressures. Therefore it is impossible to distinguish the waves: the results are useless. Whether water is called deep or shallow depends on the relation between wave length and the water depth. When the wavelength is smaller than two times the water depth, the water is deep. When the wavelength is much larger than the water depth, the water is shallow. Although the pressure meter is made for shallow water, this type of water has another problem. Lee and Wang (1984) say: "As water becomes shallower, nonlinearity effect and current influence may also become more prominent." According to Bishop and Donelan (1987) there is now considerable information affirming that linear wave theory is adequate to compensate pressure data and give reliable estimates of the surface wave heights. A well-designed pressure transducer system with proper analysis techniques should give estimates of surface wave heights accurate to within +/- 5%. They also mention that only spectral analysis of the data will give an adequate result. A wave-by-wave analysis would not.

3.3 Other ways of measuring waves

3.3.1 Buoys

There are different ways to measure waves. The most customary way to measure waves is using buoys on different locations in the water. These buoys float on the water surface and measure the vertical acceleration of the buoy. The measured acceleration is integrated two times to receive the wave height. Some buoys also measure the angle of the buoy, which can be translated to the wave period. Depending on the type of buoy, these buoys can measure other things, like the wave direction. The biggest advantage of this type of measuring is the fact these buoys are very solid and reliable. On top of that, a buoy can easily be used anywhere in the world, also for temporary experiments. The biggest disadvantage is the fact that the results of the measuring should be integrated two times, which has a negative effect on the accuracy of the outcomes.

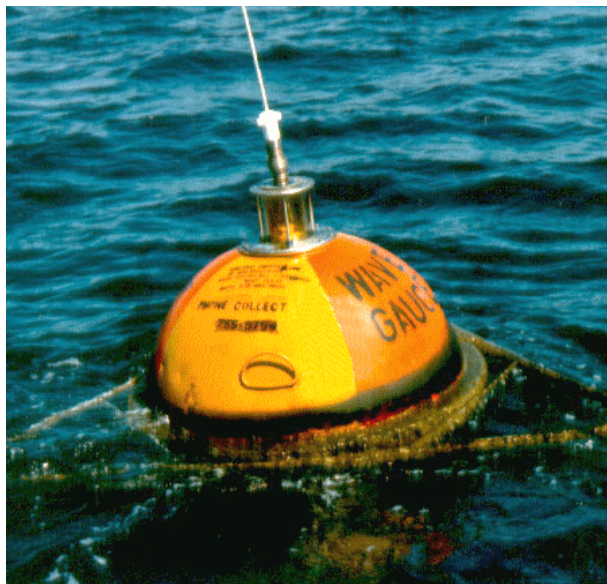


Figure 3.1 An example of a wave buoy

3.3.2 Solid construction

Another way to measure waves is a solid construction, like Rijkswaterstaat uses nearby Petten. These constructions measure the water level with a so-called "step gauge", which can be translated to

wave height and wave period. This type of instrument is often used in shallow water or in combination with another construction, like an offshore platform. An advantage of a construction like this is that it is possible to use the construction for other measuring, like current direction, current velocity, wind direction and wind speed. Of course are these constructions more expensive than a buoy.



Figure 3.2 A detail of a step gauge



Figure 3.3 Wave height meter of Rijkswaterstaat nearby Petten

3.3.3 Radar

Another way to measure the wave height is with radar. This type of measuring is often used at places where it is important to avoid direct contact with the water, like measuring waves with a ship. Another example of this is an offshore platform in deep water with high currents. Due to this deep water and the currents, it is very difficult to use a buoy. The radar could be placed on the offshore platform, so it does not need a construction of its own. A special usage of radar is with a satellite. This type of radar measures the scattering of the water level. With this information, an average wave height can be calculated. The outcomes of radar from satellites are not for one point, but for a larger area, like one square kilometer.

3.3.4 Lidar

A special type of this is the usage of lidar. This works the same as radar, but instead of using radio waves, it uses light. A lidar system can be placed at the bottom and it gives a very good image of the water level. A lidar-system is quite expensive and it is difficult to install.

3.3.5 Pressure meter

The last method to measure waves is with an instrument like the pressure meter, on the bottom or a subsurface buoy. This measured pressure can be translated to the height of the water level and so it can be translated to wave height and wave period.

4. Data processing

MATLAB is used to convert the measured values to pressure values and after that to a wave spectrum for one MATLAB-script and to a Rayleigh-distribution for the other MATLAB-script. The meaning of the scripts is to prevent hand calculations and to get the wave spectrum or the Rayleigh-distribution with just putting in the data from the pressure meter. These scripts also take difference of density into account, so the density must be entered by hand in the script, just as the calibration coefficients. For the analysis of the data, three MATLAB-scripts are used: *crosgk.m*, *spectrum.m* and *rayleigh.m*. These scripts are explained in the next sections. The entire scripts can be found in appendix C. The file with data from the pressure meter must be named as *rawdata.txt*

4.1 Crosgk.m

This script is made by G. Klopman of Deltares to compute a spectrum. This script is used in *spectrum* and it turns a pressure signal with a fast Fourier transform into a pressure spectrum.

4.2 Spectrum.m

In the first part of this script the measured values for the pressure are converted to the real pressure. After this, a regression analysis is made. This regression analysis compensates for changes in the water depth during the measuring, like tides, or changes in air pressure. After this, *crosgk.m* turns the pressure signal into a pressure spectrum. This pressure spectrum is recalculated to the energy spectrum, which is plotted at the end of the script. Just in front of the plot, some characteristic values are calculated. The m_0 is the zeroth spectral moment, which is equivalent to the area under the wave spectrum curve. The m_1 is the first spectral moment, which is the area times the arm of the moment. The m_2 is the second spectral moment, which is the area times the squared arm. The m_{01} is the m_{-1} , which is the minus oneth spectral moment. This is given by the area divided by the arm. After this, T is calculated as function of m . T_m is the square root of m_0/m_2 . T_{01} is given as m_0/m_1 and T_{10} is given as m_{01}/m_0 . T_{10} is the period based on the first negative moment. H_{m0} is written as the square root of four times the square root of m_0 and H_{rms} is written as the square root of eight times m_0 .

4.3 Rayleigh.m

The start of *rayleigh.m* is the same as the start of *spectrum.m*: it starts with converting the measured values for the pressure to the real pressure and after that it makes a regression analysis.

After this, the water depth is calculated out of the pressure values. In the loop, the number of waves is counted by counting each downward zero crossing. With this number of waves, the mean period, T_{mean} , and the wave height H , calculated from the individual pressure variation, is determined. In the next loop, the water level variations, η (or eta), are estimated to turn the pressure signal into a surface signal.

In the third loop the individual waves are determined from the water level. H_{xx} is the wave height for each individual wave. These waves are sorted in order of height in $H_{sorted3}$. Then, there is a loop to ignore waves smaller than a certain wave height, H_{min} . The remaining set of wave heights is called $H_{sorted2}$. With this set H_s and H_{rms} are determined.

At last, some characteristic values are calculated and given in two different ways. The first way is with the measured data, the second way is with the Rayleigh Distribution. These characteristic values are the $H_{2\%}$, $H_{1\%}$ and $H_{1\%o}$. On top of that, the transition wave height according to Battjes and Groenendijk, H_{tr} , and the normalized transition wave height, H_{trNorm} , are given.

5. Experiments

5.1 Instruments

The instrument that is used is a pressure meter, shown in Figure 5.1 and Figure 5.2. It is designed by Environment Mapping & Surveying (EMS) and it is meant to be as simple and cost effective as possible. Because of this, this pressure meter is very appropriate for low budget experiments or fieldwork. The pressure is measured by a Honeywell pressure sensor of the MLH-series at a frequency of four Hertz and saved on a Secure Digital memory card with a capacity of two gigabyte. The power supply can be fixed in two ways. The first way is with four AA batteries. This way is recommended when working in a lab. The second way, for longer deployments, is with two D Cell 3.6v Lithium Ion 16500Ahr batteries.

The data file starts with the burst number, time, temperature (a measured value in Volts) and date. After that, the burst number and the measured values are given and it ends with the final burst number and the end time. It is possible to use the pressure meter to a depth of fifteen meter. The pressure meter measures in a burst of a certain amount of minutes each hour. This amount of minutes can be adjusted and varies from zero to fifty-five minutes per hour. An hour after the start of the first burst, a new burst is started. This continues until the power supply is removed.



Figure 5.1 The pressure meter



Figure 5.2 The inside of the pressure meter

The biggest advantage of this instrument is the fact that it is inexpensive, in comparison with other types of wave height meters. Because of this, the pressure meter is very appropriate for low-budget projects or fieldwork. Appendix E contains the concept advertising brochure of the pressure meter, which contains more information about this instrument.

5.1.1 Preparations

Because the pressure meter is rather light, extra weight needs to be added. This is not only necessary to prevent floating, but also to keep the pressure meter at the required position during the wave tests. During the tests there is a considerable water velocity acting on the meter (due to orbital velocity). To prevent this kind of moving, the pressure meter is tied to a grid of steel, together with

two blocks of lead. The mass of the grid and the pressure meter below water level are negligible. The blocks of lead are weighing twelve kilograms, which is nearly eleven kilograms below the water level. This should be enough to hold the pressure meter on its location in the Delta Flume during the verification tests. The Delta Flume is described in section 5.3.1.



Figure 5.3 The pressure meter in combination with the lead blocks.

5.2 Calibration tests

The first tests took place in the water laboratories of the Faculty of Civil Engineering of the Delft University of Technology. These were tests to be sure the pressure meter was working and to get a view on what type of outcomes the pressure meter gives. On top of that, the results of the first tests were used to calibrate the pressure meter, to give a relation between the outcomes of the pressure meter and the pressure. For this project, there are two pressure meters of the same type. Both are used in the Delta Flume and therefore it is necessary to calibrate both pressure meters. The test, results and calibration of the first pressure meter is described in section 5.2.1 to 5.2.4. The test, results and calibration of the second pressure meter is described in section 5.2.4 to 5.2.6.

5.2.1 First test

Before testing the pressure meter in the Delta Flume, it is necessary to know how the pressure meter works and what the received data looks like. On top of that, it is sensible to do some calculations to calibrate the pressure meter, to get a working MATLAB-script for converting the measured pressure to wave heights and to test this script. At last it is also sensible to test the MATLAB-script, to be sure it is working before the tests in the Delta Flume start.

The first test took place in a large water basin beneath the water laboratories of the Faculty of Civil Engineering of the Delft University of Technology. This basin is about 3.5 meters deep. The pressure meter was lowered in the water by a crane. Before lowering the pressure meter into the water, the water level was marked. After that, the pressure meter was lowered twenty to thirty centimeters and then held still to mark the depth of the pressure meter. This process continued nine times, to a depth of 2.86 centimeter. When rising the pressure meter, there were no stops for marking.



Figure 5.4 Lowering the pressure meter into the water basin

5.2.2 Results of the first test

The pressure meter measures fifty-five minutes per hour, so there were 13,200 results for measured values. The lowering and rising of the pressure meter took nearly nine minutes, so only 2,112 results were relevant for our results. The other 11,000 results were all the same, namely the air pressure. The results of the first test are shown in figure 5.5.

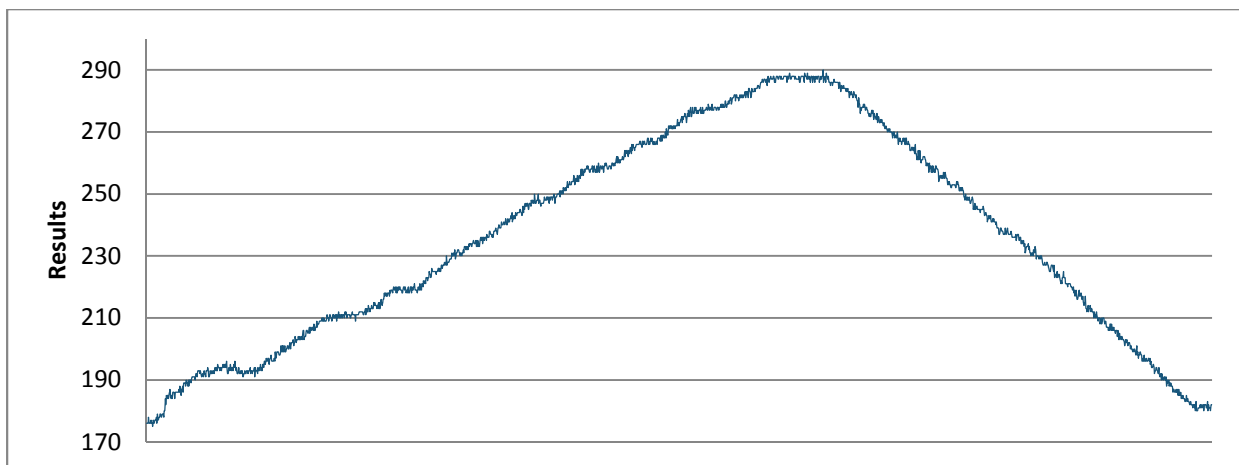


Figure 5.5 Results of the first test

At the left side of the graph, there are some horizontal intervals. These intervals are the moments of marking, when the pressure meter did not move, so the measured values did not change. The rising line shows the increasing of the measured values when increasing the water depth. The descending line shows the decreasing of the measured values when decreasing the water depth. There were no marking stops during the rising of the pressure meter, so there are no horizontal intervals shown in the graph.

The horizontal intervals are the reference to the water depth. The results of the combination of the water depth and the measured values are shown in figure 5.6

Water depth (m)	Measured values
2.86	288
2.61	278
2.35	267
2.13	258
1.86	248
0	176

Figure 5.6 Measured values at several water depths

Due to the unclear locations of the horizontal intervals between measured values of 248 and measured values of 220, only the first five measurements are used for the calibration.

5.2.3 Calibration of the first pressure meter

The relation between pressure P and the measured value, V_m , can be described as:

$$P = A * V_m + B \quad (4a)$$

Where A and B are the coefficients for calibration. The relation between pressure P and depth h can be written as:

$$P = \rho * g * h \quad (5)$$

For this case, $\rho = 1000 \text{ kg/m}^3$ and $g = 9.81 \text{ m/s}^2$. The pressure at each point is shown in figure 5.7.

Water depth (m)	Measured values	Pressure (Pa)
2.86	288	28056.6
2.61	278	25604.1
2.35	267	23053.5
2.13	258	20895.3
1.86	248	18246.6
0	176	0

Figure 5.7 Pressure at several water depths

With this information it is possible to make a scatter plot of the relation between the output of the pressure meter and the pressure. The relation between the pressure and the measured value can be determined with a trend line. With the equation of the trend line, A and B can be determined.

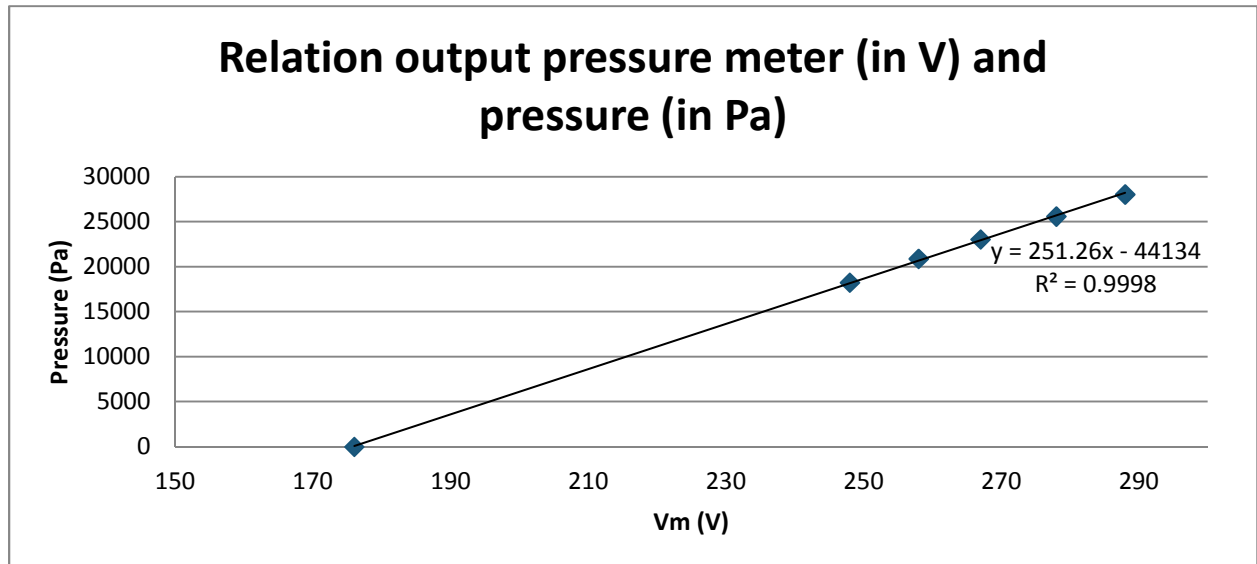


Figure 5.8 Scatter plot and trend line of the relation between the output of the pressure meter and the pressure

Figure 5.8 shows that the equation for the trend line:

$$y = 251.26x - 44134 \quad (4b)$$

This means that the relation between the output of the pressure meter, V_m , and the pressure, p , is described by:

$$P(V_m) = 251.26 * V_m - 44134 \quad (4c)$$

Which means that for this test, $A = 251.26$ and $B = 44134$. The outcomes of the pressure meter vary with plus one and minus one, which corresponds with a deviation of plus 251.26 Pa and minus 251.26 Pa. The trend line shows also that the correlation coefficient, R^2 , is 0.9998, which means that the correlation between the output of the pressure meter and the pressure is very high.

5.2.4 Second test

The second test was the same as the first, with some small changes. This time, the pressure meter was lowered to a depth of 1.86 meters. In the first test, some horizontal intervals were difficult to locate. To prevent this in the second test, there is taken more time for the pressure meter to remain on the same depth. This test took place in a shorter time interval than the first test, which gives 1735 usable measured values.

5.2.5 Results of the second test

The results of the first test are shown in figure 5.9. The measured values that belong to a certain water depth are shown in figure 5.10.

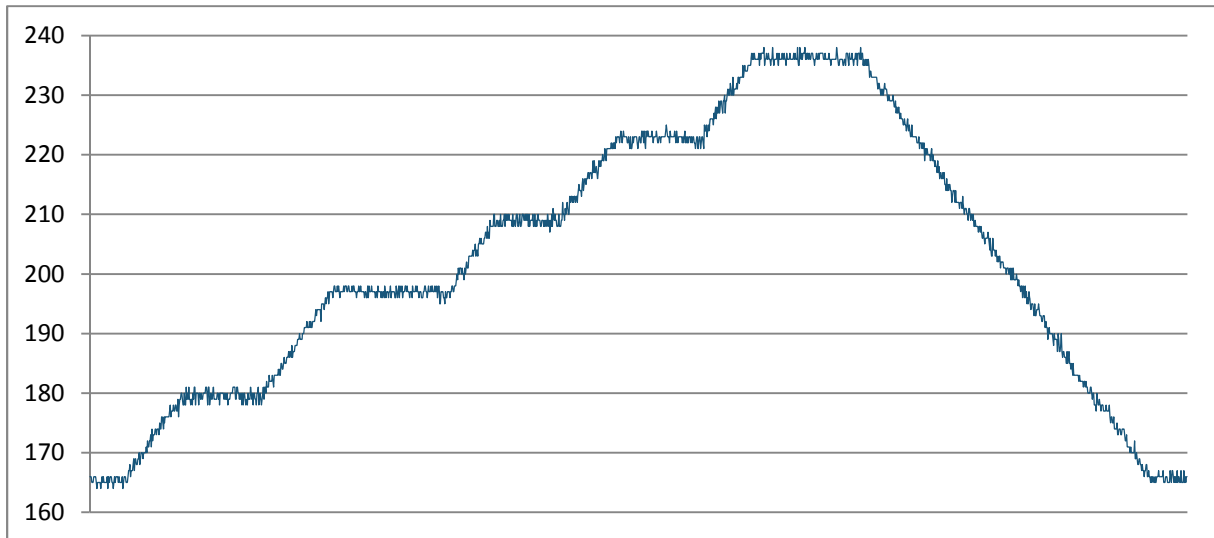


Figure 5.9 Results of the second test

Water depth (m)	Measured values
1.86	236
1.51	223
1.19	209
0.80	197
0.38	179
0	165

Figure 5.10 Measured values at several water depths

5.2.6 Calibration of the second pressure meter

The way of calibrating the second pressure meter is the same as for the first pressure meter, the only difference are the values and depths. The pressure at each water depth is shown in figure 5.11. The relation between the measured value and the pressure is shown in figure 5.12.

Water depth (m)	Measured values	Pressure (Pa)
1.86	236	18246.6
1.51	223	14813.1
1.19	209	11673.9
0.80	197	7848.0
0.38	179	3727.8
0	165	0

Figure 5.11 Pressure at several water depths

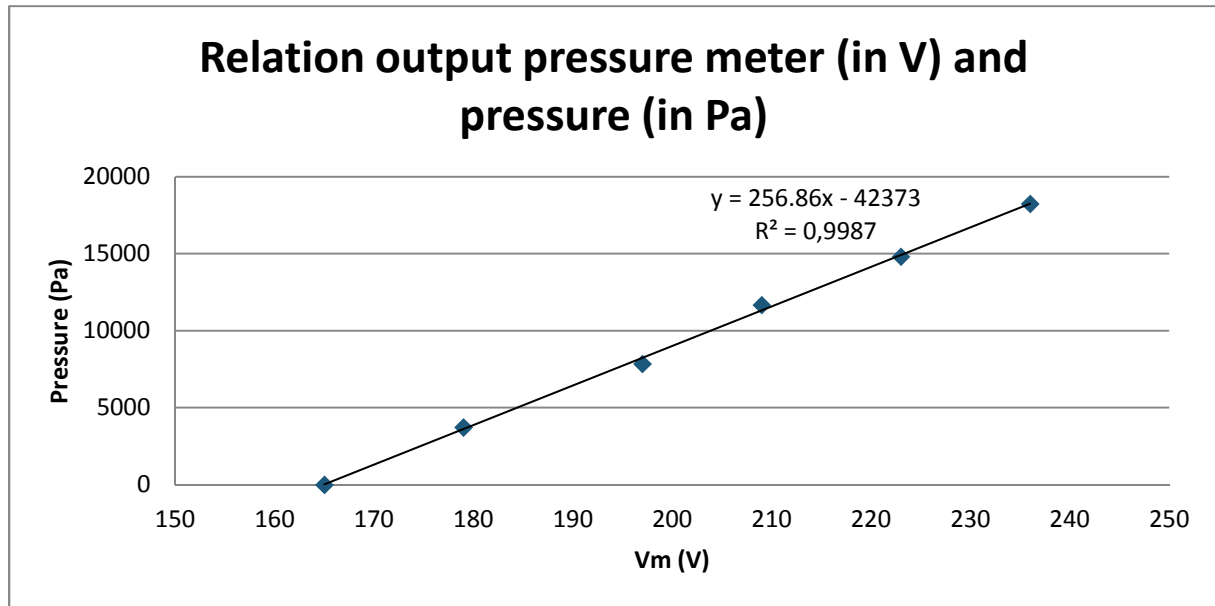


Figure 5.12 Scatter plot and trend line of the relation between the output of the pressure meter and the pressure

This graph shows a trend line in the same order of magnitude as the trend line for the first pressure meter. Nevertheless, there are some deviations in the values for A and B. For the second pressure meter, the relation between the output of the pressure meter, V_m , and the pressure, p , is described by:

$$P(V_m) = 256.86 * V_m - 42373 \quad (5)$$

This calibration gives, like the first calibration, a correlation coefficient of nearly one, which means the correlation between the measured values and the pressure is very high.

5.2.7 Final results of the calibration test

There is not much difference between both equations of the calibration test. To make the MATLAB-scripts user-friendly, the results of both calibrations are combined to one equation. For both A and B, the mean value is taken. This means that $A = 254$ and $B = -43250$. The general equation for the relation between the output of the pressure meter and the pressure is:

$$P(V_m) = 254 * V_m - 43250 \quad (6)$$

The effects of variation in air pressure are ignored for two reasons. At first, linear changes of the air pressure are compensated in the regression analysis for changes in the water level. The second reason is the fact that the air pressure does not have influence on the wave height. It is only important when the water depth is calculated very accurate, which is an exceptional situation for this pressure meter. There are better and easier ways to measure the water depth than with the pressure meter. The only way the air pressure influences the outcomes of the Rayleigh distribution and the wave spectrum is via the wave length. The calculated water depth depends on the air pressure and is used to calculate the wave length. This is a minimal effect and therefore it is possible to ignore this effect.

5.3 Verification tests

5.3.1 The Delta Flume

The Delta Flume is a wave flume of Deltares and it is located in the Noordoostpolder. The wave flume has a length of 240 meters, a width of five meters and a depth of seven meters. Because of this size, there are hardly any scale effects to take into account. The Delta Flume is able to generate both regular and irregular waves, with a maximum significant wave height H_s of 2.5 meters.

5.3.2 The verification test

From May to July of 2012, a cooperation of nine universities did experiments in the Delta Flume. This project is called Barrier Dynamics Experiments II (BARDEX II). With these experiments, they used waves to test their barriers. A more extensive description of the BARDEX II project is given in appendix B.

The verification tests of the pressure meter took place at the seventh of June, 2012. The day started with tests with smaller intervals of ten minutes and ended with intervals of thirty minutes. The pressure meter was placed at the concrete bottom of the flume with a water depth of three meters, at a distance of sixteen meters away from the wave board. The lowering of the pressure meter into the flume is showed in figure 5.13. At this location, the pressure meter was in front of the barrier and instruments of BARDEX II, so there were clean waves. Both pressure meters are tested. At first, the first meter was lowered into the Delta Flume for one test. After this test, the meter was brought up to get the data, after which it was lowered again for the second test. When the second test was finished, the first pressure meter was swapped with the second. While the second pressure meter was working during five tests, the data of the first meter was analyzed. When the pressure meters were brought up, it appeared that the pressure meter had overturned and due to the overturning had moved roughly two meters towards the barrier. Figure 5.14 shows the lines, which were perfectly vertical when the pressure meter was lowered in the water. This means that the construction with the lead was not heavy enough to keep the pressure meter exactly at its location.

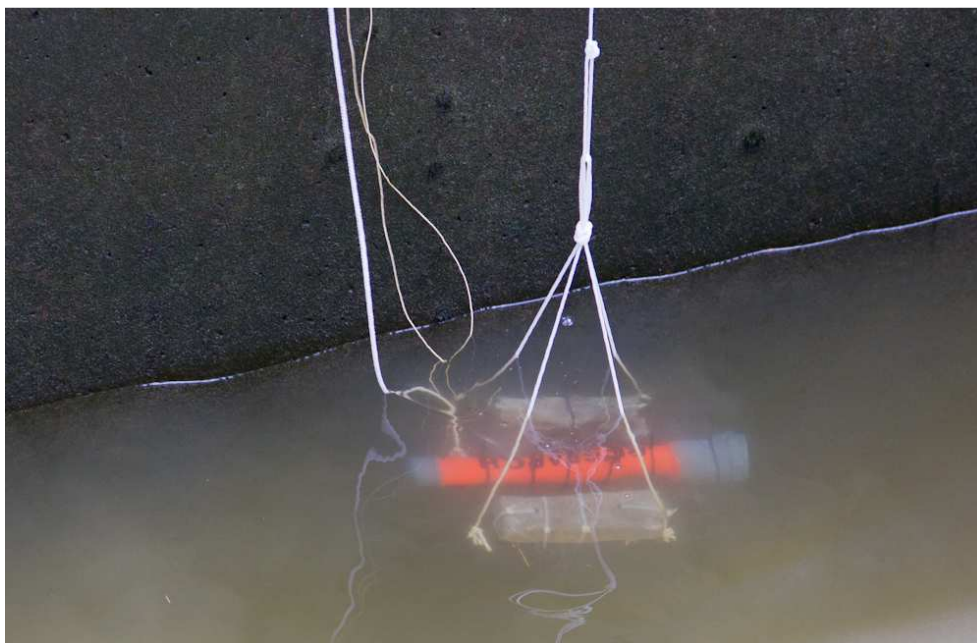


Figure 5.13 The pressure meter is lowered into the water of the Delta Flume

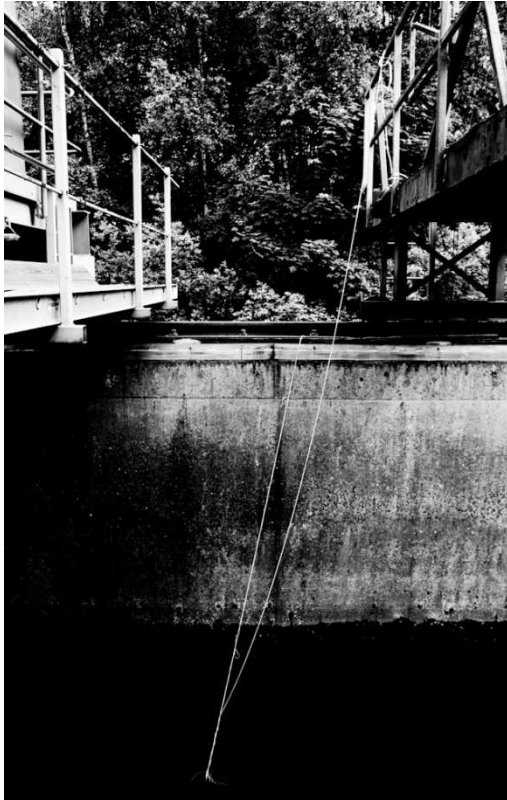


Figure 5.14 The lines to the pressure meter were vertical when the waves started

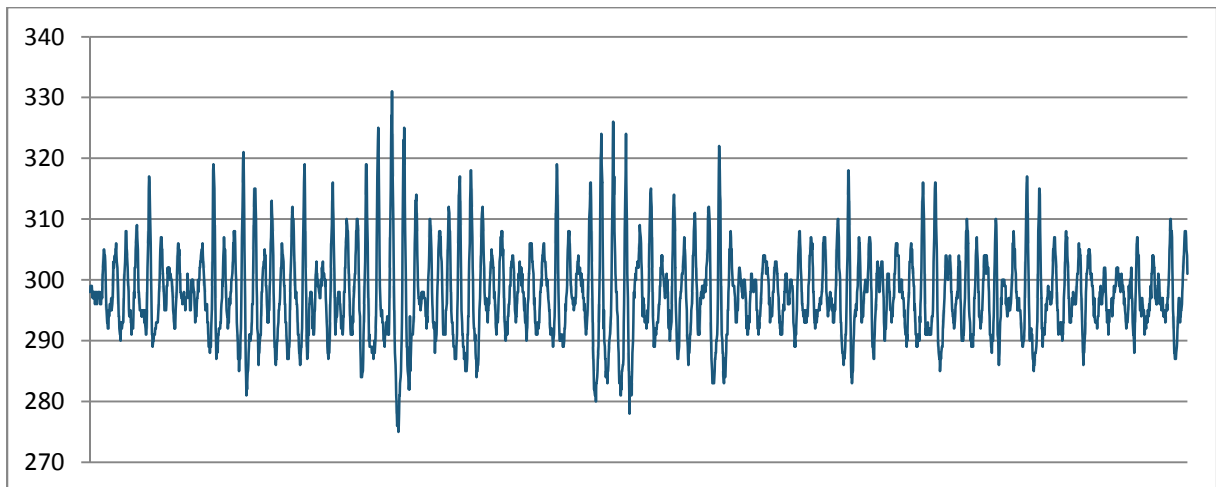


Figure 5.15 The outcomes of the first 12.5 minutes of the pressure meter during the last test

5.3.3 Outcomes of the tests

At the end of the day, seven series of data were measured by the pressure meters. Unfortunately is the third set incomplete. The pressure meter is able to measure at most fifty-five minutes in an hour and during the third measuring, the waves continued in the five minutes the pressure meter did not measure. Figure 5.16 shows which pressure meter is used during each test, which SD-card, the number of received values and the time interval of each measuring.

File name	Meter	SD-card	Number of values	Time interval
Bardex01	1	1	2280	9 minutes, 30 seconds
Bardex02	1	2	2348	9 minutes, 47 seconds
Bardex03 (incompl.)	1	2	1148	4 minutes, 47 seconds
Bardex04	1	2	3300	13 minutes, 45 seconds
Bardex05	1	2	3200	13 minutes, 20 seconds
Bardex06	2	1	7160	29 minutes, 50 seconds
Bardex07	2	1	7140	29 minutes, 45 seconds
Total			26576	1 hour, 50 minutes, 44 seconds

Figure 5.16 Overview of the individual tests and the sum of these tests

The waves in the Delta Flume are also measured by Deltares, with the GHM. This GHM consists of a probe and a control unit. The water level is measured by the probe, by means of conductivity. This signal is converted by the control unit to an output voltage. This GHM measures with a frequency of 20 Hertz. The results of Deltares only contain the data of all intervals that day, in one file. Therefore, the outcomes of Deltares only give characteristic values, a Rayleigh distribution and a wave spectrum for the full day. In this case, the full day contains three hours of waves.

6. Analysis

The comparison of the results of the pressure meter and the results of Deltares consist three parts: The Rayleigh distribution, the wave spectrum and the comparison of some characteristic values.

6.1 Rayleigh distribution

The Rayleigh distribution of Deltares is shown in figure 6.1. Figure 6.2 shows the Rayleigh distribution of the pressure meter, obtained with the MATLAB-script *rayleigh.m* for the complete data set, *Total.txt*. Both figures are on the next page. Nota bene, the axes of the Deltares Rayleigh distribution are opposite to the Rayleigh distribution of the pressure meter. On top of that, the Deltares Rayleigh distribution gives a probability of exceeding a certain wave height, while the Rayleigh distribution of the pressure meter gives a probability of falling below a certain wave height.

Both figures give a straight line to approximately a wave height of 1.3 meters or a probability of 2.0 percent. After this point, the line is bending. This is caused by the fact that larger waves will break in shallow water, so the probability of a large wave height is decreasing. This is also mentioned in section 2.3 and 3.1 of this report.

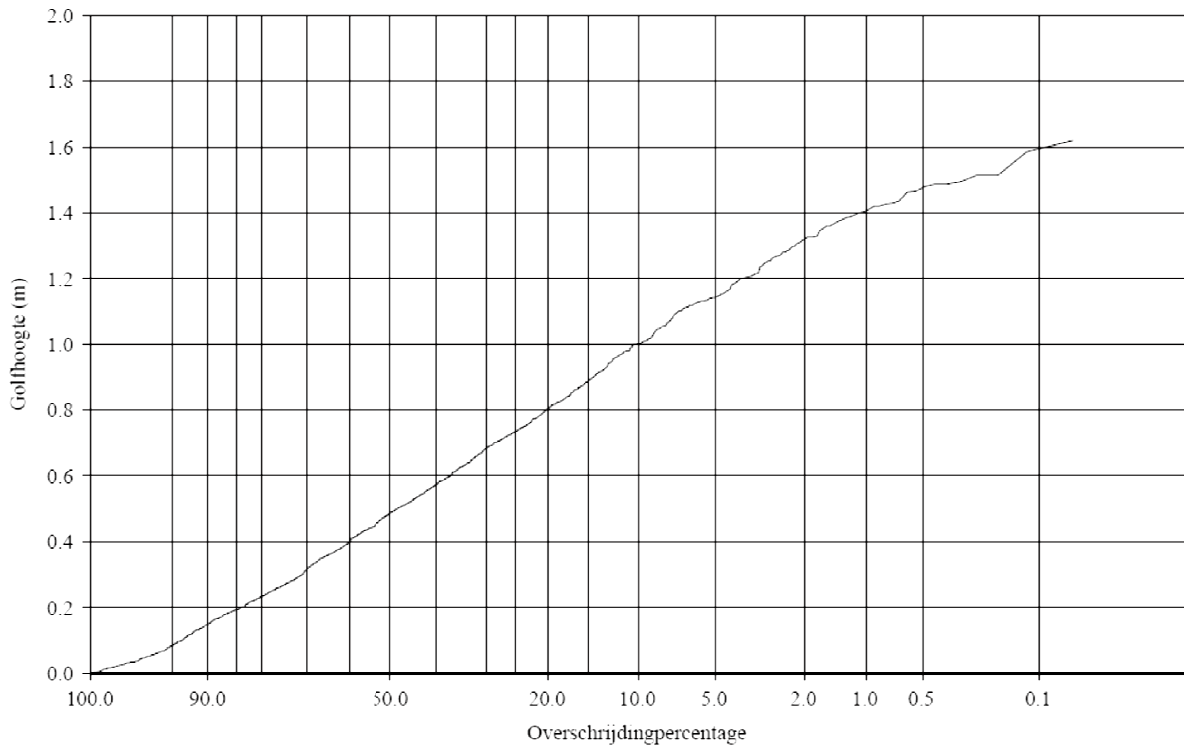


Figure 6.1 The Rayleigh distribution of Deltares, which shows the probability of exceeding (overschrijdingpercentage) for a certain wave height (golfhoogte)

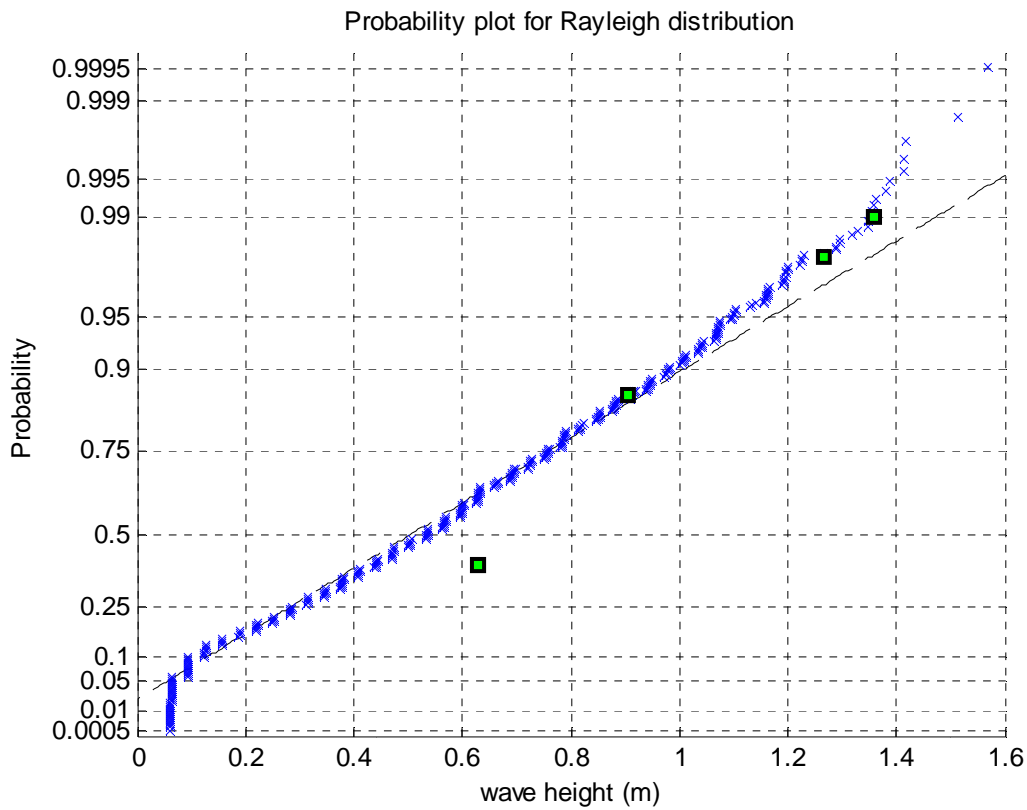


Figure 6.2 The Rayleigh distribution of the pressure meter

6.2 Wave distribution

The wave distribution of Deltares is given in figure 6.3, while the wave distribution of the pressure meter is given in figure 6.4. Both figures are on the next page. The wave distribution of the pressure meter is obtained with the MATLAB-script *spectrum.m*, for the complete data set, *Total.txt*. The spectrum is cut off at a frequency of 0.4 Hertz. With larger frequencies, the waves become too small. This are waves for deep water and these give a deviate result in the spectrum, as mentioned in section 2.2 and 3.2 of this report.

Both figures give a comparable line. The frequencies belonging to the first to peaks are nearly the same, 0.13 Hertz for the first peak and 0.24 Hertz for the second peak. The values of the peaks in figure 6.4 are a little lower. This is caused by the number of frequency bins over which is smoothed. A larger number gives a smoother spectrum, but narrow peaks are averaged over a wider range of frequencies.

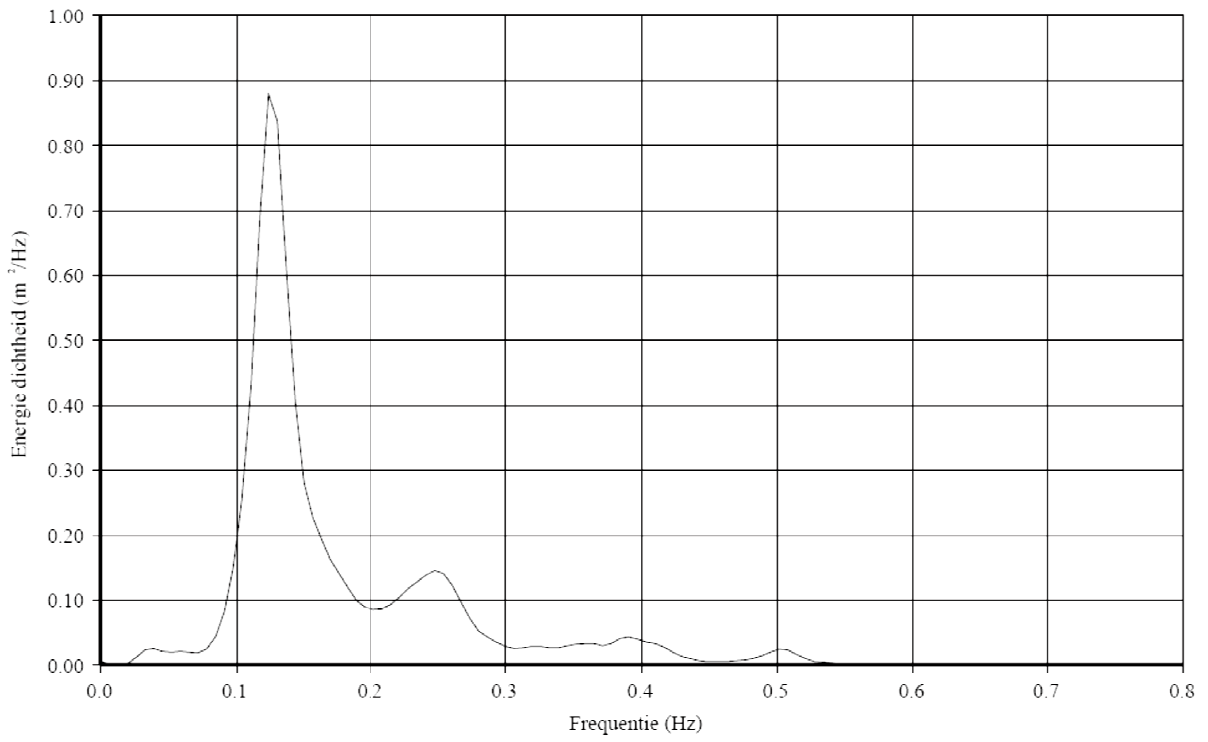


Figure 6.3 The wave spectrum of Deltares, which gives the frequency (frequentie) and the energy density (energie dichtheid)

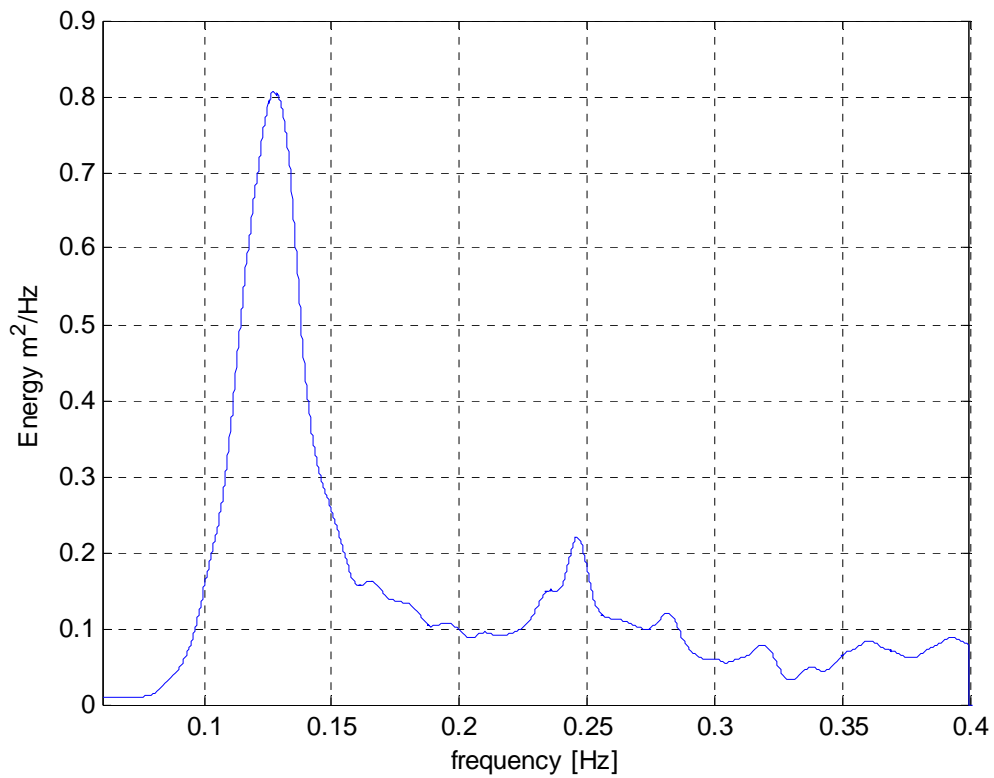


Figure 6.4 The wave spectrum of the pressure meter

6.3 Characteristic values

Both MATLAB-scripts give, besides the figures, some characteristic values of the waves. Deltares provided also some characteristic values with their data of their measurements. The first four values are determined with the Rayleigh distribution, the last four with the wave spectrum. All values are determined with the complete data set, *Total.txt*.

The H_{rms} is the root mean square wave height. H_{rms} is exceeded by 37% of the waves. H_s is the significant wave height, which is equal to the average wave height of the $\frac{1}{3}$ part of the highest waves, also called $H_{1/3}$. H_s is exceeded by 13.5% of the waves. $H_{2\% (measured)}$ is the wave height with a probability of exceeding of two percent, based on the measured values. The $H_{2\% (Rayleigh)}$ is the wave height with a probability of exceeding of two percent, based on the Rayleigh distribution. The outcomes of Deltares have only one value for $H_{2\%}$. Both the $H_{2\% (measured)}$ and the $H_{2\% (Rayleigh)}$ are compared to this value.

H_{m0} is the significant wave height, based on m_0 . The surface under the line of the wave spectrum is called m_0 . T_{01} is the period based on the first moment of the wave spectrum. T_{10} is the period based on the first negative moment of the wave spectrum.

	H_{rms}	H_s	$H_{2\% (measured)}$	$H_{2\% (Rayleigh)}$		H_{m0}	H_{rms}	T_{01}	T_{10}
Deltares	0.6440	0.9110	1.3210	1.3210		0.9210	0.6440	5.6690	6.8560
Pressure meter	0.6297	0.9047	1.2274	1.2665		0.9098	0.6433	5.3945	6.5868

Figure 6.5 Comparison of the characteristic value of Deltares and the pressure meter

The outcomes of the both the values of Deltares and the values of the pressure meter are nearly the same. For each of the separate data files, Bardex01 up to and including Bardex07, there also is a Rayleigh distribution and a wave spectrum and there are characteristic values. These figures and a table with all characteristic values are given in appendix A.

7. Conclusion

The purpose of this survey is to test the pressure meter and to convert the outcomes of the pressure meter into wave heights. These wave heights are compared to the wave heights measured by Deltares. The results of the pressure meter are comparable with the results received from Deltares. Therefore, the pressure meter is reasonable instrument to use for the measuring of waves.

Figure 7.1 shows the deviations of the results of the pressure meter, compared to the results of Deltares in percents. The largest deviation is shown by the $H_{2\% \text{ (measured)}}$. When the value for $H_{2\%}$ is demanded, it is better to use the $H_{2\% \text{ (Rayleigh)}}$ value. When this value is used, it turns out that the results of the pressure meter have maximum deviation of roughly five percent. For the most important values, the H_{rms} , the H_s and the H_{m0} , the pressure meter is even more accurate.

	H_{rms}	H_s	$H_{2\% \text{ (measured)}}$	$H_{2\% \text{ (Rayleigh)}}$		H_{m0}	H_{rms}	T_{01}	T_{10}
Deltares	0.6440	0.9110	1.3210	1.3210		0.9210	0.6440	5.6690	6.8560
Pressure meter	0.6297	0.9047	1.2274	1.2665		0.9098	0.6433	5.3945	6.5868
Deviation (%)	2.27	0.70	7.63	4.30		1.23	0.11	5.09	4.09

Figure 7.1 Overview of the deviations of the results in percents

The wave spectrum is usable between a frequency of 0.4 Hertz and 0.05 Hertz. This corresponds with waves with a period of 2.5 seconds to twenty seconds. Beyond this range, the deviations increase quickly. The spectrum is more accurate with a larger data set. When there are too less input values, the spectrum gives a less accurate figure.

The line of the Rayleigh distribution bends for higher waves and therefore it is not a straight line at the end of the figure. To calculate a $H_{1\% \text{ (measured)}}$ and a $H_{1\% \text{ (Rayleigh)}}$, the script needs at least a hundred and a thousand input values, respectively. With less values, both outcomes give *NaN*, which means *Not a Number*. Although, it is possible to calculate a value for $H_{1\% \text{ (Rayleigh)}}$ and $H_{1\% \text{ (measured)}}$ with less than a hundred and a thousand input values, respectively.

The calibration of the pressure meters shows that the relation between the measured value and the pressure is described as:

$$P (V_m) = 254 * V_m - 43250 \quad (6)$$

During the tests in the Delta Flume turned out that the nearly eleven kilograms under water level were not enough to hold the pressure meter on its location. This was on a flat, concrete bottom.

In view of the outcomes of figure 7.1 is the pressure meter a quite accurate instrument to measure waves, with an accuracy of roughly five percent. Due to the fact that this instrument is inexpensive in comparison to other wave meters, it is a very usable instrument for fieldwork or low-budget projects.

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List of symbols

a	Wave amplitude	[m]
A	Calibration coefficient	[-]
B	Calibration coefficient	[-]
g	Gravity acceleration (9.81 m/s ²)	[m/s ²]
h	Water depth	[m]
H	Wave height	[m]
H _{1% (measured)}	Wave height with a probability of exceeding of 1%, based on the measured data	[m]
H _{1% (Rayleigh)}	Wave height with a probability of exceeding of 1%, based on the line of the Rayleigh distribution	[m]
H _{2% (measured)}	Wave height with a probability of exceeding of 2%, based on the measured data	[m]
H _{2% (Rayleigh)}	Wave height with a probability of exceeding of 1%, based on the line of the Rayleigh distribution	[m]
H _{m0}	Significant wave height, calculated with m ₀	[m]
H _p	Subsurface pressure head	[m]
H _{rms}	Root mean square wave height	[m]
H _s	Significant wave height	[m]
H _{tr}	Transition wave height, according to Battjes and Groenendijk	[m]
H _{trNorm}	Normalized transition wave height	[m]
K	Wave number	[-]
K _p	Pressure response factor	[-]
L	Wave length	[m]
m ₀	Surface under the line of the wave spectrum	[m ²]
N	Empirical correction factor	[-]
P	Pressure	[Pa]
p'	Fluctuation of wave pressure	[Pa/s]
R	Correlation coefficient	[-]
t	Time	[s]
T	Wave period	[s]
T ₀₁	Wave period, based on the first moment of the wave spectrum	[s]
T ₁₀	Wave period, based on the first negative moment of the wave spectrum	[s]
T _m	Mean wave period	[s]
T _{peak}	Peak period	[s]
V _m	Measured value	[V]
x	Distance	[m]
z	Depth of the pressure meter under still water level	[m]
θ	Phase	[Rad]
ρ	Density of water	[kg/m ³]
ω	Angular frequency	[Rad/s]

Appendix A: Complete results

Figure A.1 gives the characteristic values calculated with the Rayleigh distribution. The third file, Bardex03, is unfortunately incomplete and due to that it has to not enough values to calculate a $H_{1\%}$. This results in a *NaN* outcome for the $H_{1\%(\text{measured})}$, which means *Not a Number*. Although, it is possible to calculate a value for $H_{1\%}$, with the line of the Rayleigh distribution. This results in a $H_{1\%(\text{Rayleigh})}$.

	Hrms	Hs	H2% Meas	H2% Ray	H1% Meas	H1% Ray	Htr	Htr Norm
Bardex01	0.6521	0.9140	1.2864	1.2797	1.3508	1.3711	1.2621	1.9353
Bardex02	0.6283	0.8585	1.2624	1.2019	1.2630	1.2877	1.1800	1.8779
Bardex03 (incompl.)	0.6454	0.9015	1.0883	1.2620	NaN	1.6670	1.2061	1.8687
Bardex04	0.6490	0.9552	1.4459	1.3373	1.5132	1.4329	1.2111	1.8662
Bardex05	0.6230	0.9051	1.1664	1.2671	1.2331	1.3576	1.1998	1.9256
Bardex06	0.6378	0.9186	1.1887	1.2861	1.2764	1.3780	1.1458	1.7964
Bardex07	0.6050	0.8875	1.2298	1.2425	1.3914	1.3312	1.1686	1.9315
Total	0.6297	0.9047	1.2274	1.2665	1.3477	1.3570	1.1821	1.8772
Deltares	0.6440	0.9110	1.3210					

Figure A.1 The characteristic values of the Rayleigh distribution

In figure A.2 are the characteristic values given that are calculated with the wave spectrum.

	m0	Hm0	Hrms	Tm	T01	T10	Tpeak
Bardex01	0.0641	1.0128	0.7161	4.6104	5.0632	6.3875	7.1250
Bardex02	0.0554	0.9418	0.6660	4.7074	5.1756	6.5139	7.3375
Bardex03 (incompl.)	0.0578	0.9613	0.6798	4.1960	4.5279	5.5363	5.5192
Bardex04	0.0567	0.9521	0.6733	4.8410	5.2636	6.3416	7.3009
Bardex05	0.0508	0.9018	0.6377	4.9902	5.4699	6.6794	7.4766
Bardex06	0.0546	0.9349	0.6611	5.0625	5.5520	6.8026	7.8509
Bardex07	0.0519	0.9111	0.6443	4.9335	5.4106	6.6987	7.8960
Total	0.0517	0.9098	0.6433	4.9192	5.3945	6.5868	7.8720
Deltares		0.9210	0.6440		5.6690	6.8560	

Figure A.2 The characteristic values of the wave spectrum

On the next two pages are the Rayleigh distributions and the wave spectra of the separate files given. The wave spectrum of Bardex03 deviates from the other spectra, due to the lack of enough data to make a better figure. It is also shown that the more data are used, the more the spectrum corresponds to the spectrum of Deltares.

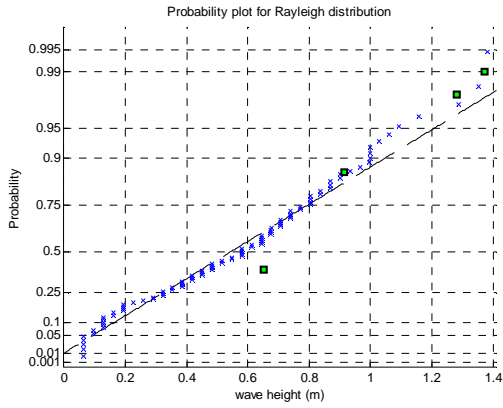


Figure A.2 Rayleigh distribution of Bardex01

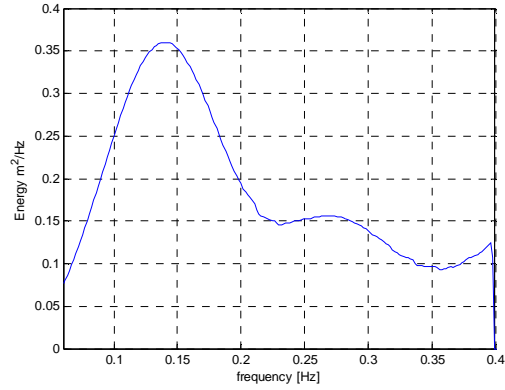


Figure A.3 Wave spectrum of Bardex01

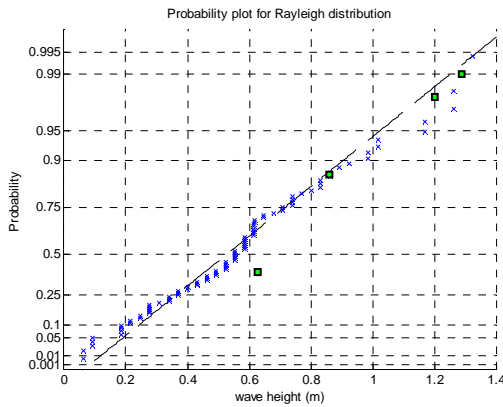


Figure A.4 Rayleigh distribution of Bardex02

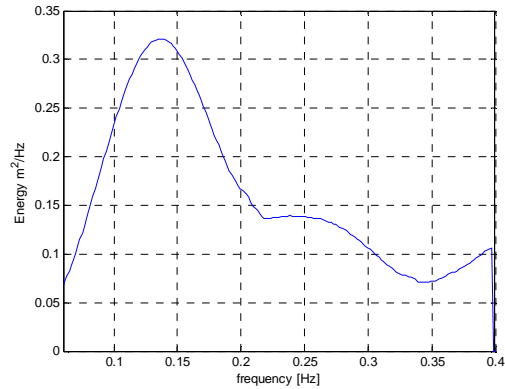


Figure A.5 Wave spectrum of Bardex02

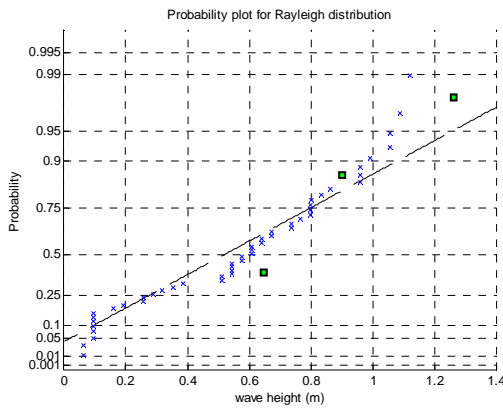


Figure A.6 Rayleigh distribution of Bardex03

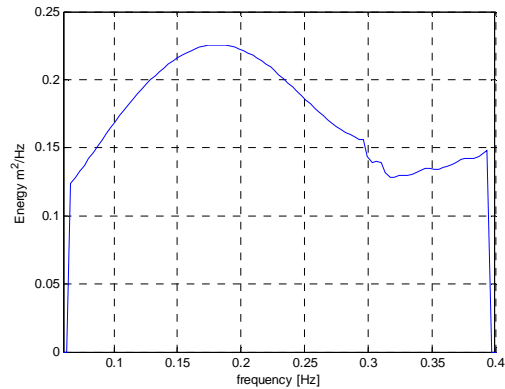


Figure A.7 Wave spectrum of Bardex03

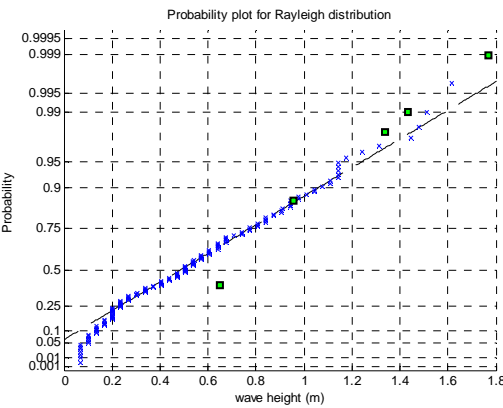


Figure A.8 Rayleigh distribution of Bardex04

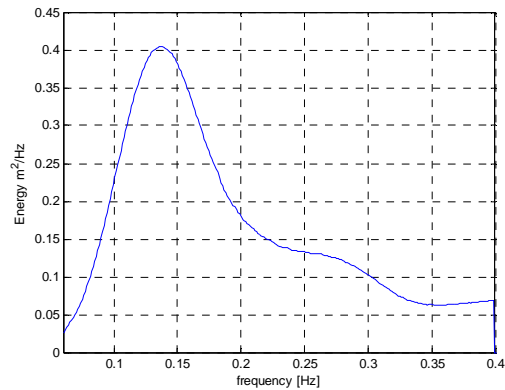


Figure A.9 Wave spectrum of Bardex04

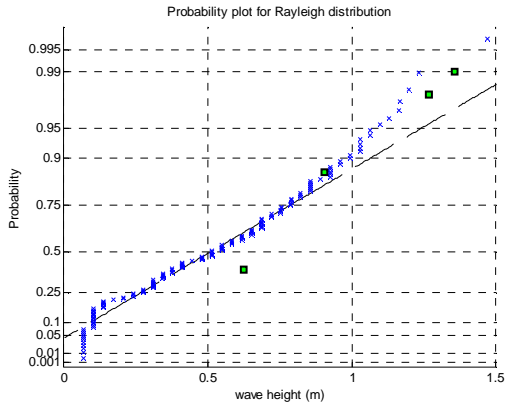


Figure A.10 Rayleigh distribution of Bardex05

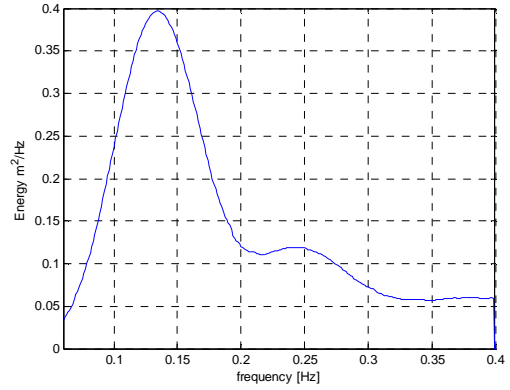


Figure A.11 Wave spectrum of Bardex05

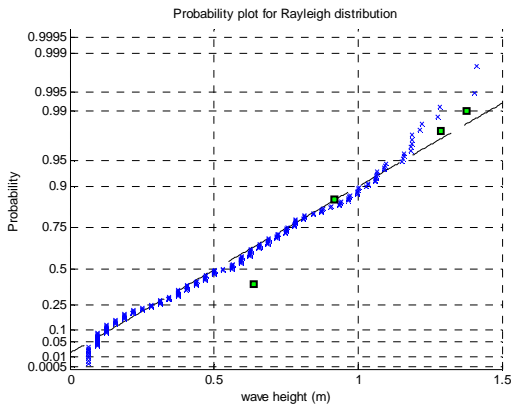


Figure A.12 Rayleigh distribution of Bardex06

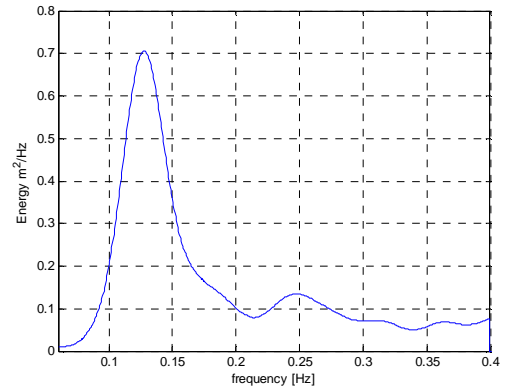


Figure A.13 Wave spectrum of Bardex06

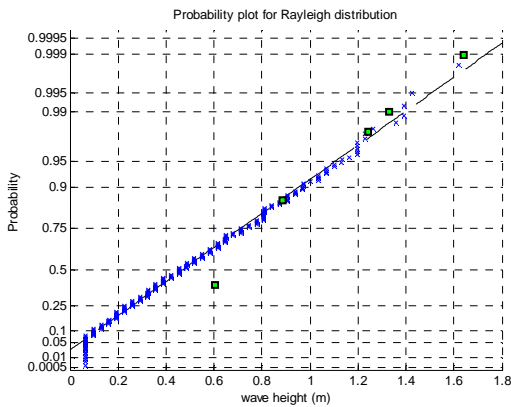


Figure A.14 Rayleigh distribution of Bardex07

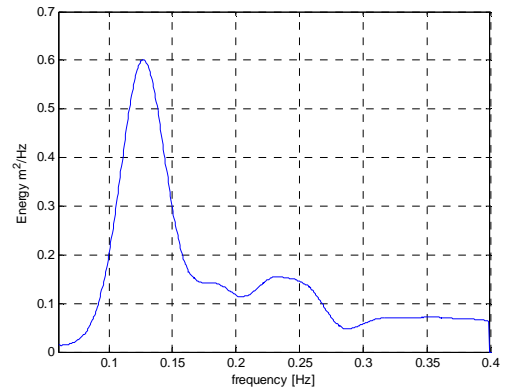


Figure A.15 Wave spectrum of Bardex07

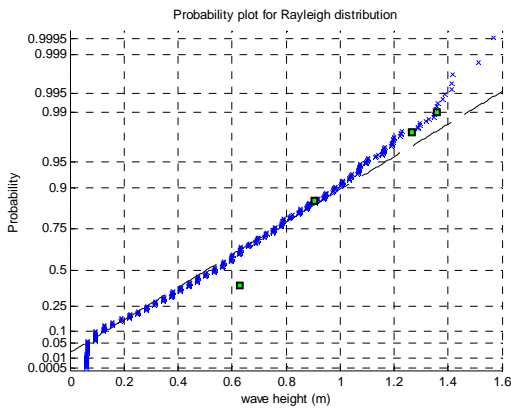


Figure A.16 Rayleigh distribution of Total

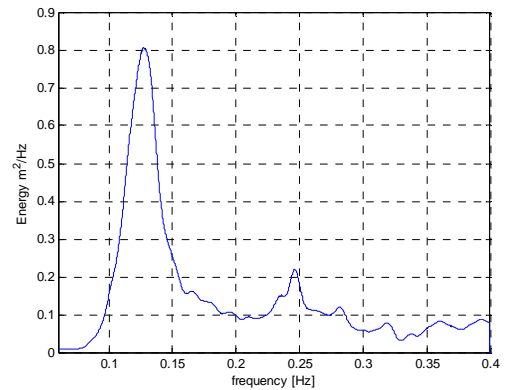


Figure A.17 Wave spectrum of Total

Appendix B: BARDEX II

The BARDEX II took place from May to July of 2012. It is a cooperation of 25 researchers of nine different universities: Algarve, Bordeaux, Copenhagen, Delaware, New Hampshire, New South Wales, Plymouth, Southampton and Utrecht, managed by G. Masselink. The main goal of the project is to increase the understandings of sediment transport processes on sandy beaches. In the Delta Flume, a barrier of 50 meters wide and 4.5 meters high is made. There was 1,400 cubic meters sand required to make this barrier. Behind this barrier, a 4.5 meter high retaining wall is placed. Behind this wall a lagoon is created. The water level in this lagoon can be varied.



Figure B.1 The BARDEX II barrier, seen towards the wave generator. Photo from <http://bardex2.blogspot.com>

When this barrier was finished, the measure instruments were placed. Lots of different instruments are used, like pressure transducers, electromagnetic current meters, optical backscatterance sensors, fibre-optical backscatterance sensors et cetera. All instruments are time-synched using GPS-time-server. The project is divided in five phases. The first phase is to test the beach response to varying wave conditions and different water levels of the lagoon. These tests are done without tide. The second phase is to test the bar dynamics due to different sea levels. In this phase, there also is no tide taken into account. In the third phase the beach response to varying wave conditions is tested, this time with tide. The fourth phase gives an identification of overtopping and overwash threshold. The sea level is increased until overwash occurs. The fifth and last phase shows the destruction of the barrier. Once overwash starts, the conditions are kept the same until the barrier crest is below sea level. More information about the BARDEX II project can be found at <http://bardex2.blogspot.com>.

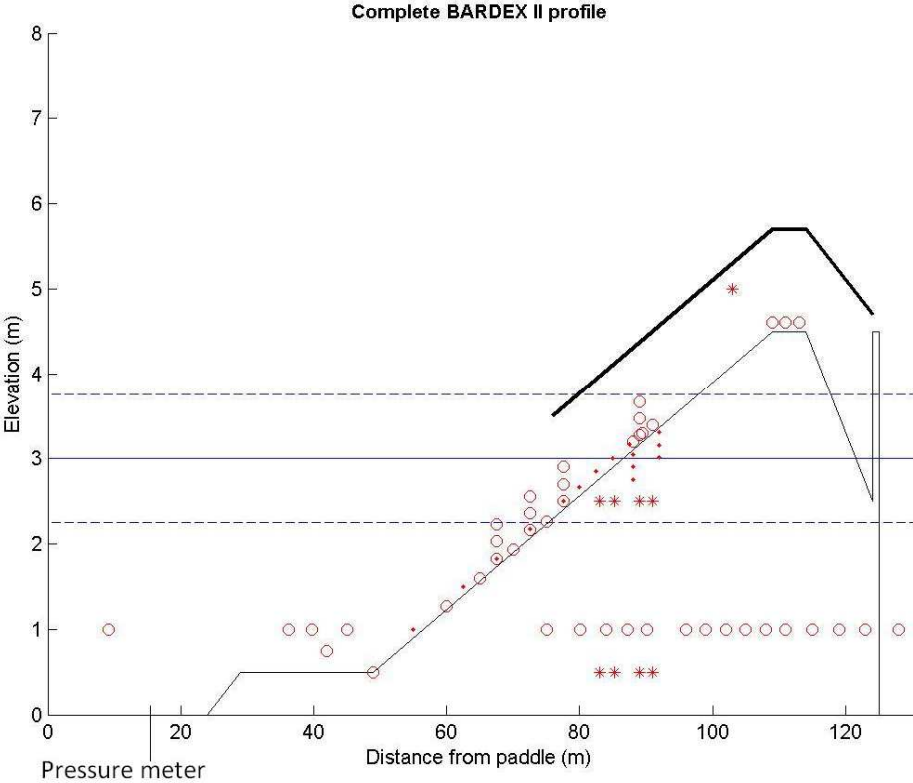


Figure B.2 Overview of the location of the instruments, including the pressure meter. Based on a figure from <http://bardex2.blogspot.com>



Figure B.3 The barrier during irregular waves



Figure B.4 The barrier during the waves, seen from the 'seaside'



Figure B.5 A wave coming to the barrier

Appendix C: MATLAB-scripts

Crosgk.m:

```

function [P,F,dof]=crosgk(X,Y,N,M,DT,DW,stats);

% CROSGK   Power cross-spectrum computation, with smoothing in the
%          frequency domain
%
% Usage: [P,F]=CROSGK(X,Y,N,M,DT,DW,stats)
%
% Input:
% X   contains the data of series 1
% Y   contains the data of series 2
% N   is the number of samples per data segment (power of 2)
% M   is the number of frequency bins over which is smoothed (optional),
%     no smoothing for M=1 (default)
% DT  is the time step (optional), default DT=1
% DW  is the data window type (optional): DW = 1 for Hann window (default)
%     DW = 2 for rectangular window
% stats : display resolution, degrees of freedom (optimal, YES=1, NO=0)
%
% Output:
% P contains the (cross-)spectral estimates: column 1 = Pxx, 2 = Pyy, 3 =
Pxy
% F contains the frequencies at which P is given
%
%
% Gert Klopman, Delft Hydraulics, 1995
%

if nargin < 4,
    M = 1;
end;

if nargin < 5,
    DT = 1;
end;

if nargin < 6,
    DW = 1;
end;

if nargin < 7,
    stats = 1;
end;

df = 1 / (N * DT) ;

% data window

w = [];
if DW == 1,
    % Hann
    w = hanning(N);
    dj = N/2;

```

```

else,
    % rectangle
    w = ones(N,1);
    dj = N;
end;
varw = sum (w.^2) / N ;

% summation over segments

nx = max(size(X));
ny = max(size(Y));
avgx = sum(X) / nx;
avgy = sum(Y) / ny;
px = zeros(size(w));
py = zeros(size(w));
Pxx = zeros(size(w));
Pxy = zeros(size(w));
Pyy = zeros(size(w));
ns = 0;

for j=[1:dj:nx-N+1],

    ns = ns + 1;

    % compute FFT of signals

    px = X([j:j+N-1]') - avgx;
    px = w .* px ;
    px = fft(px) ;

    py = Y([j:j+N-1]') - avgy;
    py = w .* py ;
    py = fft(py) ;

    % compute periodogram

    Pxx = Pxx + px .* conj(px) ;
    Pyy = Pyy + py .* conj(py) ;
    Pxy = Pxy + py .* conj(px) ;

end;

Pxx = (2 / (ns * (N^2) * varw * df)) * Pxx ;
Pyy = (2 / (ns * (N^2) * varw * df)) * Pyy ;
Pxy = (2 / (ns * (N^2) * varw * df)) * Pxy ;

% smoothing

if M>1,
    w = [];
    w = hamming(M);
    w = w / sum(w);
    w = [w(ceil((M+1)/2):M); zeros(N-M,1); w(1:ceil((M+1)/2)-1)];
    w = fft(w);
    Pxx = fft(Pxx);
    Pyy = fft(Pyy);
    Pxy = fft(Pxy);
    Pxx = ifft(w .* Pxx);

```



```

    Pyy = ifft(w .* Pyy);
    Pxy = ifft(w .* Pxy);
end;

Pxx = Pxx(1:N/2);
Pyy = Pyy(1:N/2);
Pxy = Pxy(1:N/2);

% frequencies

F = [];
F = ([1:1:N/2]' - 1) * df;

% signal variance

if DW == 1,
    nn = (ns + 1) * N / 2;
else,
    nn = ns * N;
end;
avgx = sum(X(1:nn)) / nn;
varx = sum((X(1:nn) - avgx).^2) / (nn - 1);
avgy = sum(Y(1:nn)) / nn;
vary = sum((Y(1:nn) - avgy).^2) / (nn - 1);
covxy = sum((X(1:nn) - avgx) .* (Y(1:nn) - avgy)) / (nn - 1);

m0xx = (0.5 * Pxx(1) + sum(Pxx(2:N/2-1)) + 0.5 * Pxx(N/2)) * df;
m0yy = (0.5 * Pyy(1) + sum(Pyy(2:N/2-1)) + 0.5 * Pyy(N/2)) * df;
m0xy = (0.5 * Pxy(1) + sum(Pxy(2:N/2-1)) + 0.5 * Pxy(N/2)) * df;

%disp(['m0x / varx = ' num2str(m0xx./varx) ' ; m0y / vary = '
num2str(m0yy./vary) ' ; m0xy / varxy = ' num2str(real(m0xy)./covxy) ' '])

Pxx = Pxx * (varx / m0xx);
Pyy = Pyy * (vary / m0yy);
Pxy = Pxy * (covxy / real(m0xy));

P = [Pxx, Pyy, Pxy];

% output spectrum characteristics
dof = floor(2*ns*(M+1)/2/(3-DW));
if stats == 1
    fprintf('number of samples used : %8.0f\n', nn);
    fprintf('degrees of freedom      : %8.0f\n', floor(2*ns*(M+1)/2/(3-DW)));
    fprintf('resolution                    : %13.5f\n', (3-DW)*df*(M+1)/2);
end
%
```

Spectrum.m:

```

clear;
clc;
%define basic variables
Rho=1000;
g=9.81;
Avolt=254; %Calibration value A of the pressure meter
Bvolt=-43250; %Calibration value B of the pressure meter
load rawdata.txt;
%transformation from Volts to pressure using calibration constants Avolt
%and Bvolt
%Avolt has dimension Pa/V, Bvolt has dimension Pa
P=Avolt*rawdata+Bvolt;
%interval is the sample frequency interval of the sensor
interval=.25;
n=numel(rawdata); %count number of samples
tottime=n*interval; %calculate total duration of observation in sec
ttime=(interval:interval:tottime); %create array with time
time=ttime.'; %change orientation of matrix
% calculate regression coefficients to compensate for change in waterlevel
% during the observations
%plot(time,rawdata);
%plot(time,P);
BB=polyfit(time,P,1); %regression analysis to determine real waterdepth at
any moment
                                %and correct for hydrostatic pressure

Intercept=BB(2);
Slope=BB(1);
Pwave=P-Intercept-time*Slope;
Pstatic=P-Pwave; %Hydrostatic pressure
depth=mean(Pstatic/Rho/g);
%=====
% simple script utilizing croschk (by G. Klopman) to obtain
% spectral estimate
%=====
% data contains the data
% N is the number of samples per data segment (power of 2)
% M is the number of frequency bins over which is smoothed (optional),
% no smoothing for M=1 (default)
% DT is the time step (optional), default DT=1
% DW is the data window type (optional): DW = 1 for Hann window (default)
% DW = 2 for rectangular window
% stats : display resolution, degrees of freedom (optimal, YES=1, NO=0)
%
% Output:
% P contains the (cross-)spectral estimates: column 1 = Pxx, 2 = Pyy, 3 =
Pxy
% F contains the frequencies at which P is given load time series

M = 100; %higher values of M give more smoothing of the spectrum
DT = interval;
data = Pwave;
[P,F,dof]=croschk(data,data,length(data),M,DT,1,0);

%plot the pressure spectrum
%figure
%plot(F,P(:,1)) % F is pressure^2/Hz
%axis ([0 0.3 0 1500])
%axis 'auto y'

```

```

xlabel('frequency [Hz]');
ylabel ('pressure Pa^2/Hz');

%recalculatate pressure spectrum to energy spectrum
eta=1:length(F); % length (F) is number of frequency bins
for i=1:length(F)
    eta(i)=0;
end;
m0=0; %zero-th moment
m1=0; %first moment
m2=0; %second moment
m01=0; %first negative moment {m(-1,0)}
deltaF= F(31)-F(30);
upgrade=1.00; %calabration coeffectien for transformation pressure to
height
emax=0;
% claculation loop to transform pressure spectrum to energy spectrum and
% to calculate the moments of the spectrum
% low and high frequencies are deleted, range from 200 to 0.2*max
% frequency bin, 200 means f= 200*deltaF, which is approx. 30 seconds
% 0.2*length(F)*deltaF = 0.4, so Tmin - 2.5 seconds
for i=20:0.20*length(F)
    T=1/F(i);
    pr=sqrt(P(i,1)); %pr=pressure value in pressure spectrum
    L0=1.56*T*T;
    if (depth/L0<0.36)
        L=sqrt(g*depth)*(1-depth/L0)*T;
    else
        L=L0;
    end;
    e=(upgrade*pr/(Rho*g)*cosh(2*pi/L*depth))^2; %e=energiedichtheid in
Hz/m2
    eta(i)=e; %replacing pressure value to energy value in spectrum
    if e>emax
        emax=e;
        Tpeak=T;
    end;
    m0 =m0 +e*deltaF;
    m1 =m1 +e*deltaF*F(i);
    m2 =m2 +e*deltaF*F(i)^2;
    m01=m01+e*deltaF/F(i);
end;
m0
Hm0=4*sqrt(m0) %one may assume Hs = Hm0
Hrms=sqrt(8*m0)
Tm=sqrt(m0/m2)
T01=m0/m1
T10=m01/m0 %Period based on first negative moment
Tpeak % peak period

figure
plot(F,eta)
axis([0.06 0.4 0 10000])
axis 'auto y'
xlabel('frequency [Hz]');
ylabel ('Energy m^2/Hz');
grid on;

```

Rayleigh.m:

```

%define basic variables
clear;
clc;
Rho=1000;
g=9.81;
Avolt=254;
Bvolt=-43250;
load rawdata.txt;
%transformation from Volts to pressure using calibration constants Avolt
%and Bvolt
%Avolt has dimension Pa/V, Bvolt has dimension Pa

P=Avolt*rawdata+Bvolt;
%interval is the sample frequency interval of the sensor
interval=.25;
n=numel(rawdata); %count number of samples
tottime=n*interval; %calculate total duration of observation in sec
ttime=(interval:interval:tottime); %create array with time
time=ttime.'; %change orientation of matrix
% calculate regression coefficients to compensate for change in waterlevel
% during the observations
%plot(time,P);
B = [ones(length(time),1) time] \ P;
Slope=B(2);
Intercept=B(1);
Pwave=P-Intercept'-time*Slope;

%figure
%plot(time,Pwave);
%xlabel('time (sec)');
%ylabel('pressure (Pa)');

Pstatic=P-Pwave;
Depth=Pstatic/Rho/g;
AverageDepth=mean(Depth);

%figure
%plot(time,Depth);
%ylabel('depth (m)');
%xlabel('time (sec)');

counter=0;
Pmin=0;
Pmax=0;
period=0;
upgrade=1.00; %calabration coeffient for transformation pressure to height
for k=1:n-1
    if(Pwave(k+1)*Pwave(k)<0 && Pwave(k+1)<0) %new wave starts at k+1
        counter=counter+1;
        T(counter)=period;
        L0=g/2/pi*period*period;
        if (Depth(k)/L0 < 0.36)
            L=sqrt(g*Depth(k))*(1-Depth(k)/L0)*period;
        else
            L=L0;
        end;
        H(counter)=(Pmax-Pmin)/Rho/g*cosh(2*pi/L*Depth(k));
        % H(i) is wave heighth calculated from individual pressure variation
    end
end

```

```

        Pmax=0;
        Pmin=0;
        period=0;
    end;
    if(Pwave(k)>Pmax) Pmax=Pwave(k);
    end;
    if (Pwave(k)<Pmin) Pmin=Pwave(k);
    end;
    period=period+interval;
end;
% counter = number of waves found
Hsorted=sort(H); % sorted waves in order of height
%statistic of Hsorted is not used in this program

Tsorted=sort(T);
Tmean = mean (Tsorted);

%loop to estimate water level variations
for k=1:n
    period=Tmean;
    L0=g/2/pi*period*period;
    if (Depth(k)/L0 < 0.36)
        L=sqrt(g*Depth(k))*(1-Depth(k)/L0)*period;
    else
        L=L0;
    end;
    eta(k)=upgrade*(Pwave(k))/Rho/g*cosh(2*pi/L*Depth(k));
end;

%eta is the calculated waterlevel as function of time
figure
plot(time,eta);
xlabel('time (sec)');
ylabel('waterlevel (m)');
%end waterlevel loop

%start loop to determine individual waves from waterlevel
etamin=0;
etamax=0;
counter=0;
for k=1:n-1
    if(eta(k+1)*eta(k)<0 && eta(k+1)<0) %new wave starts at k+1
        counter=counter+1;
        Hxx(counter)=etamax-etamin; %Hxx is wave height using recreated
surface
        etamin=0;
        etamax=0;
    end;
    if(eta(k)>etamax) etamax=eta(k);
    end;
    if (eta(k)<etamin) etamin=eta(k);
    end;
end;
%end loop to determine individual waves

Hsorted3=sort(Hxx); % sorted waves in order of height

%optional loop to ignore wave less then Hmin (m)
Hmin =0.05;
kk=0;

```

```

for k=1:counter
    if Hsorted3(k)>Hmin
        kk=kk+1;
        Hsorted2(kk)=Hsorted3(k);
    end;
end;
counter=kk; %reduce number of waves

for k=1 : counter
    prob(k)= (counter-k+1)/counter;
end;

Hmean=mean(Hsorted2);
Hrms = sqrt(mean(Hsorted2.^2)) % rms wave height

%calculation of the H1/3
from=round(2*counter/3);
to=round(counter);
Hs=mean(Hsorted2(from:to)) % significant wave height

%calculation of the H2%
Twopercent=round(counter-counter/50);
if (Twopercent==counter)
    H2percentMeasured=NaN;
else
    H2percentMeasured=Hsorted2(Twopercent);
end;
H2percentMeasured
H2percRayleigh=1.4*Hs

%caculation of the H1%
Onepercent=round(counter-counter/100);
if (Onepercent==counter)
    H1percentMeasured=NaN;
else
    H1percentMeasured=Hsorted2(Onepercent);
end;
H1percentMeasured
H1percRayleigh=1.5*Hs

%calculation of the H0.1%
Onepermille=round(counter-counter/1000);
if (Onepermille==counter)
    H1permilleMeasured=NaN;
else
    H1permilleMeasured=Hsorted2(Onepermille);
end;
H1permilleMeasured
H1permilleRayleigh=1.85*Hs

TanAlfa = 0.001; %bedslope
Htr=(0.35+5.8*TanAlfa)*AverageDepth % Transistion wave height acc. to BG
HtrNorm=Htr/Hrms %normalised transition height

figure
subplot('rayleigh',Hsorted2(1:counter));
hold all;
plot(Hs,2,'--rs','LineWidth',2,...
      'MarkerEdgeColor','k',...
      'MarkerFaceColor','g',...

```

```
        'MarkerSize',5);
plot(Hrms,1,'--rs','LineWidth',2,...
     'MarkerEdgeColor','k',...
     'MarkerFaceColor','g',...
     'MarkerSize',5);
plot(H2percRayleigh,2.8,'--rs','LineWidth',2,...
     'MarkerEdgeColor','k',...
     'MarkerFaceColor','g',...
     'MarkerSize',5);
plot(H1percRayleigh,3.03,'--rs','LineWidth',2,...
     'MarkerEdgeColor','k',...
     'MarkerFaceColor','g',...
     'MarkerSize',5);
plot(H1permilleRayleigh,3.7,'--rs','LineWidth',2,...
     'MarkerEdgeColor','k',...
     'MarkerFaceColor','g',...
     'MarkerSize',5);

grid on;
xlabel('wave height (m)');
```

Appendix D: Example of measured values

This is a small part of the results of the pressure meter, to get an idea what they look like. The first line shows the starting time (13:0:45), a value for the temperature (71) and the date (5/1/12). The last line shows the time at the end of the burst (13:55:45). The value for the temperature is given in Volts and therefore should be converted to the temperature in Celsius or Fahrenheit. The \$S means that this line is a starting line, the \$D means that this line contains the measured data and the \$E means that this line is an ending line.

\$S,1,13:0:45,71,5/1/12	\$D,1,278
\$D,1,277	\$D,1,278
\$D,1,276	\$D,1,278
\$D,1,277	\$D,1,277
\$D,1,277	\$D,1,278
\$D,1,277	\$D,1,278
\$D,1,278	\$D,1,278
\$D,1,276	\$D,1,279
\$D,1,277	\$D,1,278
\$D,1,276	\$D,1,279
\$D,1,278	\$D,1,278
\$D,1,276	\$D,1,279
\$D,1,276	\$D,1,278
\$D,1,277	\$D,1,278
\$D,1,277	\$D,1,278
\$D,1,277	\$D,1,280
\$D,1,277	\$D,1,280
\$D,1,278	\$D,1,278
\$D,1,278	\$D,1,278
\$D,1,277	\$D,1,279
\$D,1,277	\$D,1,279
\$D,1,279	...
\$D,1,278	...
\$D,1,277	...
\$D,1,278	...
\$D,1,278	...
\$D,1,277	...
\$D,1,277	...
\$D,1,279	...
\$D,1,277	\$D,1,177
\$D,1,277	\$D,1,177
\$D,1,277	\$D,1,177
\$D,1,278	\$D,1,178
\$D,1,278	\$D,1,177
\$D,1,278	\$D,1,176
\$D,1,278	\$D,1,177
\$D,1,277	\$D,1,176
\$D,1,277	\$E,1,13:55:45,

Appendix E: Concept advertising brochure

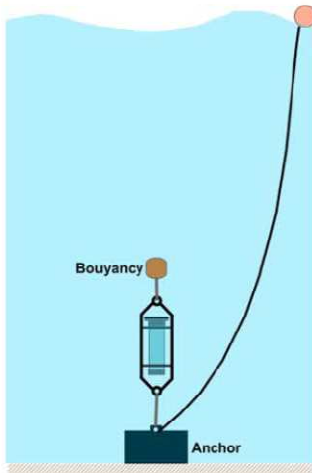
WAVE LOGGER



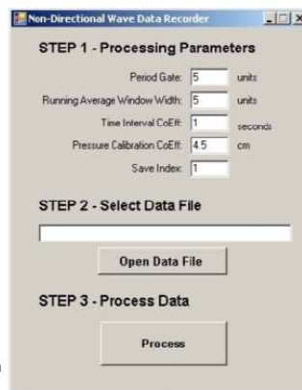
The Philosophy...

- A need for a cost effective wave recording instrument
- A need for an adaptable shallow water wave recorder.
- Simple instrument deployment and recovery.
- Increase spatial resolution of wave dynamics through multiple instrument deployment.
- One-stop-shop approach: instrument, data collection, data processing software, final usable results.

Right: Non-Directional Wave Logger with acrylic end plate and rugged PVC housing.



Left: Typical deployment mooring with stabilizing float and marker buoy.



Right: Screenshot of data processing software.

Physical Properties

-Size:	500mm X 155mm OD
-Weight:	3 kg
-Material:	PVC & Acrylic
-Operating Depth:	20m
-Burst Pressure:	500 psi

Electrical Features

-Batteries:	3 X 4.5Ahr 6v
-Operating Voltage:	5v
-Endurance:	up to 30 Days
-Operating Current:	30 mA
-Standby Current:	16 mA

Sampling Properties

-Sampling Period:	20min *Programmable
-Sampling Interval:	1 Hr *Programmable
-Burst Sampling Rate:	4Hz *Programmable
-Memory:	SD Card up to 2GB

Pressure Transducer

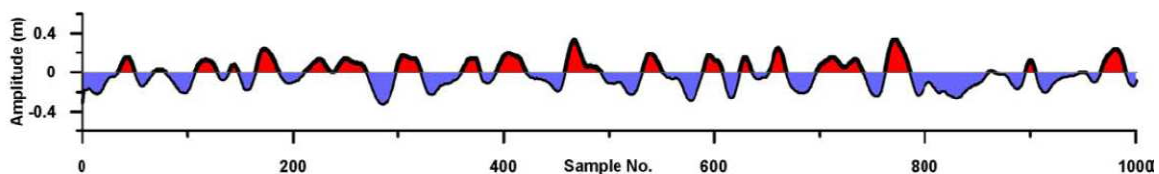
-Type:	Honeywell MHL Series
-Accuracy:	~0.5% FSS
-Resolution:	~5cm

Temperature Sensor

-Type:	Internal
-Accuracy:	0.5 C
-Temp Range:	-50 to 150 Deg C

Wave Parameters

- No. of Waves per sampling period
- Period
- H1/3
- Maximum Wave Amplitude
- Average Wave Amplitude
- Wave Energy



Above: Sample raw data from actual deployment.

"We can build it."