Experimental study on the performance of different wave absorbers in a wave flume

Maarten Delafontaine

Supervisors: Prof. dr. ir. Andreas Kortenhaus, Dr. Varjola Nelko

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Civil Engineering

Department of Civil Engineering
Chair: Prof. dr. ir. Peter Troch
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Abstract

EXPERIMENTAL STUDY ON THE PERFORMANCE OF DIFFERENT WAVE ABSORBERS IN A WAVE FLUME

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Master's dissertation submitted in order to obtain the academic degree of Master of Science in Civil Engineering

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This Master’s Dissertation is an experimental study on the performance of different wave absorbers in a wave flume. In wave flumes and wave basins it is of paramount importance to have spending beaches, which reflect the incident waves as little as possible. The efficient design of highly absorbing beaches results in the correct reproduction of both coastal and nearshore phenomena in a laboratory testing facilities. Many different wave absorbers can be used as spending beaches in wave flumes or wave basins. An extensive review of the existing literature was prepared here. The most promising wave absorbers were selected and evaluated from the experimental tests in the small wave flume of the department of Civil Engineering of the Faculty of Engineering and Architecture of Ghent University. The wave absorber(s) with the best absorbing capability were determined.

The results of this Master’s Dissertation will be used in the design of the upcoming large wave basin that will be built on the Greenbridge-site in Ostend.

Key words: Wave absorber, energy dissipation, reflection coefficient

Experimental study on the performance of different wave absorbers in a wave flume

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Supervisors: Prof. dr. ir. Andreas Kortenhaus, Dr. Varjola Nelko

***Abstract*—In laboratory testing facilities, it is very important to dispose of wave absorbers with very good wave absorbing properties. For this reason the objective of this research is to determine which wave absorber one should use when designing a laboratory testing facility in order to achieve the best wave absorbing characteristics. This objective is reached by performing tests on several wave absorbers in a wave flume. A sloping beach is found to show the best performance. However, if no space is available to build a proper sloping beach the designer of a laboratory testing facility can also install a vertical mesh or an absorber based on blue foam. Also with these absorbers quite nice wave energy dissipating characteristics can be obtained.**

***Keywords*—Wave absorber, energy dissipation, reflection coefficient**

INTRODUCTION

In wave flumes and wave basins it is of paramount importance to have spending beaches, which reflect the incident waves as little as possible. The efficient design of a highly absorbing beach leads to the correct reproduction of both coastal and nearshore physical phenomena in a laboratory testing facility. The objective of this research is to determine which wave absorber one should use when designing a wave flume or a wave basin in order to achieve the best wave absorbing characteristics.

The research is structured as follows: first, a literature review is performed. Second, the most promising wave absorbers are selected and evaluated in a hydraulic test program. Finally, based on the results, conclusions concerning the performance of wave absorbers are drawn.

LITERATURE REVIEW

An extensive literature review was performed in preparation of the test program. During this phase, four different wave absorbers were selected for the hydraulic model tests: the SIPWA (Superposed and Inclined Planes Wave Absorber), the vertical mesh, the porous parabola and the sloping beach.

The first absorber, SIPWA, consists of several superposed and inclined planes as can be seen in Figure 1.

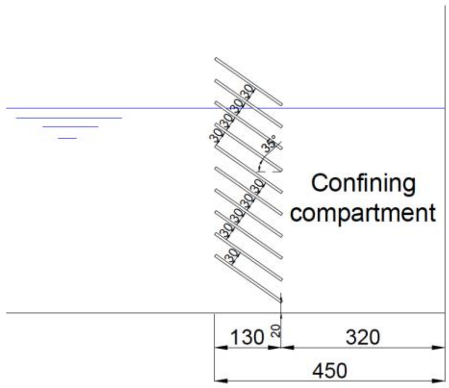

Figure 1 Side view of the Superposed and Inclined Planes Wave Absorber

Two flows are observed around the planes of the SIPWA: a local flow around the individual planes and an overall flow around the combined planes. The latter is of importance for the working principle of the SIPWA, which is twofold. On the one hand there is viscous dissipation, originating from breaking up of the eddies, formed at the edges of the planes where the overall flow is passing by. On the other hand, there is the resonance effect. This effect implies that, when the wave crest arrives at the absorber, the water level increases in the confining compartment (space at the back of the superposed planes) and that, when the wave trough arrives, the decrease in water level at the left side of the absorber is compensated by the water accumulated in the confining compartment. As such, the resonance effect contributes to the damping of the waves. The combination of both the viscous dissipation and the resonance effect leads to the breaking of the incident waves [1].

The second wave absorber, the vertical mesh, consists of subsequent vertical perforated plates (see Figure 2). As the water needs to flow through the

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openings of the consecutive perforated plates the wave energy is dissipated and the amplitude of the reflected wave becomes small which results in a small reflection coefficient.

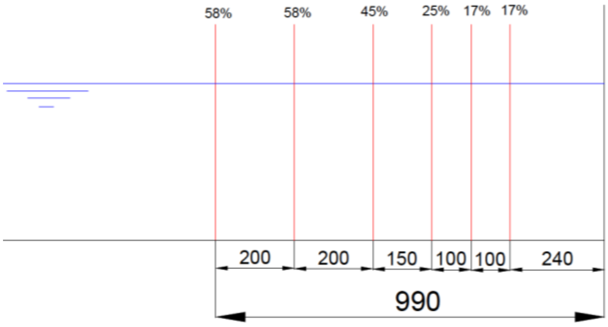

Figure 2 Side view of the vertical mesh absorber. The porosities of the different plates used in the vertical mesh are mentioned above each plate. Dimensions are in millimetres.

The third wave absorber, presented in Figure 3, is the porous parabola. The energy dissipation of this absorber is reached through the breaking of waves [3].

The fourth and final wave absorber that was selected was a sloping beach. Also this wave absorber makes use of wave breaking in order to dissipate the wave energy [2].

TEST PROGRAM

Tested configurations

The tests were conducted in the small wave flume of the department of Civil Engineering of the Faculty of Engineering and Architecture of Ghent University. The flume has a length of 15 m, a width of 35 cm and a height of 60 cm.

In the test program a total of eight different configurations were tested, including the four absorbers selected from the literature review. These four absorbers resulted in five configurations as two spending beaches were tested. Geometrical details of the tested SIPWA and vertical mesh absorber are shown in Figure 1 and Figure 2, respectively.

Concerning the vertical mesh, both the porosities of the different plates and the spacings between them are decreasing in the direction of the incident waves. These ideas were found to be interesting in the research of Twu and Lin [4] and the research of Tiedeman [3], respectively. The exact values of the spacings were chosen in such a way that the total length of the absorber comes close to 1 m, which is a fine length for a wave absorber in the small wave flume.

For the porous parabola, three different cross sections were used in order to have a mild slope at the still water level for each of the three water depths used in the test program (see *Performed tests* for the different water depths). In Figure 3 the cross section used at a water depth of 25 cm is shown. As can be seen in this figure, blue foam is placed behind the backside of the parabola in order to achieve additional wave absorbing capability.

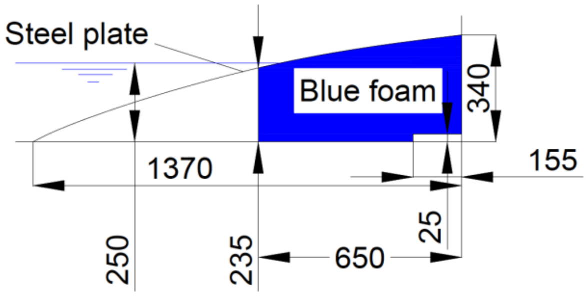

Figure 3 Side view of the porous parabola with blue foam

The fourth wave absorber selected from the literature is a sloping beach made of stones. Two sloping beaches were tested, a sloping beach with small stones (diameter of 10-16 mm) and a sloping beach with large stones (diameter of 30-35 mm). Considering that the space limitation is usually an issue in the laboratory, we tested a beach slope of 2/7, relatively on the steep range. The side view of these configurations is illustrated in Figure 4.

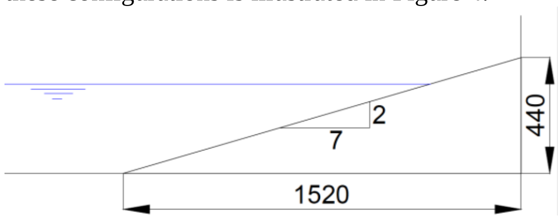

Figure 4 Side view of both sloping beaches

Finally, two additional wave absorbing materials were tested that weren't investigated in earlier research but that demonstrated good wave damping properties. The materials are polyether foam and hexablocks.

When testing the wave absorbing properties of polyether foam, two different configurations were tested. First, a vertical wall of polyether foam using two different porosities in its design and second, a parabolic shaped surface with only one porosity. The two different porosities include rough textured polyether foam and fine textured polyether foam. Both configurations are illustrated in Figure 5 and Figure 6, respectively.

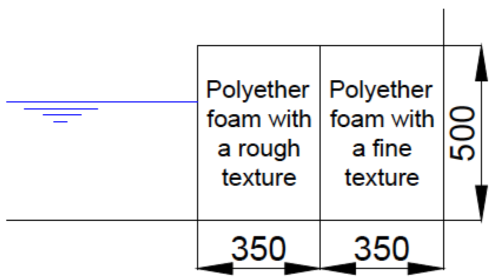

Figure 5 Side view of the vertical wall of polyether foam

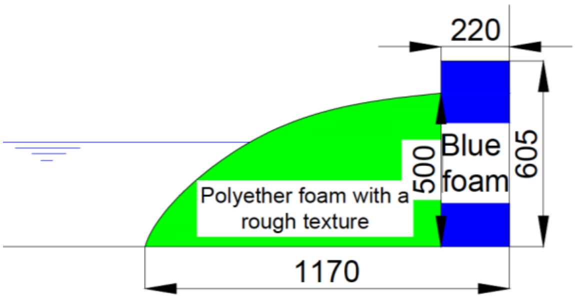

Figure 6 Side view of the parabola made out of polyether foam

Hexablocks are already used for a long time at the department of Civil Engineering, but its performance was never studied before. A picture of a hexablock installed in the wave flume is shown in Figure 7. The used hexablock has a thickness of 30 cm and behind the hexablock there is a confining chamber of 24 cm. Like the SIPWA, the hexablock uses the principle of resonance to initiate wavebreaking, but does not have viscous dissipative properties.

Figure 7 Hexablock installed in the wave flume

Performed tests

The full test matrix of the performed tests is given in Table 1. The parameters h, H_s, S_p and T_p represent respectively the used water depth, the significant wave height, the peak wave steepness and the peak wave period used in the different tests. The wave conditions consist of several irregular waves with a Jonswap spectrum. All thirteen tests have been executed for each of the above-mentioned configurations, resulting in a total of 104 tests.

Table 1 Characteristics of the different tests in the test program

Test number	h [cm]	H_s [cm]	S_p [-]	T_p [s]
1	40	3	0.05	0.6201
2	40	3	0.025	0.8901
3	40	7	0.05	0.9734
4	39	7	0.025	1.5961
5	34	3	0.05	0.6204
6	34	3	0.025	0.9020
7	34	7	0.05	0.9928
8	34	7	0.025	1.6703
9	34	10	0.05	1.2744
10	25	3	0.05	0.6232
11	25	3	0.025	0.9432
12	25	7	0.05	1.0533
13	25	7	0.025	1.8776

As can be seen in Table 1 three different water depths have been used: 40 cm, 34 cm and 25 cm. Only test number 4 has been executed at 39 cm instead of 40 cm due to wave overtopping at the end of the beach. However, in the discussion of this research this test is also treated as a test performed at 40 cm water depth.

RESULTS

The test data were analysed using the program WAVELAB 3.675. The reflection coefficients for every configuration were calculated and are shown in Figure 8, Figure 9 and Figure 10. Each graph shows the reflection coefficients for the different configurations at a different water depth (40 cm, 34 cm and 25 cm for Figure 8, Figure 9 and Figure 10, respectively). The results show that the reflection coefficients of the sloping beach with large stones are generally lower than those of the other configurations at water depths of 34 cm and 25 cm. At a water depth of 40 cm, this isn't the exact case, however, the sloping beach still performs very well. After analyzing the results of all the tests, we can conclude that the sloping beach with large stones is the most efficient absorber out of all the wave absorbers tested in this study.

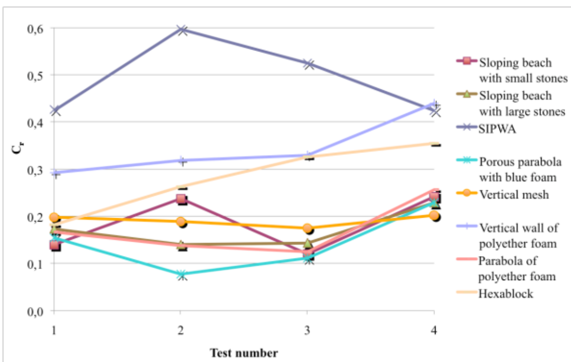

Figure 8 Reflection coefficients at a water depth of 40 cm

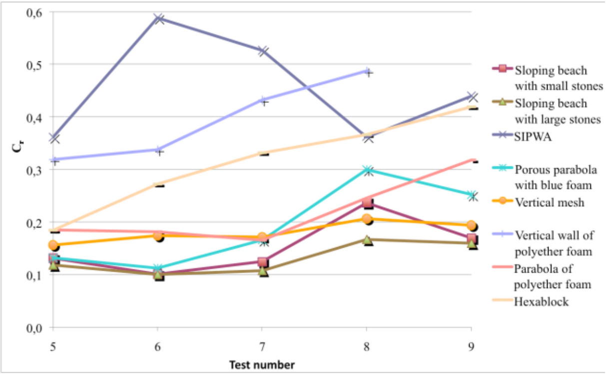

Figure 9 Reflection coefficients at a water depth of 34 cm

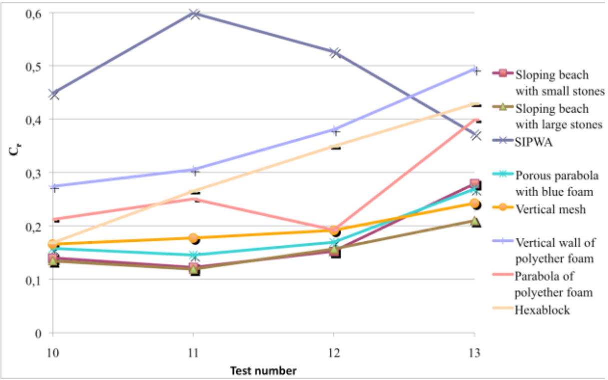

Figure 10 Reflection coefficients at a water depth of 25 cm

A disadvantage of the sloping beach configuration is that it is quite long and sometimes it is not possible to have enough space available for this absorber. In this case, one should look for another wave absorber that can be installed in the facility and still shows good wave damping properties. Referring to Figure 8, Figure 9 and Figure 10, two other options are recommended: a porous parabola with blue foam and a vertical mesh. Placing a parabola constructed out of polyether foam is not an option as its performance is not good enough at a water depth of 25 cm.

Concerning the first alternative (placing a porous parabola with blue foam), it has been observed during the test program that hardly any wave is breaking on the parabola. Consequently, the porous parabola isn't dissipating much wave energy and can actually be omitted. As a result, only the blue foam remains, and a much shorter evenly efficient wave absorber is obtained. This wave absorber is depicted in Figure 11 in the case of a water depth of 25 cm. Besides its shorter length the blue foam is also 16.7% cheaper than the vertical mesh. In addition, the vertical mesh configuration also requires more space in the flume/tank. The blue foam shows also slightly better wave damping properties at a water depth of 40 cm (see Figure 8). However, the disadvantage of the blue foam with respect to the vertical mesh is that the geometry needs to be changed whenever the water level changes in order to have a curved surface at the still water level.

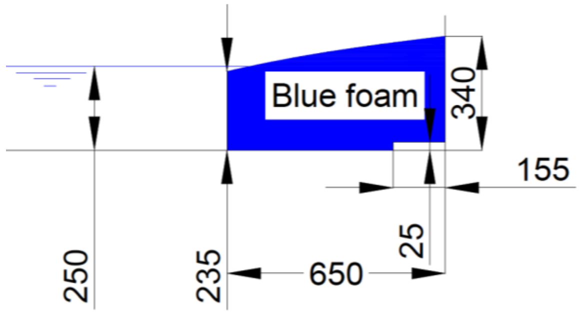

Figure 11 Alternative for the configuration depicted in Figure 3

As a consequence, it isn't perfectly clear whether one should choose the blue foam or the vertical mesh when there is no room to install a sloping beach with slope 2/7. It depends on the project itself. When the available space is limited and only tests at high water levels are performed (at which the performance of the blue foam is the best), without changing this level a lot (so that the geometry doesn't need to be changed), the configuration with the blue foam should be selected. If there is an intention of changing the water level very frequently, it is probably more convenient to work with a vertical mesh.

Alternatively, if there is no space to install a sloping beach with a slope of 2/7, one can still opt to build a sloping beach with a steeper slope. When the smallest feasible slope does not exceed 2/7 too much, this is probably a better option than placing blue foam or a vertical mesh as the sloping beach is a lot cheaper (85% and 87.5%, respectively) than these options and will still perform quite well.

One could also wonder why the sloping beach with large stones is performing better than the sloping beach with small stones. Two reasons can be brought forward. The first one is that the sloping beach with small stones is probably not porous enough as not much pores are present between the small stones. The second reason is that the sloping beach with small stones was reshaped under wave attack and that as such a slightly steeper slope was created just beneath the still water level. The stones of the sloping beach with large stones did stay in their places (not considering some very small movements).

CONCLUSION

The following advice to the designer of a wave flume or a wave basin can be given, based on the results of this study:

The first option should always be to build a sloping beach with a slope of 2/7, made out of stones of diameter 30-35 mm (stone-sizes should of course be scaled to the dimensions of the facility that one is designing). Also, if no space is available to build a sloping beach with a slope of 2/7 but there is space to build a slope that is somewhat steeper, a sloping beach should still be built. If however, no space is available to build a sloping beach, a wave absorber based on blue foam or a vertical mesh should be selected. When there is a need to change the water level in the facility frequently, the designer should opt for a vertical mesh.

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α (alpha)

α	Slope-angle of a standard sloping beach
α	Inclination angle of the planes of a Superposed and Inclined Planes Wave Absorber

Δ (Delta)

$\Delta\phi_{j,pq}$	Phase difference associated with the spacing between gauges p and q for the angular frequency ω_j corresponding to the wavelength L
Δf	Frequency bandwidth

δ (delta)

δ_o	Steepness of the incident wave
δ_m	Maximum wave steepness that will be totally reflected by a certain impermeable and smooth standard sloping beach

η (èta)

η	Water surface elevation
η_i	Water surface elevation caused by the incident wave
η_r	Water surface elevation caused by the reflected wave

ρ (rho)

ρ	Factor in the formula for the reflection coefficient of a standard sloping beach according to Miche that is dependent on the incident wave height and the characteristics of the slope structure

Φ (Phi)

Φ_i	Phase-angle of the incident wave
Φ_r	Phase-angle of the reflected wave
$\Phi_i^{(1)}$	Phase-angle of the incident wave of the first harmonic
$\Phi_r^{(1)}$	Phase-angle of the reflected wave of the first harmonic
$\Phi_{i,B}^{(n)}$	Phase-angle of the incident bounded wave of the n^{th} harmonic
$\Phi_{i,F}^{(n)}$	Phase-angle of the incident free wave of the n^{th} harmonic

$\Phi_{r,B}^{(n)}$	Phase-angle of the reflected bounded wave of the n^{th} harmonic
$\Phi_{r,F}^{(n)}$	Phase-angle of the reflected free wave of the n^{th} harmonic
A	Parameter without physical meaning used in the calculation of the reflection coefficient of a standard sloping beach according to Twu and Liu
a_i	Amplitude of the incident wave
a_r	Amplitude of the reflected wave
$a_i^{(1)}$	Amplitude of the incident wave of the first harmonic
$a_r^{(1)}$	Amplitude of the reflected wave of the first harmonic
$a_{i,B}^{(n)}$	Amplitude of the incident bounded wave of the n^{th} harmonic
$a_{i,F}^{(n)}$	Amplitude of the incident free wave of the n^{th} harmonic
$a_{r,B}^{(n)}$	Amplitude of the reflected bounded wave of the n^{th} harmonic
$a_{r,F}^{(n)}$	Amplitude of the reflected free wave of the n^{th} harmonic
B	Parameter without physical meaning used in the calculation of the reflection coefficient of a standard sloping beach according to Twu and Liu
C_r	Reflection coefficient
$C_{r\ ZS\ 5}$	Reflection coefficient calculated with the method of Zelt and Skjelbreia using 5 different wave gauges
$C_{r\ ZS\ 4}$	Reflection coefficient calculated with the method of Zelt and Skjelbreia using 4 different wave gauges
$C_{r\ MF\ 3}$	Reflection coefficient calculated with the method of Mansard and Funke using 3 different wave gauges
$C_{r\ GS\ F2}$	Reflection coefficient calculated with the method of Goda and Suzuki using the first two wave gauges
$C_{r\ GS\ L2}$	Reflection coefficient calculated with the method of Goda and Suzuki using the last two wave gauges
D	Width of the confining compartment of a Superposed and Inclined Planes Wave Absorber

E_i	Incident wave energy
E_r	Reflected wave energy
e	Space between two planes of a Superposed and Inclined Planes Wave Absorber
e(t)	Error function accounting for noise
f	Wave frequency
f_{min}	Frequency that is used as lower bound in the calculation of the incident and reflected wave energy
f_{max}	Frequency that is used as upper bound in the calculation of the incident and reflected wave energy
$G(\Delta\phi_{j,pq})$	'Goodness' function
G_s	Global size of a Superposed and Inclined Planes Wave Absorber
g	Gravitational acceleration (=9.81 m/s^2)
H	Water depth
H_i	Incident wave height
H_r	Reflected wave height
H_s	Significant wave height
h	Water depth
h	Height of the top of the plate of a Marcou wave absorber with respect to the bottom of the laboratory testing facility
i	Iterator used in the sums in formulas (2.6), (2.7) and (2.8)
k	Wave number
L	Wavelength
L	Length of a Marcou wave absorber
L	Length of the planes of a Superposed and Inclined Planes Wave Absorber
L_p	Peak wavelength
N	Number of stairs in a N-step staircase, used as an analogy for a sloping beach
n	Number indicating the order of a specific higher harmonic
O	Rotation axis of the plate in a Marcou wave absorber
p	Random wave gauge different from random wave gauge q

q	Random wave gauge different from random wave gauge p
R	Parameter without physical meaning used in the calculation of the reflection coefficient of a standard sloping beach according to Twu and Liu
S	Horizontal distance between the toe of a standard sloping beach and the intersection of the water surface with the standard sloping beach
$S_i(f)$	Incident energy spectral density
S_p	Peak wave steepness
$S_r(f)$	Reflected energy spectral density
T_0	Duration of the test
T_p	Peak wave period
T_t	Total running time of the test
x_1	Distance between the wave paddle and the wave gauge situated the closest to the wave paddle
$x_{1,2}$	Distance between the wave gauge situated the closest to the wave paddle and the wave gauge situated on the second position with respect to the wave paddle
$x_{1,3}$	Distance between the wave gauge situated the closest to the wave paddle and the wave gauge situated on the third position with respect to the wave paddle
$x_{1,4}$	Distance between the wave gauge situated the closest to the wave paddle and the wave gauge situated on the fourth position with respect to the wave paddle
$x_{1,5}$	Distance between the wave gauge situated the closest to the wave paddle and the wave gauge situated on the fifth position with respect to the wave paddle
x_p	Position of wave gauge p with respect to the wave paddle
x_q	Position of wave gauge q with respect to the wave paddle

Chapter 1

Introduction

This Master's Dissertation focuses on the topic of passive wave absorbers in laboratory testing facilities. In physical modelling two types of laboratory testing facilities exist, namely wave flumes and wave basins. Both are used to evaluate the behaviour of scale models of hydraulic structures under wave attack. A wave flume has a length much longer than its width and is used for tests in two dimensions. In a wave basin, which has a width and a length in the same order of magnitude, tests in three dimensions can be performed.

In both types of facilities reflected waves disturb the correct reproduction of both coastal and nearshore physical phenomena and should therefore be damped as much as possible. This damping is done by wave absorption with spending beaches. Different wave absorbers can be used as a spending beach. A set of interesting absorbers has been investigated in a wave flume during a test program executed within the scope of this thesis.

A typical test setup in this wave flume is depicted in Figure 1-1. The wave paddle, situated at the right side of the facility, generates the waves. The wave absorbing structure/beach that is tested, is placed at the other side and can have any shape.

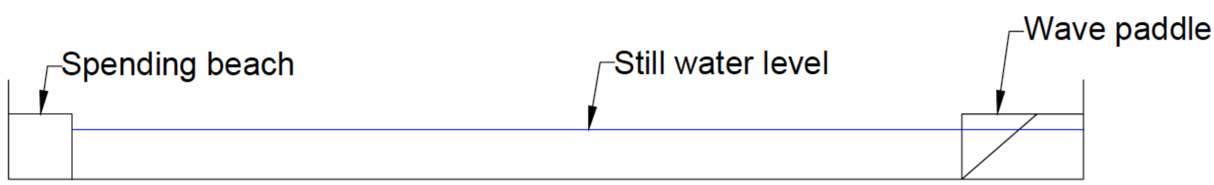

Figure 1-1: Typical test setup

The main intention is to determine which wave absorber is giving the best performance. However, this thesis does have other goals too. A list of the different objectives is given below.

1) To determine which wave absorber one should use when designing a wave flume or a wave basin in order to achieve the best wave absorbing characteristics.
2) To identify the gaps in the knowledge related to passive wave absorption.
3) To find how the accuracy in the analysis is affected by the use of different numbers of wave gauges.

These objectives are reached through physical model tests in the small wave flume of the department of Civil Engineering of the Faculty of Engineering and Architecture of Ghent University. These model tests are preceded by an extensive literature review, which is presented in chapter 2. The test program, the execution of it and the measurements that have been done are described in chapter 3. In chapter 4, the reflection analysis and the test results are discussed. Finally, chapter 5 draws up the conclusions of this study.

Chapter 2

Literature review

A lot of different wave absorbers were found in literature. An extensive review is given in this chapter. Before we continue with the discussion of the different wave absorbers, the reflection coefficient, an important parameter that determines the performance of a wave absorber, will be introduced.

When an incident wave with wave height H_i encounters a certain structure that reflects the wave for a certain amount and produces as such a reflected wave with wave height H_r, the reflection coefficient C_r is defined as the ratio of the wave heights of the reflected and the incident wave:

$$C_r = \frac{H_r}{H_i} \tag{2.1}$$

The higher the reflection coefficient, the higher the wave height of the reflected wave will be. The lower the reflection coefficients a certain wave absorber produces, the better it performs. The reflection coefficient is equal to one when the beach is perfectly reflective. Impermeable vertical walls with a smooth surface are an example of such beaches [21].

The following presents a review of different wave absorbers as found in literature.

2.1. Standard sloping beach

This wave absorber is the regular wave absorber that is used in most of the wave flumes and basins around the world. The absorber consists of a simple straight slope (see Figure 2-1). Different materials are used, but mostly this absorber is constructed out of granular material. The general principle of this wave absorber is based on the dissipation of wave energy due to wave breaking caused by the reducing water depth.

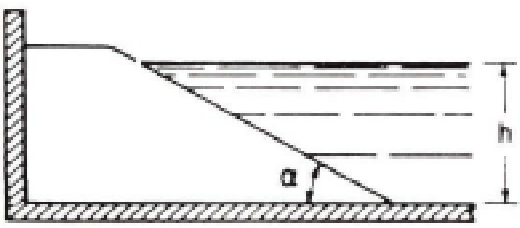

Figure 2-1: Standard sloping beach [15]

If one chooses very mild slopes very low reflection coefficients can be obtained. At the University of Bristol, for example, there is a beach with a slope of 1/11, which results in a reflection coefficient smaller than 0.04. In the St. Anthony Falls Hydraulic Laboratory, however, slopes are steeper and range between 1/1 and 1/3.7. As a consequence the reflection coefficients of these slopes will be a lot higher, which is confirmed by the value of 0.35 reported by the St. Anthony Falls Hydraulic Laboratory. More information concerning used slopes, construction materials, permeability and reflection coefficients of standard sloping beaches used in different research centres around world is given in Table A.1 of Annex A [15].

Through the years quite some research has been done on the reflection coefficient of sloping beaches. The three below mentioned points are found to be of importance for the performance of this wave absorber.

1) The steepness of the slope
2) The steepness of the incident wave
3) Characteristics of the slope-structure

Already in 1944, Miche developed an important formula, which brings these three elements together [13]. This formula is the following:

$$C_r = \rho \cdot \frac{\delta_m}{\delta_o} \tag{2.2}$$

The symbol δ_m represents the maximum wave steepness that will be totally reflected by the slope in case it is impermeable and smooth. Waves with small steepnesses, i.e. with large wavelengths, will experience a sloping beach as a vertical wall and will be reflected totally. Waves with steepnesses smaller than or equal to δ_m are long enough to experience the sloping beach as a vertical wall. However, waves with steepnesses higher than δ_m experience the sloping beach as a true slope and will only be reflected partially. It is clear that δ_m is dependent on the steepness of the slope: the steeper the slope, the higher δ_m becomes. So here the first abovementioned point is of importance. Miche deducted an analytical relation between δ_m and the slope-angle α:

$$\delta_m = \sqrt{\frac{2\alpha}{\pi}} \frac{\sin^2 \alpha}{\pi} \tag{2.3}$$

The second abovementioned point, the steepness of the incident wave, is represented by the symbol δ_o in formula (2.2).

If δ_m increases, the way the sloping beach is experienced by the incident wave will go more to the side of the vertical wall and the reflection coefficient will increase. If, however, the steepness of the incident wave increases, it will experience the sloping beach less like a vertical wall and more like a true slope. As a consequence the reflection coefficient C_r will decrease. Both phenomena are contained in formula (2.2). Finally ρ is determined by both the characteristics of the slope-structure (the third abovementioned point) and the incident wave steepness. ρ should be determined experimentally. The characteristics of the slope structure are determined by the roughness of the surface and the permeability of the structure. Permeable slopes have better wave absorbing capacities than impermeable ones, so ρ will have a significantly lower value if the slope has a certain permeability. The same is valid for rough structures. For impermeable structures ρ might vary from 0.68 to 1.0 with 0.68 corresponding to a rough structure and 1.0 corresponding to a completely smooth structure. For a rubble mound structure, which can also be seen as a sloping beach, and which is certainly a permeable structure, a value of only 0.32 needs to be used [14]. Of course the value of C_r obtained with (2.2) should always be restricted to one.

It is clear that formula (2.2) is not giving exact values for C_r. The values obtained with this formula are rather indications of what the reflection coefficient of a certain slope will be under the attack of a certain incident wave.

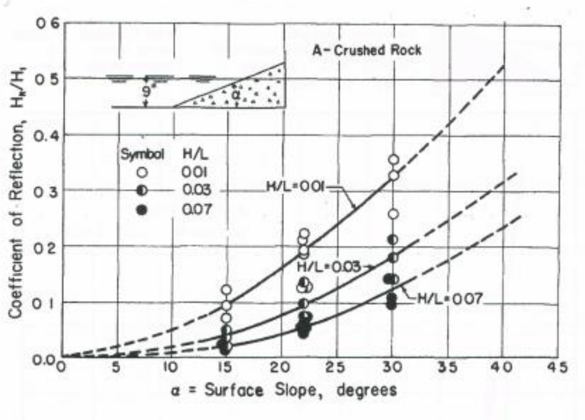

Figure 2-2: Reflection coefficient in function of slope-angle for crushed rock [17]

It was mentioned above that ρ should be determined experimentally. Miche did this for sloping beaches of crushed rock. The results of his study gave the dependency between the reflection coefficient and the slope-angle shown in Figure 2-2. Out of this dependency ρ-values could be determined. The ρ-values that were found as such are shown in Table 2-1.

Table 2-1: ρ-values for sloping beaches of crushed rock

	ρ
δ_o=0.01	0.11
δ_o=0.07	0.19

Later, another method to calculate reflection coefficients for this wave absorber was developed by Twu and Liu [24]. The method is completely based on analytical calculations. In the calculations the sloping beach is simulated as a N-step staircase (see Figure 2-3) and is assumed to be impermeable. If one chooses N (the number of stairs) sufficiently large, the N-step staircase will reflect approximately the same wave as a sloping beach. The formulas needed to calculate the reflection coefficient according to this method are as follows:

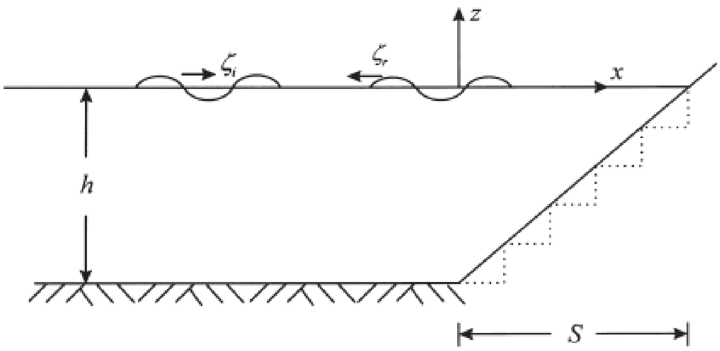

Figure 2-3: Standard sloping beach as a N-step staircase [24]

$$C_r = \frac{a_i}{a_r} \tag{2.4}$$

$$a_r = \sqrt{A^2 + B^2} \tag{2.5}$$

$$A = \frac{a_i}{R} \cdot \sum_{i=1}^{N} \sqrt{\cosh\left(2k \cdot \frac{i-1}{N} \cdot h\right)} \cos\left(2k \cdot \frac{i-1}{N} \cdot S\right) \tag{2.6}$$

$$B = \frac{a_i}{R} \cdot \sum_{i=1}^{N} \sqrt{\cosh\left(2k \cdot \frac{i-1}{N} \cdot h\right)} \sin\left(2k \cdot \frac{i-1}{N} \cdot S\right) \tag{2.7}$$

$$R = \sum_{i=1}^{N} \sqrt{\cosh\left(2k \cdot \frac{i-1}{N} \cdot h\right)} \tag{2.8}$$

where a_r is the amplitude of the reflected wave, a_i is the amplitude of the incident wave, k is the wave number, h is the water depth and S is the horizontal distance between the toe of the sloping beach and the intersection of the water surface with the sloping beach. A, B and R are parameters used in the calculation, which do not have a physical meaning. Remark that the reflection coefficient is defined as the ratio of the reflected and incident wave amplitude in formula (2.4) instead of the ratio of the reflected and incident wave height as in formula (2.1). However, the calculations are based on the linear wave theory. As a consequence (2.4) is equivalent to (2.1).

Choosing a value of 30 for N is normally more than big enough in order to purchase a staircase with the wave reflection properties of an equivalent sloping beach. The calculations can be performed easily using a symbolic software package such as Maple or Mathematica.

With these formulas graphs such as the one depicted in Figure 2-4 can be drawn (with L denoting the wavelength). Out of this graph Twu and Liu draw the following conclusions:

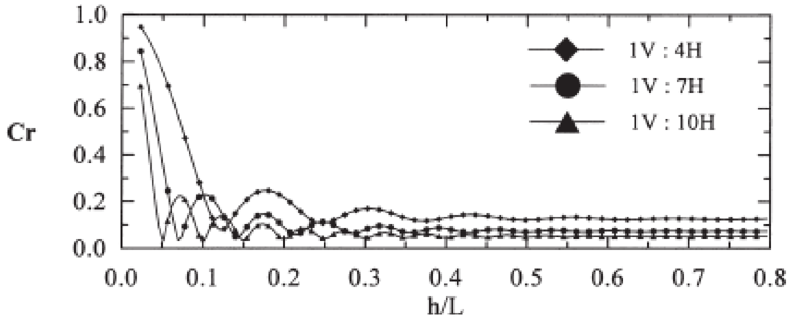

Figure 2-4: Reflection coefficients for different slopes [24]

1) It is very difficult to damp waves with a very long wavelength (i.e. h/L approaches zero). This is a well-known phenomenon in physical modelling.
2) For h/L<0.5 (i.e. transitional and shallow water) C_r is dependent on h/L, which means different waves may yield different reflection coefficients for the same structure. As a consequence, a reflection coefficient of a sloping beach cannot be seen as a fixed number, but will always be a range of numbers. This could also be concluded out of the method of Miche as the incident wave steepness occurs in (2.2). This observation is not only valid for sloping beaches but it is a general fact that is valid for every wave absorber.
3) For h/L≥0.5 (i.e. deep water) C_r becomes constant. This indicates that in deep water conditions the reflection coefficient depends only on the slope, according to Twu and Liu. According to Miche, however, the reflection coefficient is always dependent on the wave steepness, also in deep water conditions.
4) Like the theory of Miche showed already, it can also be seen in Figure 2-4 that C_r decreases with decreasing slope.

It is not clear which of the above two methods (the method of Miche and the method of Twu and Liu) is the best one. If one wants to have an estimate on what kind of reflection coefficients one can expect for a certain slope, it is possibly a good idea to use both of the abovementioned theories and use the obtained values as a range of possible reflection coefficients. Determining which one of the above two methods is performing the best is something that could also be investigated during this Master's Dissertation as a minor extra objective.

As the sloping beach is a popular wave absorber different variations on it exists. The wave absorbers discussed in sections 2.2. up to 2.9. can be seen as variations on this first wave absorber.

2.2. Sloping beach that doesn't reach the bottom

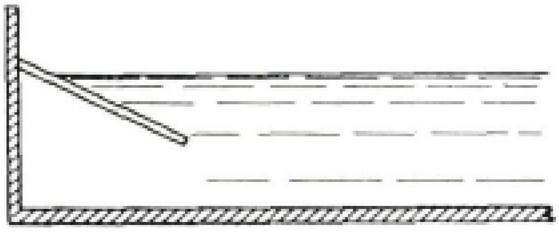
Figure 2-5: Sloping beach that doesn't reach the bottom [15]

The difference between this wave absorber and the standard sloping beach is that the slope is cut off at a certain depth beneath the still water level as can be seen in Figure 2-5. A first advantage of this absorber is that less material needs to be consumed. The increase of the reflection coefficient due to the fact that the slope doesn't reach the bottom anymore is in most cases small. Most of the wave energy is indeed situated close to the still water level, where the wave propagates, and here the slope is present to dissipate this energy. As such, one comes to the most interesting advantage of this wave absorber, namely the fact that at the most important area, i.e. close to the still water level, a smaller slope can be used than an equivalent standard sloping beach taking the same space in the facility. This should result in a better performance of the sloping beach that doesn't reach the bottom with respect to its equivalent standard sloping beach.

If one wants to make this wave absorber usable at different water levels, one needs to make the position of the slope adjustable, so that it can be moved up or down when the water level increases or decreases. This makes the construction of a standard sloping beach easier.

It is also important to make the wave absorber long enough to make sure that no significant amount of energy is able to flow under the slope. In shallow water conditions, where the wave energy is distributed more evenly over the depth, the use of this absorber can therefore be questioned.

An overview of some research centres using this wave absorber with the specific characteristics of the absorbers can be found in Table A.2 [15].

2.3. Sloping beach with a mesh in front

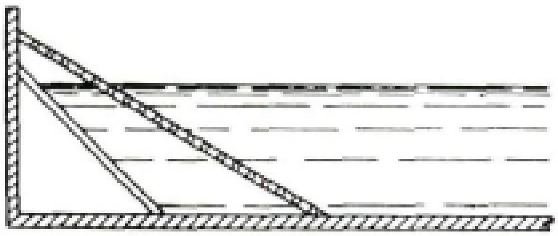
Figure 2-6: Sloping beach with a mesh in front [15]

This wave absorber resembles much to the standard sloping beach but in this case a mesh is placed in front of it (see Figure 2-6). This mesh has the intention to dissipate already some wave energy before the waves reach the beach. However, if one wants to maintain the same total length as a standard sloping beach, the beach needs to be made steeper. If the mesh can compensate for the loss of efficiency cause by this, this wave absorber will perform better than a standard sloping beach. If this is not the case, however, the standard sloping beach will perform better. As lots of parameters are of importance (e.g.: used materials, porosities, spacing between the sloping beach and the mesh, …) it is impossible to say in advance whether this wave absorber will perform better or not. For the mesh different materials can be utilised. The laboratory of the company Arctec Canada Ltd. used a wire screen. The AMTE (Admiralty Marine Technology Establishment) laboratory in the United Kingdom used transversal bars with a certain spacing in between them. More details about the usage of this wave absorber in these laboratories can be found in Table A.3 [15].

2.4. Broken slope

This wave absorber has a steeper slope at higher depths and a milder slope closer to the still water level as is depicted in Figure 2-7. As such the smaller slope is present where the wave energy is the highest and as a consequence the waves will be damped more than a standard sloping beach with the same length would damp them. If, however, the water level is located beneath the kink in the slope, where the slope is steeper, this wave absorber is less efficient. This is a disadvantage of this wave absorber with respect to the sloping beach that doesn't reach the bottom that, if the position of the slope is made adjustable, can be used efficiently at different water levels. Different research centres over the world use a wave absorber like this one (see Table A.4). In Ottawa a reflection coefficient ranging between 0.02 and 0.1 was found for a setup with values of the slopes of 1/2 and 1/6 for the steep and the mild slope respectively [15].

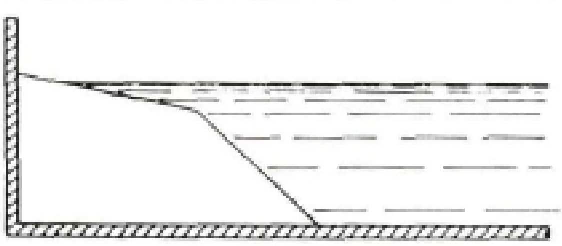

Figure 2-7: Broken slope [15]

2.5. Broken slope that doesn't reach the bottom

This wave absorber does, just like the absorber discussed in section 2.2., not reach the bottom of the wave flume or wave basin. However, in contrast this earlier discussed absorber this wave absorber doesn't have a constant slope but a slope build up out of three different parts (see Figure 2-8). The lowest part is the least important as the wave energy is the lowest there. Therefore, this part has the highest steepness. The part of the slope in the middle has a lower steepness as it is more important and the upper part, which is located in the region of the still water level, where the wave energy is the highest, has the lowest steepness, as it is the most important part. Due to the fact that this absorber doesn't reach the bottom, the position of it can be made adjustable, which makes it efficient at different water levels. However, in shallow water where the wave energy is distributed more evenly over the depth, the advantage of the varying slope and the fact that the wave absorber doesn't reach the bottom isn't present. In the Danish Hydraulic Institute in Horsholm,

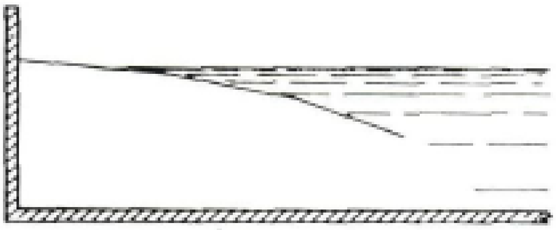

Figure 2-8: Broken slope that doesn't reach the bottom [15]

Denmark, a wave absorber of this type is used. Detailed information on it can be found in Table A.5 [15].

2.6. Slope with a front wall

This wave absorber is very similar to the wave absorber that doesn't reach the bottom. However, one can see in Figure 2-9 that the slope of this wave absorber is connected with the bottom by a front wall. This causes the wave absorber to be fixed. As a consequence, it will only be efficient for water levels, which are higher than the height of the front wall. This is a disadvantage with respect to wave absorber that doesn't reach the bottom, but if the designers know that no tests will be carried out in the facility with water levels lower than (or in the circumference of) the height of the front wall this wave absorber can be used and no system to make the position of the slope adjustable is necessary. In the St. Anthony Falls Hydraulic Laboratory a wave absorber of this type can be found. Table A.6 summarizes some specific information on this absorber [17].

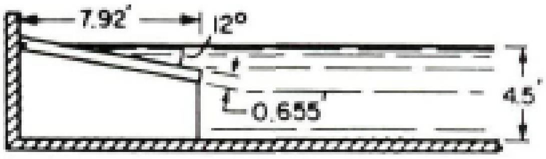

Figure 2-9: Slope with a front wall [15]

2.7. Marcou wave absorber

This wave absorber can still be seen as a variation on standard sloping beach, but it is already more sophisticated. It was designed by Marcou in 1954. The absorber consists of a thin aluminium plate that on its right side (backside of the facility) is resting in its corners on a frame and that on its left side is able to rotate around an axis denoted with O in Figure 2-10. The plate is raised and lowered in a periodic way under the incident wave attack. Every incident wave pushes the plate against its supports, but during running over the plate the wave breaks and in contrast to the previous wave absorbers the water from the breaking wave is not turning back to the flume but this water and the energy which it possesses is evacuated as it flows over the top of the plate, ending up in the compartment at the back of the plate. Once the incident wave is passed, the plate springs back a bit and comes loose from its supports (see Figure 2-11). This is essential to prevent the water in the compartment at the back of the plate from flowing over the top of the plate back into the flume. Next, a new wave reaches the plate and the plate is pushed once more against its supports, the wave breaks and everything starts over. Of course the water

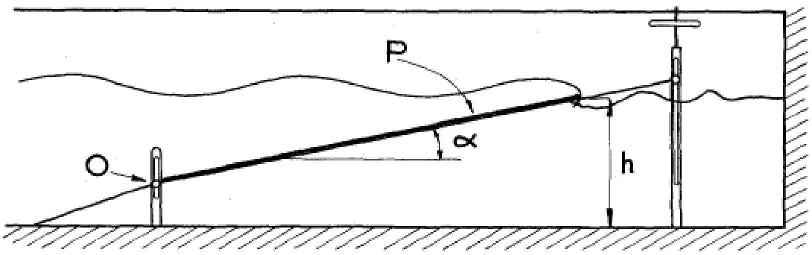

Figure 2-10: Marcou wave absorber during wave attack [12]

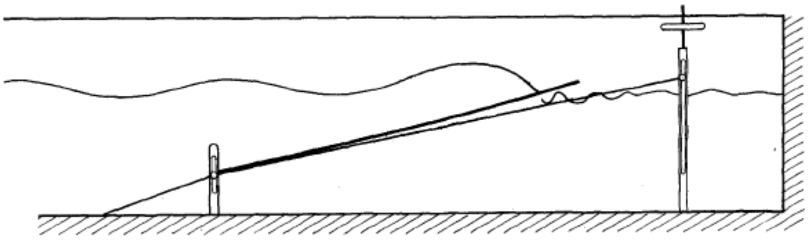

Figure 2-11: Marcou wave absorber between two wave attacks [12]

in the compartment at the back should be allowed to flow back into the flume in one way or another because otherwise the compartment becomes too full. This is allowed close to the bottom of the flume beneath the rotation axis O where the water is a lot more quiet than it is close the top of the plate where the water flowing over the top is still carrying a considerable amount of energy and is causing quite some turbulence.

A test program on this wave absorber took place in the National University of electrical engineering and hydraulics of Grenoble. In this test program there was investigated what the ideal thickness of the plate is and also what the ideal value is for the ratio h/H with h the height of the top of the plate with respect to the bottom of the flume and H the water depth. The conclusion was that the minimal reflection coefficient was found for a thickness of 4 mm and a value of h/H equal to 1. For this case the best-fitting line between all the tests with a plate with a thickness of 4 mm gave a reflection coefficient of 4.3% and for one single test there was even found a reflection coefficient of 2.1% as can be seen in Figure 2-12. In this figure L is the length of the wave absorber [12]. During the test program regular waves with a wave period of 1.063 s and wave height of 6 cm were used in water depth of 30 cm.

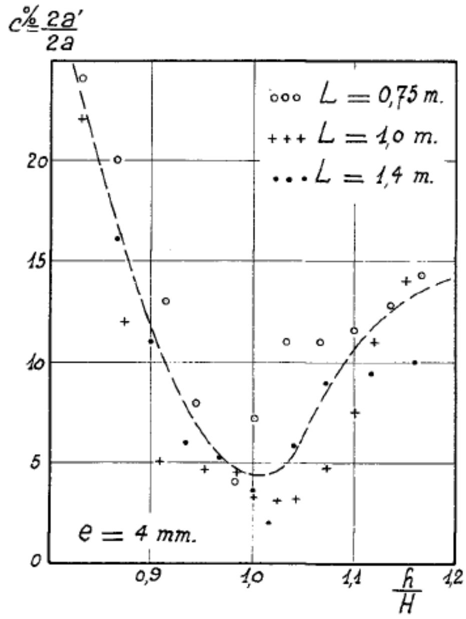

Figure 2-12: Reflection coefficient in function of h/H for a plate-thickness of 4 mm [12]

2.8. Submerged slope

The submerged slope uses actually the same principle as the previous absorber. However, for this absorber the plate is replaced by a slope made out of crushed stones (see Figure 2-13). The slope is, using the same idea as the broken slope, steeper closer to the bottom and milder closer to the

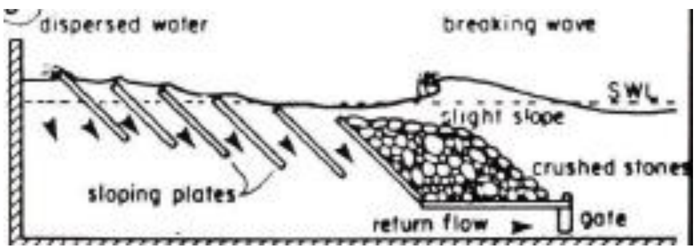

Figure 2-13: Submerged slope [15]

free surface. The waves break at the height of the slope and, as the slope is slightly submerged, the water from the broken waves is able to flow to the backside of the slope easily. There, some sloping plates try to prevent the water from flowing over the top of the slope back into the flume. Instead, they try to guide the water to the bottom of the flume and let it escape beneath the slope. There is a gate provided beneath the slope that ensures that water can only flow from the backside of the slope to the flume and not from the flume to the backside of the slope. Although a test program on this wave absorber was performed in which wave periods ranging between 1.15 s and 2.35 s and wave heights ranging between 4 cm and 20 cm were applied, no reflection coefficient is given for this wave absorber [7].

2.9. Perforated slope

This wave absorber is just like the previous two trying to prevent the water from the breaking waves from flowing immediately back into the flume. This is done by using a slope, which consists of a perforated wooden plate. As such the water from the breaking waves flows through the plate to the backside of it where it is guided by ten short plates to the bottom of the flume (see Figure 2-14). Here, the water is more quiet and it can flow back into the flume causing fewer disturbances to the incident waves. Reflection coefficients for this wave absorber are found to range between 0.05 and 0.2 [15].

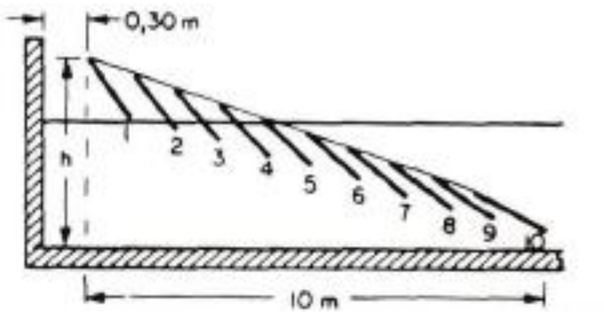

Figure 2-14: Perforated slope [15]

2.10. Standard parabolic slope

As can be seen in Figure 2-15 this wave absorber doesn't have a straight slope anymore. The slope of the absorber has, however, a parabolic shape. This has the same advantage as the wave absorbers discussed in sections 2.2., 2.4., 2.5. and 2.6., namely that, by choosing a parabolic shape for the cross-section of the beach, the smallest slope is present where the water has the most energy, i.e. in the circumference of the still water level. As a consequence the wave energy is dissipated more efficiently. Different materials are possible for this wave absorber, going from gravel over transversal bars to wire screens. In the Laboratory of Fluid Mechanics in Delft a standard parabolic slope was built, having a reflection coefficient of 0.05. Extra information on standard parabolic slopes around the world can be found in Table A.7 [15].

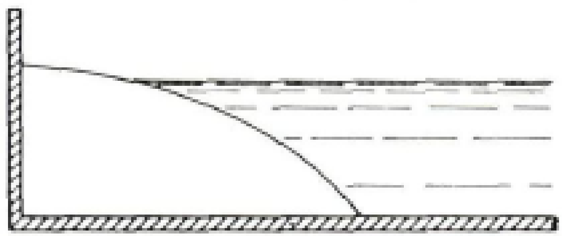

Figure 2-15: Standard parabolic slope [15]

2.11. Parabolic slope that doesn’t reach the bottom

This wave absorber is a variant on the previous one. In contrast to the standard parabolic slope, this wave absorber doesn't reach the bottom (see Figure 2-16). This saves material and reduces the length of the absorber. The increase of the reflection coefficient is small due to the fact that at higher depths the wave energy is small. Most of the energy is situated at lower depths and here the parabola is present to dissipate this energy. However the use of this wave absorber is again questioned in shallow water where the wave energy is spread more evenly over the depth. Table A.8 summarizes information on this type of absorber in different research centres around the world [15].

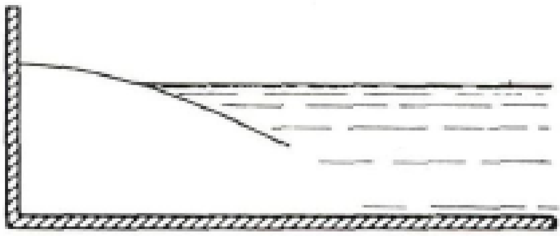

Figure 2-16: Parabolic slope that doesn't reach the bottom [15]

2.12. Parabolic slope with a front wall

This wave absorber is very similar to the previous one. The difference is that there is a front plate, which connects the parabola with the bottom of the facility (see Figure 2-17). As the wave energy is mostly limited at the location of the front plate, this absorber will show more or less the same absorption capacities as the parabolic slope that doesn’t reach the bottom. Tiedeman (2012) designed this absorber for large scale laboratory testing facilities and worked during his test program, which was on a smaller scale, with a prototype water depth of 5 m, prototype wave periods of 2 to 3 seconds and a prototype wave height of 35 cm. He found reflection coefficients smaller than 0.05 using a perforated parabola and a non-perforated front plate. For some particular tests reflection coefficients as low as 0.01 were even found [19].

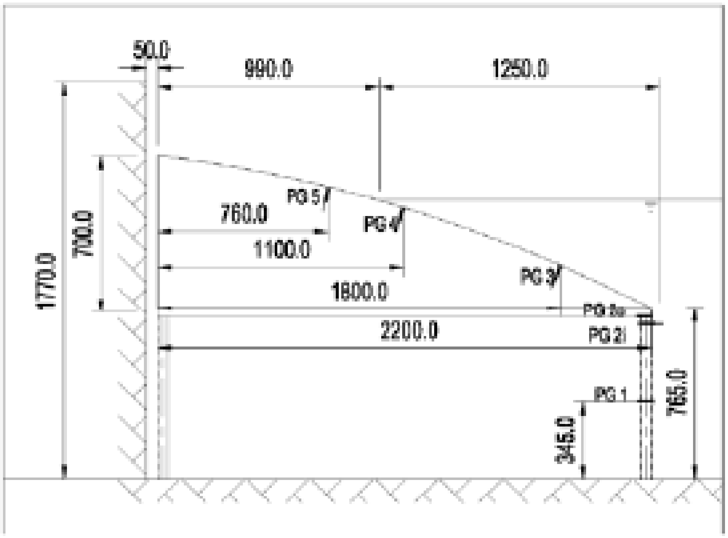

Figure 2-17: Parabolic slope with a front plate [19]

2.13. Combination of a straight and parabolic slope

This wave absorber is a combination of both a straight and a parabolic slope. A straight slope is placed at the bottom and three different parabolic slopes are placed on top of it as is depicted in Figure 2-18. The absorber is made out of a wire screen in combination with a transversal bars, sand, gravel and stones. No information on the reflection coefficient can be found [15]. However, the reflection coefficient of this wave absorber will of course be dependent on the used value of the straight slope.

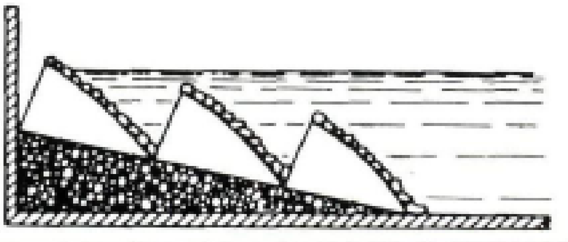

Figure 2-18: Combination of a straight and a parabolic slope [15]

2.14. Vertical mesh

In this configuration vertical perforated plates with a certain spacing in between them are placed at the end of the wave flume to function as a wave absorber (see Figure 2-19). As the water needs to flow through the openings of the consecutive perforated plates the wave energy is dissipated and the amplitude of the reflected wave becomes small which results in a small reflection coefficient. Of course this reflection coefficient will decrease with increasing amount of vertical plates, but using a very high amount of plates would take a lot of place in a wave flume and wouldn't be economical. Also it is intuitively clear that the more vertical plates there are already installed the smaller the contribution of an extra vertical plate to the decrease of the reflection coefficient will be. The question now raises from which amount of plates onwards the influence of adding an extra plate can be neglected with respect to the extra space and cost it creates. Besides this it is also important to know the ideal spacing between the vertical plates in order to minimize the reflection coefficient. Another question that can be asked, is in which sequence one should place the perforated plates, in case these have different porosities. Should these plates be placed in order of decreasing or increasing porosity or doesn't this make any difference? Linked to this question one can also wonder if it is better to use a constant change in the porosity over the different plates or if it would be better to use another

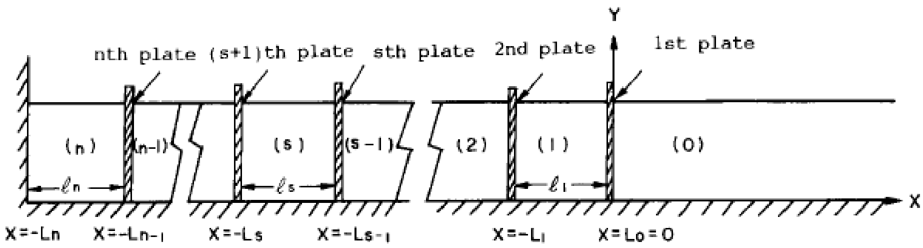

Figure 2-19: Vertical mesh [23]

course for the change in porosity, a monotonical course for example. All these questions were asked and answered by Twu and Lin [23]. To solve these questions they performed theoretical calculations, which were validated with physical tests. The outcomes of the theoretical calculations will be discussed below.

For the sequence of the plates it is concluded that is important to place the plate with the highest porosity first (i.e. the closest to the incident waves). The following plates are placed in order of decreasing porosity. Only if all the plates are placed at the position of a clapotis wave node the sequence of the plates doesn't make any difference. This is because in this situation the fluid has a maximum horizontal velocity and each porous plate can offer its utmost limit of wave damping efficiency. In practice, however, it is difficult to maintain a porous plate at such a particular location because of the variable incident wave height. As a consequence porous plates aren't placed in clapotis nodes and only part of the wave damping efficiency is provided and in this case it is crucial to place the plates with the highest damping capacity (the most porous plates) in front as the wave energy is the greatest there.

Concerning the spacing between the plates, it was found that a spacing of 0.88*h, with h the water depth, is the ideal spacing that should be used. To show this the researchers did analytical calculations for different spacings. The calculations showed that spacings lower than 0.88*h as well as spacings higher than 0.88*h gave higher reflection coefficients. In a first phase the researchers performed this calculations for six porous plates. After this they redid the calculations for ten and for fifteen plates and each time they found that 0.88*h was the best possible spacing between the porous plates. The same conclusion was also drawn in an earlier publication from the same authors [22] for smaller amounts of plates. Comparison of the obtained reflection coefficients for the arrangements with 6, 10 and 15 plates led to the conclusion that the arrangement with ten plates is the best. The arrangement with 15 plates did give still a lower reflection coefficient than the one with 10 plates but the difference didn't counterbalance the extra cost and place needed for five additional plates.

The above-mentioned calculations for 6, 10 and 15 plates were all done twice. In a first instance the calculations were done for a constant decrease in the porosity of the plates. In a second instance a monotonical decrease of the porosity, along the direction of the incident wave, was used. The calculation with the monotonical decrease of porosity gave smaller reflection coefficients for all three cases and therefore a monotonical decrease of porosity should be preferred above a constant decrease. The calculation with the monotonical decrease of porosity with ten plates separated from each other by 0.88*h gave reflection coefficients lower than 0.04 in transitional water ($1/20<h/L<1/2$).

In a last instance the correctness of the calculations was verified with physical model tests. In the experiments a water depth of 50 cm and a wave height ranging between 2 and 4 cm was adopted. The wave period varied from 0.85 to 3 s and the wavelength varied from 112.0 to 639.6 cm. In general the agreement between the experimental results and the outcome of the calculations was very good. So one can conclude that in general the results of the calculations are valid.

Also Simon Tiedeman did research on the vertical mesh [19]. However, his research was much less extensive than that from Twu and Lin. He developed the vertical mesh depicted in Figure 2-20. In this mesh the distances between the plates are no longer constant but are decreasing in the incident wave direction. No reason for this decrease is mentioned in the publication, in which this configuration is analysed, but it might have been done in order to decrease the porosity at the back of the absorber like Twu and Lin did by decreasing the porosity of the plates. One could indeed suppose that the researchers had the idea that placing two plates with a certain porosity closer to each other would have the same effect as decreasing the porosity of the plates while keeping the distance between them the same. With this configuration reflection coefficients beneath 0.1 were found.

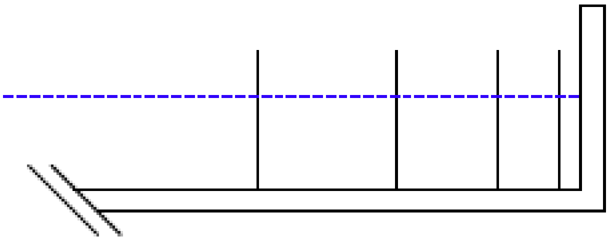

Figure 2-20: Test setup for the vertical mesh in the research of Tiedeman [19]

2.15. Mesh screens

This wave absorber uses a series of mesh screens to dissipate the wave energy as is depicted in Figure 2-21. One could see this wave absorber as a variation on the vertical mesh with the meshes placed very close together. The reflection coefficient varies a lot. Values between 0.05 and 0.92 are possible [15]. This wave absorber is very permeable, as the permeability equals 92%.

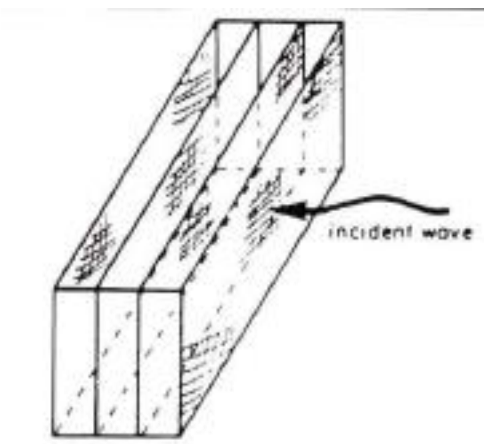

Figure 2-21: Mesh screens [15]

2.16. Chicken wire

This wave absorber is made out of a chicken wire. The cells of the chicken wire are partly filled with aluminum shavings. For the filling of the cells the same principle as used for the vertical mesh is used: the cells the closest to the incident waves are made the most porous and the cells the furthest away from the incident waves are made the least porous. This is done by leaving the cells the closest to the incident waves empty and by filling the cells further away from the incident waves with aluminum shavings. The furtherer from the incident waves the cells are located the more the shavings are compacted (see Figure 2-22). Reflection coefficients smaller than 0.07 can be obtained with this absorber [15].

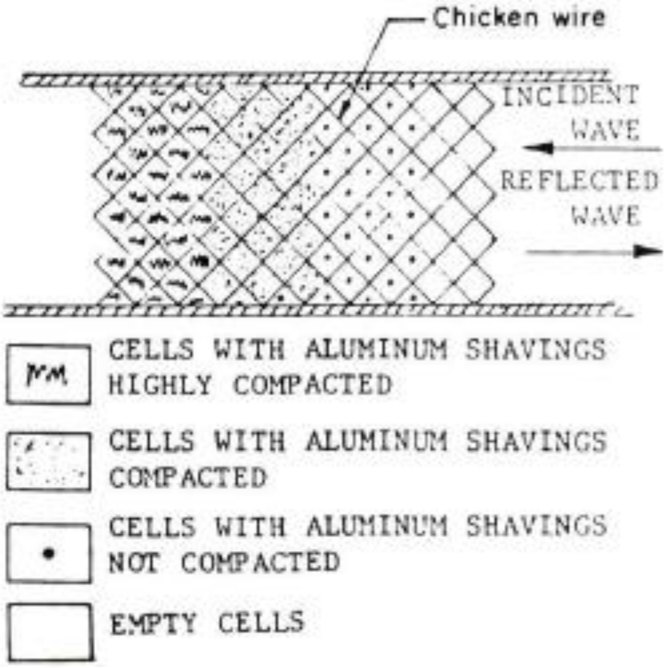

Figure 2-22: Chicken wire [15]

2.17. Expanded metal held in a triangular wedge shaped cage

The wave absorber depicted in Figure 2-23 is a new kind of compact and efficient beach that was developed for the narrow tank at the School of Engineering & Electronics of the University of Edinburgh. It consists of loose sheets of expanded metal (slit, stretched and corrugated aluminium foil) held in a triangular wedge shaped cage [18]. The idea of the absorber is that the incident waves lose their energy by bouncing around from one side to the other between the wedges. This principle is also shown in Figure 2-23 in which the blue lines present the incident waves. For the reflection coefficient of this absorber values higher than 10% were found for low steepnesses (H/L<0.01) and values lower than 5% were found for higher steepnesses (H/L>0.01) [6].

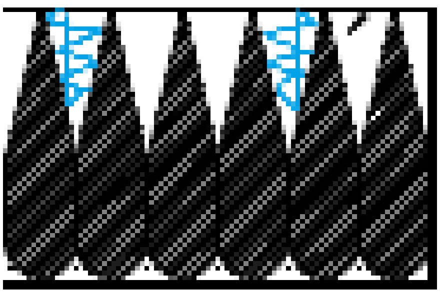

Figure 2-23: Expanded metal held in a triangular wedge shaped cage [18]

The idea of this wave absorber was also used in the caisson breakwater of the harbour of Naples. This breakwater has a surface that consists of a series of semicircles between which the incident waves can bounce around (see Figure 2-24) [8].

Figure 2-24: The caisson breakwater of the harbour of Naples [8]

2.18. Superposed and Inclined Planes Wave Absorber

The Superposed and Inclined Planes Wave Absorber, abbreviated with SIPWA is, as the name suggests, built up out of superposed inclined planes (see Figure 2-25). The determining geometrical characteristics of the SIPWA are the slope-angle α between the planes and the horizontal, which is positive clockwise, the space between two planes e, the plane length L and the space between the planes and the wall D. The global size of the absorber, G_s, is of course dependent on the above parameters and can be calculated using the following simple formula:

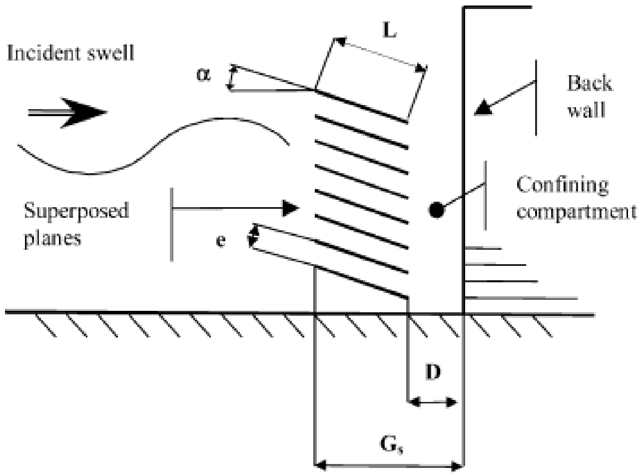

Figure 2-25: Superposed and Inclined Planes Wave Absorber [9]

$$G_s = L \cdot \cos\alpha + D \tag{2.9}$$

Now, the working-principle of the SIPWA will be discussed. Visualisations showed that when a swell arrives a fluid motion around the individual planes is always present. When the slope of the planes is positive also a fluid motion around all the planes exists. In case the planes have a negative slope this last motion is nearly zero. This motion is, however, of big importance for the good functioning of SIPWA and therefore one should always choose a positive value for the slope-angle α. It causes in the first place the formation of eddies at the edges of the planes (see Figure 2-26). These eddies are dragged into the confining compartment where they are broken up and so transformed into turbulence. As such the viscous dissipation of the swell energy takes place.

Figure 2-26: Eddy formation [9]

Besides this there is also the mechanism of resonance that plays an important role in the working-principle of the SIPWA. When the wave crest reaches the structure, it causes, with some retardation due to the positive slope of the planes, an increase in the water level in the confining compartment. When the wave trough arrives, a downward movement of the water level in the confining compartment is caused due to the positive inclination of the planes. This produces a fluid motion around all the planes and especially an upward motion on the external side of the SIPWA. Actually, the SIPWA can be seen as an energy accumulator: when the crest arrives the wave energy is retained in the confining compartment as potential energy due to the rise of the water surface. When the trough arrives the energy is restored into the fluid motion around all the planes.

The combination of both dissipation of the swell energy and the resonance yields to the breaking of the incident waves. A test program on the SIPWA was carried out in a wave flume with dimensions 30cmx30cmx3m in the Laboratory of Mechanics in the University of Le Havre and a water depth of 14.5 cm was used. In this test program there was shown that the optimal wave absorbing capacities could be found for α=35°, e=25 mm and D=33 mm. All the tests were performed with a length of the planes equal to 50 mm. As a consequence G_s was equal to 80 mm. In this configuration a reflection coefficient of 0.035 was found [9].

2.19. Superposed planes wave absorber

This wave absorber uses actually the same principle as the previous one. However, in this absorber the planes are horizontal (see Figure 2-27), which decreases its performance. Reflection coefficients lower than 0.18 cannot be found. Concrete and stones are used for the construction of the superposed planes wave absorber [15].

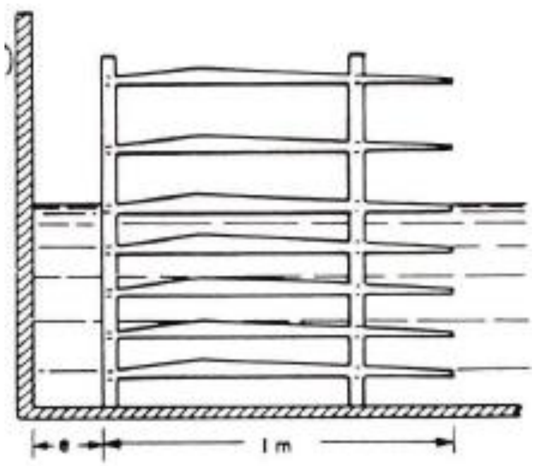

Figure 2-27: Superposed planes wave absorber [15]

2.20. Igloo wave absorber

This wave absorber is the so-called Igloo wave absorber, which was developed in Japan in the seventies [16]. It consists of separate concrete blocks, which are piled together. Principally the absorber works as follows (see Figure 2-28): the horizontal plates located between the different horizontal layers of blocks convert the circular wave movement into a horizontal flow that enters the blocks. Inside the blocks cylindrical chambers are present. These chambers reduce the energy of the entering water through the friction with the surface of the cylinders through the forced diversion and merging of the flows. The column shaped front wall lets the waves into the block smoothly, hardly reflecting the waves. A lot of tests were performed on this absorber in a wave flume as well as in a wave basin using different configurations. Water depths ranging between 16 and 22 cm were used. Wave periods between 0.8 and 2.4 s and wave heights between 2 and 6 cm were applied. However, reflection coefficients lower than 0.20 could not be found. Nevertheless, the Igloo wave absorber was used in different real life applications in order to diminish wave reflection of breakwaters in harbours with the purpose of improving the berthing and cargo-handling circumstances for ships.

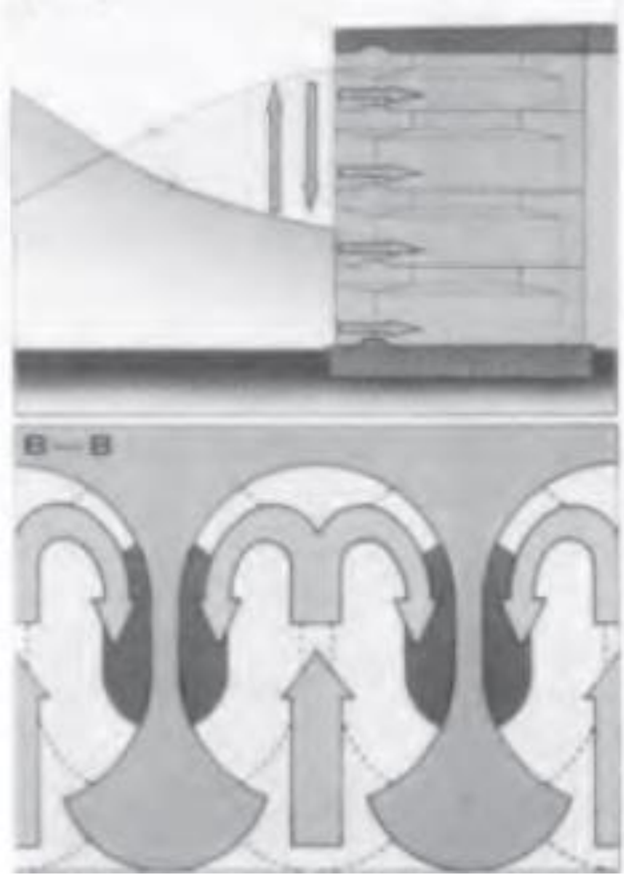

Figure 2-28: Principle sketch of the Igloo wave absorber - the lower part is showing the cylindrical chambers inside the blocks [16]

Figure 2-29 is a photograph of one of the configurations used in the research of Shiraishi, Palmer and Okamoto during a test in a wave basin.

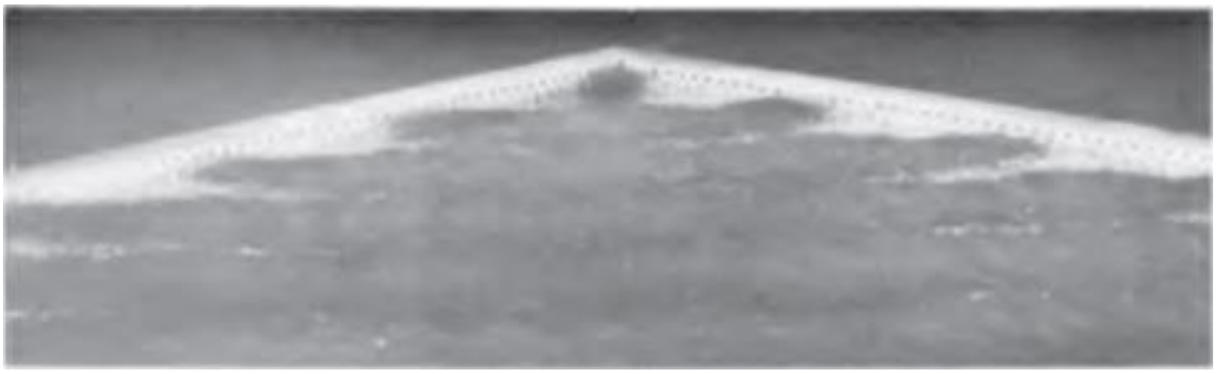

Figure 2-29: A configuration of an Igloo wave absorber tested in a wave basin [16]

2.21. Comparison of the different wave absorbers

To finalize this chapter, an overview of the results of the above literature review is given. This overview is depicted in Table 2-2. In this table the column with 'WA' (short for wave absorber) on top of it, is the column in which each element denotes the section number of the wave absorber discussed in the row of that specific element.

Table 2-2: Overview of the results of the literature review

WA	Principle of energy dissipation	Materials	Permeable?	Water depth considered in literature [m]	Wave period considered in literature [s]	Wave height considered in literature [m]	C_r
2.1.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.2.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.3.	Breaking waves + dissipation by openings	All kinds of materials possible	Yes	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.4.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.5.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.6.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.7.	Breaking waves + evacuation of water from breaking waves	Aluminium	No	0.3	1.063	0.06	4.3% in the optimal configura-tion
2.8.	Breaking waves + evacuation of water	Crushed stones and plates	Yes	Unknown	1.15->2.35	0.04->0.20	Unknown

	from breaking waves						
2.9.	Breaking waves + evacuation of water from breaking waves	Perforated plywood	Yes	Unknown	Unknown	Unknown	0.05-0.2
2.10.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.11.	Breaking waves	All kinds of materials possible	Can vary	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.12.	Breaking waves	All kinds of materials possible	Yes	5	2->3	0.35	<0.05 in the optimal configura-tion
2.13.	Breaking waves	Wire screen, transversal bars, sand, gravel and stones	Yes	High variety on water depths possible	High variety on wave periods possible	High variety on wave heights possible	High variety possible
2.14.	Dissipation by openings	Wooden or steel plates	Yes	0.5	0.85-3	0.02-0.04	<0.04 in the optimal configura-tion
2.15.	Dissipation by openings	Mesh screens	Yes	Unknown	Unknown	Unknown	0.05-0.92
2.16.	Dissipation by openings	Chicken wire and aluminium shavings	Yes	Unknown	Unknown	Unknown	<0.07
2.17.	Dissipation by around bouncing between the wedges	Expanded metal, steel	Yes	Unknown	Unknown	Unknown	>0.1 if H/L<0.01 and <0.05 if H/L>0.01
2.18.	Viscous dissipation + resonance effect	Steel planes	No	0.145	Unknown	Unknown	0.035 in the optimal configura-tion

2.19.	Viscous dissipation + resonance effect	Concrete and stones	No	Unknown	Unknown	Unknown	>0.18
2.20.	Friction	Concrete	Yes	0.16-0.22	0.8-2.4	0.02-0.06	>0.2

From the above it can be concluded that, according to the literature, the following four wave absorbers perform the best:

1) The SIPWA with C_r=0.035

2) The vertical mesh with C_r<0.04

3) The Marcou wave absorber with C_r=0.043

4) The parabolic slope with a front wall with C_r<0.05

Besides these four absorbers, Dr. Varjola Nelko indicated that also ether-based polyurethane (or polyether foam) shows very good wave absorbing properties. Another material that is used frequently at the department of Civil Engineering to absorb waves and that is said to have good wave absorbing capacities, are hexablocks. However, no information about the performance of the ether-based polyurethane or about the hexablocks could be found in literature.

At the end of this chapter one can question himself whether the objectives of this Master's Dissertation are still the same as stated at the end of the Introduction. This is quite the case. Although one minor extra objective can be joined to those already formulated in the Introduction. This objective concerns the two methods to estimate the reflection coefficients of a standard sloping beach (the method of Miche and the method of Twu and Liu). It would be interesting to know which one of these methods is giving the best results. In order to determine this we will look at the experimental results of the tests performed.

Chapter 3

Test program

In the previous chapter the existing literature on wave absorbers was thoroughly investigated and a number of absorbers were found to be promising. In this chapter, a test program for hydraulic model tests is presented and the efficiency of these absorbers is investigated. The properties of the different configurations that have been installed in the flume are discussed in detail. Also, the parameters of the different tests i.e. wave height, wave period, wave gauge spacing etc. are given. In addition, the observations made during the test program are also summarized. The next section describes the flume where the tests were performed.

3.1. Description of the wave flume

The tests were performed in the small wave flume of the department of Civil Engineering of the Faculty of Engineering and Architecture of Ghent University, which is depicted in Figure 3-1. The dimensions of this flume are 15.0 x 0.35 x 0.60 m (L x W x H). The flume is composed out of 5 independent parts and can be shortened by removing individual parts. It is made out Plexiglas and held in a metal frame. Design water depth is 0.30 m, but depths up to 0.40 m are possible as well. Maximum wave height inside the flume is about 0.20 m.

A piston type wave paddle is installed for the generation of waves. The maximum stroke is 0.40 m. The paddle displacement is accomplished by using a step motor (i.e. an electric actuator). The step motor is connected with the paddle using a spindle.

The waves are generated by the wave generation system GENESYS, which is a PC-based application for wave generation. Wave generation and data acquisition procedures have been implemented using LABVIEW software. The paddle displacements are controlled using a serial connection between PC and the steering board of the step computer.

The wave flume is also able to perform active wave absorption. This is done with the AWASYS system. With this system the wave paddle is able to perform extra movements besides his usual movements necessary in order to generate the desired wave train. These extra movements are meant to cancel the reflected waves that reach the wave paddle. The AWASYS system works on basis of the measurements of two wave gauges and separates the incident and reflected waves using digital filtering and subsequent superposition of the measured elevation signals [3].

The water level in the wave flume can be changed by pumping water in or out of the flume. The water that is pumped away is not lost but saved in a reservoir from which it can be reused. If there is not enough water in the reservoir to obtain a certain water level in the flume, it is still possible to add water with the fire hose.

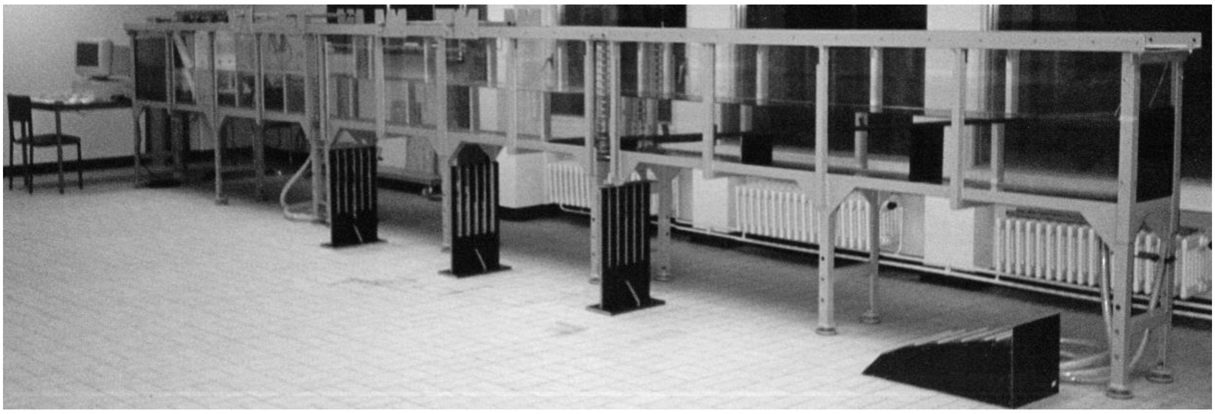

Figure 3-1: The small wave flume of the department of Civil Engineering [3]

3.2 Tested configurations

Eight configurations were investigated during the test program. Three of them correspond to three of the four wave absorbers that came out of the literature review as having the best wave absorbing capacities (the SIPWA, the parabolic slope with a front wall and the vertical mesh). Unfortunately, it was not possible to construct the Marcou wave absorber in a proper way in the wave flume used in this test program and this because one should be able to fix it at the bottom of the flume, but this is impossible as the flume is made out of Plexiglas. As a consequence, this absorber couldn't be investigated. Besides these three absorbers, also two configurations using ether-based polyurethane and one configuration using a hexablock are evaluated in the test program, and this because of the alleged good wave absorbing capacities of these materials, which were already mentioned at the end of the Literature review. Finally, two standard sloping beaches, a wave absorber that has also thoroughly been discussed in the literature review, are taken up in the test program as a reference. The properties of the different configurations are discussed in detail below. All the distances mentioned in the figures of this chapter are expressed in millimetre.

Before this discussion is started it is important to remark that all these configurations could be made more efficient if their length was increased. However, one should remember that this Master's Dissertation tries to give advice on which wave absorber one should use when designing a wave flume or wave basin such as the new wave basin that will be built on the Greenbridge-site in Ostend. The use of very long wave absorbers is dissuaded in these facilities because it takes valuable space that is lost for future physical model tests.

3.2.1. Sloping beach with small stones

This is the first reference case. It is made with rather small stones, which have an equivalent diameter ranging between 10 and 16 mm. Gravel is used for the stones. It has a height of 44 cm and a length of 152 cm resulting in a slope of approximately 2/7 as is also depicted in Figure 3-2. A picture of the slope installed in the wave flume is depicted in Figure 3-3.

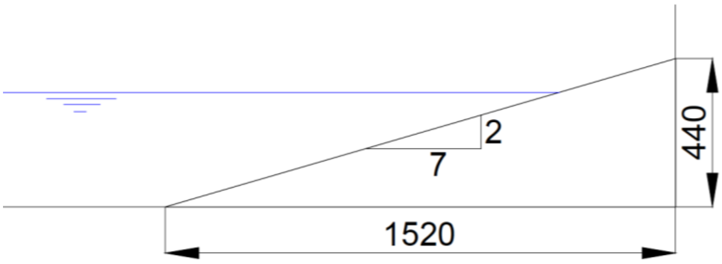

Figure 3-2: Side view of the two sloping beaches

Figure 3-3: Picture of the sloping beach with small stones

3.2.2. Sloping beach with large stones

This is the second reference case. The equivalent diameter of the stones ranges between 30 and 35 mm. Crushed rock is utilised for the stones. The absorber was constructed in such a way that it had the same dimensions as the above configuration (height of 44 cm and length of 152 cm). Consequently, the side view of this absorber is exactly the same as for the first configuration (see Figure 3-2). A picture of this configuration in the wave flume can be seen in Figure 3-4.

Figure 3-4: Picture of the sloping beach with large stones

3.2.3. SIPWA

This configuration, which can be seen in Figure 3-5, is a SIPWA. A slope-angle of 35° is used as Lebey and Rivoalen (2002) concluded that this is the optimal value for the slope-angle. For the other geometrical characteristics somewhat higher values were chosen than the values that were found to be optimal in the research of Lebey and Rivoalen and this because of the larger dimensions of the wave flume used in this test program. Due to the presence of tubing at the back of the flume (see Figure 3-6) the width of the confining compartment needed to be chosen quite large (32 cm). There was taken care that for every water level used in the test program at least four planes were submerged, as was also the case in the study of Lebey and Rivoalen [9]. The total length of this configuration is quite small in comparison with the other configurations.

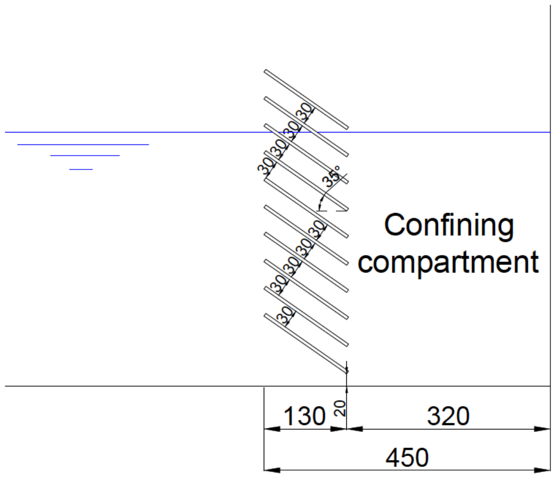

Figure 3-5: Side view of the SIPWA

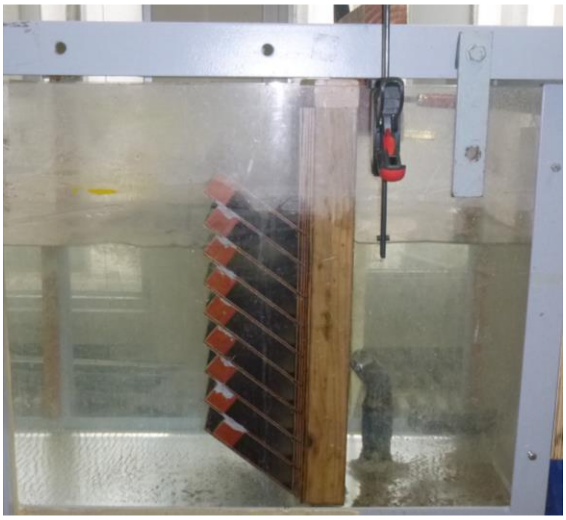

Figure 3-6: Picture of the SIPWA

3.2.4. Porous parabola with blue foam

In this configuration a parabola is used. The configuration is based on the research of Tiedeman (2012), however, the following change was made. The parabola of Tiedeman didn't reach the bottom of the facility. In this flume it is, however, easier to make a parabola that does reach the bottom of the flume. This implicates that the lowest part of the parabola is probably not always very useful. As a consequence also no front wall was used. Tiedeman used a porous steel plate for the construction of the parabola and this was maintained in the design of the parabola in this configuration. There was decided to work with a permeability of 20%, which was an advice of Prof. dr. ir. Andreas Kortenhaus. Circular holes with a

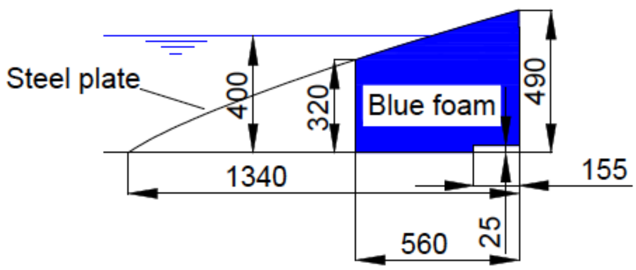

Figure 3-7: Side view of the parabola with blue foam for a water level of 40 cm

diameter of 2 cm were used to obtain this permeability. The position of the parabola is made adjustable so that a mild slope, and as a consequence a good efficiency, can be obtained in the circumference of the water level for different values of the water level. The space beneath the parabola is partly filled with the, at the department of Civil Engineering, well-known blue foam, which has fine wave absorbing capacities. As three different water levels are used in the test program (40 cm, 34 cm and 25 cm, see section 3.3.) three slightly different side views are obtained. These side views are depicted in Figure 3-7, Figure 3-8 and Figure 3-9 for water levels of 40 cm, 34 cm and 25 cm respectively. Figure 3-11 is a picture of this configuration in the wave flume. The water level was equal to 25 cm when the picture was taken.

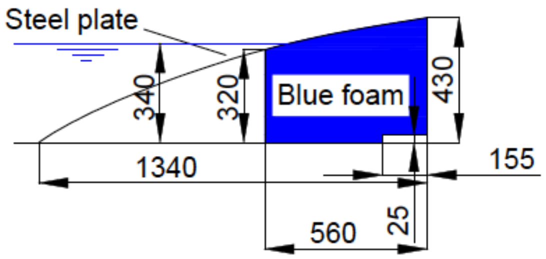

Figure 3-8: Side view of the parabola with blue foam for a water level of 34 cm

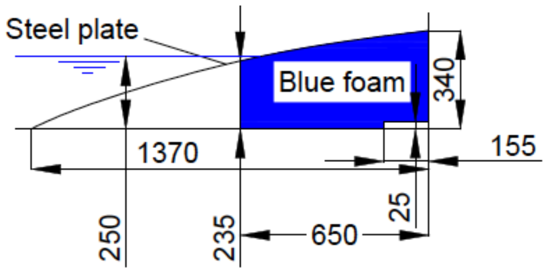

Figure 3-9: Side view of the parabola with blue foam for a water level of 25 cm

3.2.5. Vertical mesh

This configuration is the vertical mesh. In order to design this wave absorber according to the research of Twu and Lin (1991) ten plates with a spacing of 0.88*h with h the water depth should be used. However, this results already in a first obvious problem: which water level to use? This is a relevant question because during the test program different water levels are used. However, if one chooses the lowest water level that is used (25 cm, see section 3.3.), one obtains a spacing of 22 cm and a total length of 2.2 m, ignoring the thicknesses of the different plates. Remark that if one

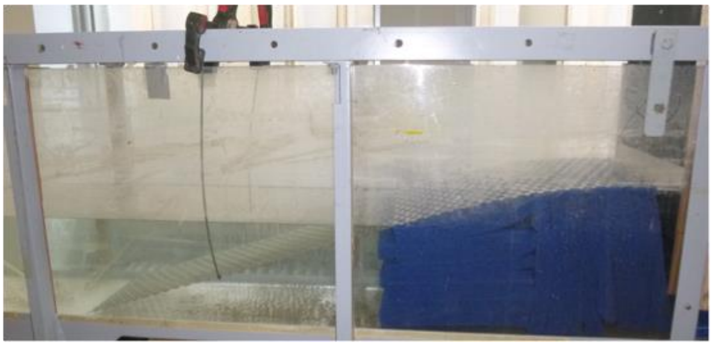

Figure 3-11: Picture of the parabola with blue foam

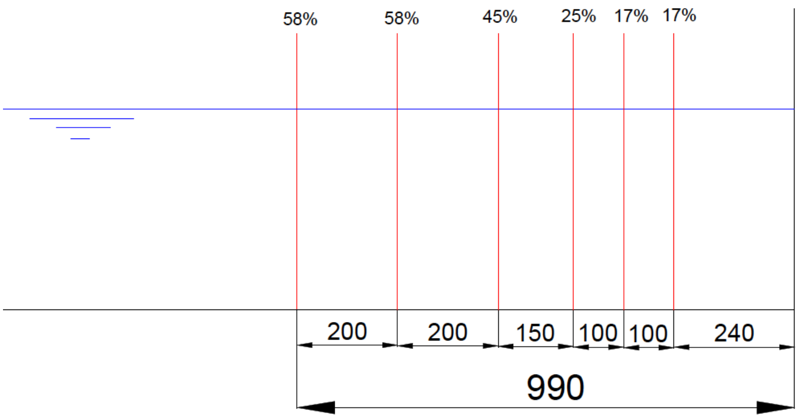

Figure 3-10: Side view of the vertical mesh

uses this spacing only optimal wave-absorbing properties will be obtained for a water depth of 25 cm and not for other water depths in the test program. Nothing objects the placement of a wave absorber with a length of 2.2 m in a wave flume with a total length of 15 m. However, this is very long. There was decided to reduce the length by using 6 plates instead of 10 and by using the idea of Tiedeman (2012) of shortening the distances between the different plates in the direction of the incident wave. Finally the configuration depicted in Figure 3-10 was obtained. The exact values of the spacings were chosen in such a way that the total length of the absorber comes close to 1 m, which is a fine length for a wave absorber in the small wave flume. The first plates were made more permeable than the plates at the back. The porosities of the different plates are indicated above each plate in Figure 3-10. In total four different porosities are used. The porosity was again obtained with circular holes with diameters of 2 cm. The first three, most porous plates were made out of steel. The latter three were fabricated out of wood as can also be seen in the picture depicted in Figure 3-12. One should be careful when observing the picture in this figure: it is taken from the other side of the flume in comparison to the previous pictures in this chapter. This implicates that the left side is the back of the flume and not the right side as was the case in the previous pictures.

Figure 3-12: Picture of the vertical mesh

3.2.6. Vertical wall of polyether foam

This is the first configuration testing the absorbing capacities of ether-based polyurethane. It has a vertical surface and consists of two different porosities. In the direction of the incident waves, the first part is ether-based polyurethane or polyether foam with a rough texture. The second part has a fine texture. As a consequence the first part is more porous than the second part. As such the same principle is used as for a vertical mesh, where the most porous plates are placed first. The total length of the configuration is 70

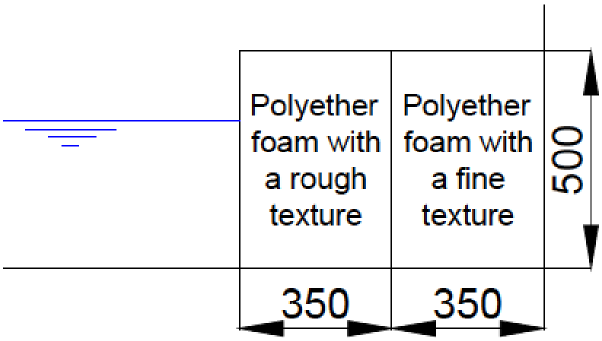

Figure 3-13: Side view of the vertical wall of polyether foam

cm. The height equals 50 cm (see Figure 3-13). Figure 3-14 is a picture of this absorber installed in the wave flume. As one can see in this picture the absorber is built up out of different plates of polyether foam. These plates have a thickness of 5 cm each.

Figure 3-14: Picture of vertical wall of polyether foam

3.2.7. Parabola of polyether foam

This is the second configuration that is meant to test the absorbing capacities of ether-based polyurethane. This time a parabolic surface is used. The parabola is made out of different plates with a thickness of 5 cm, which have been given different heights. Due to the presence of the tubing, the parabola couldn't be placed against the back wall of the flume. The space between the parabola and the back of the flume was filled with blue foam. The geometrical characteristics of this configuration are shown in Figure 3-15. A figure of the configuration installed in the wave flume is depicted in Figure 3-16.

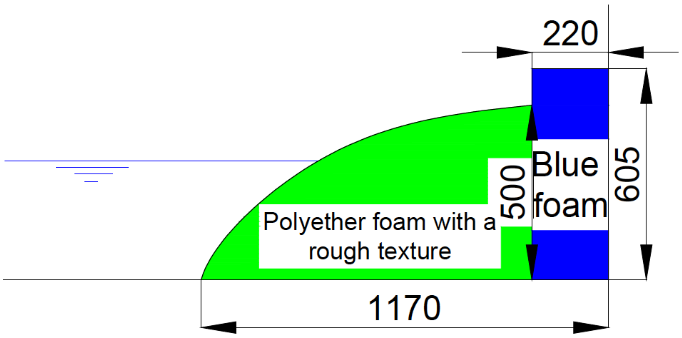

Figure 3-15: Side view of the parabola of polyether foam

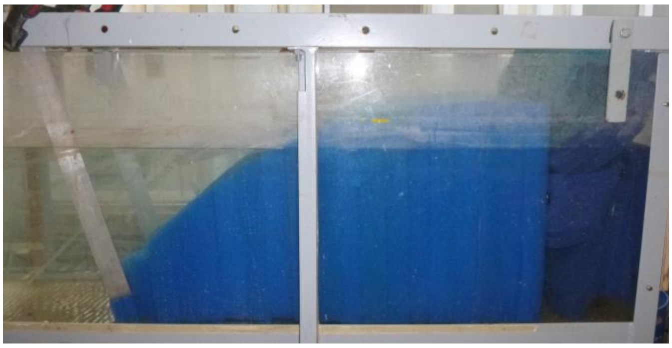

Figure 3-16: Picture of the parabola of polyether foam

3.2.8. Hexablock

This configuration consists of a hexablock. Hexablocks are used frequently at the department of Civil Engineering as a wave absorber. However, the performance of it has never been investigated. For this reason, this is done in this Master's Dissertation. A sketch of this configuration is given in Figure 3-17. The hexablock has a thickness of 30 cm. At the back of the hexablock, there is some free space. This free space has the function of a confining compartment. The working principle of this configuration can indeed be compared with the principle of the SIPWA, which also has a confining compartment. Both absorbers do work with the resonance effect, which implies that when the wave crest arrives at the absorber, the water level increases in the confining compartment and that when the wave trough arrives, the decrease in water level at the left side of the absorber is compensated by water from the confining compartment. However, the second effect that is of importance for the SIPWA, the viscous dissipation, doesn't interfere in this configuration, as there are no clear planes along which vertex shedding can occur. However, in this configuration, a lot of different channels crossing each other and having a rough surface are present at the inside of the hexablock. This leads to extra dissipation of the incident wave energy. An extra advantage of this configuration is that one can buy the hexablocks as finished products, which can be directly placed in the laboratory testing facility. As such the installation of this absorber can go very fast. Figure 3-18 is a photograph of a hexablock installed in the small wave flume of the department of Civil Engineering.

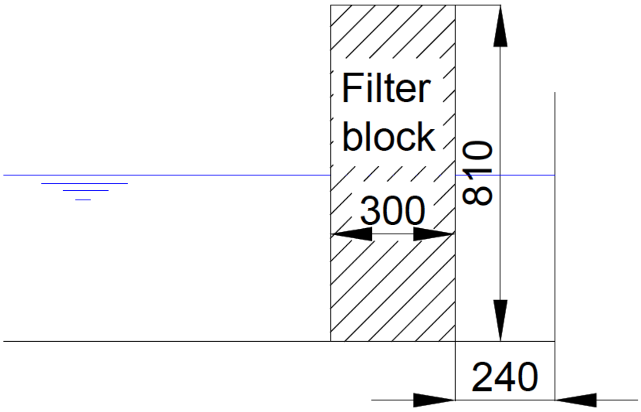

Figure 3-17: Side view of hexablock


Figure 3-18: Picture of a hexablock installed in the flume

3.3. Discussion on the tests

In the test program different tests were planned. The most important tests were performed with irregular waves and are used to compare the different wave absorbers with each other. These tests are the major part of the test program and were executed with three wave gauges. One of these tests was performed three times in order to determine the repeatability of the tests. Besides these tests also some tests with regular waves were planned, which were executed just to compare the results with the results of equivalent tests performed with irregular waves. Finally, some tests were executed with four and five wave gauges and irregular waves in order to be able to determine the difference in accuracy between tests performed with three, four or five wave gauges.

The test program with irregular waves consisted of 13 tests that were executed for each configuration. The waves were generated using the Jonswap spectrum. To be able to perform a proper comparison the same significant wave heights, peak wave steepnesses and peak wave periods were used for every configuration. In order to have a good idea of the behaviour of the absorbers at different water levels, tests were performed at three different water levels, namely 40 cm, 34 cm and 25 cm. At every level two different peak wave steepnesses (0.025 and 0.05) and two different significant wave heights (3 cm and 7 cm) were used. Every combination of these peak wave steepnesses and significant wave heights results in a test that is performed in the test program. As there are three different water levels, this results in a total of twelve tests. However, there is one extra test executed at a water level of 34 cm, namely a test with a significant wave height of 10 cm and a peak wave steepness of 0.05. This test couldn't be executed properly at the other two water levels because it showed serious problems of wave breaking at a depth of 25 cm and of overtopping the absorbing structure and hitting the back-wall of the wave flume at a depth of 40 cm. As a consequence this test cannot be used to compare the reaction of a certain absorber to such a high wave with other water levels on which a similar test has been performed, but it can be used to determine the differences between the various configurations in absorbing waves with a significant wave height of 10 cm. An overview of these 13 tests including water level, significant wave height (H_s), peak wave steepness (S_p), peak wavelength (L_p) and peak period (T_p) is given in Table 3-1. Given H_s and S_p, the values of L_p and T_p mentioned in Table 3-1 could easily be calculated using the following formulas:

$$L_p = \frac{H_s}{S_p} \tag{3.1}$$

$$L_p = \frac{gT_p^2}{2\pi} \cdot \tanh\left(\frac{2\pi \cdot h}{L_p}\right) \Leftrightarrow T_p = \sqrt{\frac{2\pi \cdot L_p}{g \cdot \tanh\left(\frac{2\pi \cdot h}{L_p}\right)}} \tag{3.2}$$

In these formulas h denotes the water depth and g the gravitational acceleration (=9.81m/s^2). If one wants to obtain a value in metres for L_p, one should of course enter a value in metres for H_s in formula (3.1). Analogous for formula (3.2), if L_p is expressed in metres, one should express h in metres too in order to obtain a value of T_p expressed in seconds.

Table 3-1: Characteristics of the different tests in the test program

Test number	**Water level [cm]**	**H_s [cm]**	**S_p [-]**	**L_p [m]**	**T_p [s]**
1	40	3	0.05	0.6	0.6201
2	40	3	0.025	1.2	0.8901
3	40	7	0.05	1.4	0.9734
4	39	7	0.025	2.8	1.5961
5	34	3	0.05	0.6	0.6204
6	34	3	0.025	1.2	0.9020
7	34	7	0.05	1.4	0.9928
8	34	7	0.025	2.8	1.6703
9	34	10	0.05	2.0	1.2744
10	25	3	0.05	0.6	0.6232
11	25	3	0.025	1.2	0.9432
12	25	7	0.05	1.4	1.0533
13	25	7	0.025	2.8	1.8776

As one can see in Table 3-1, test 4 slightly deviates from the regular pattern that was described above. The water depth of this test is indeed one centimetre lower than it should be (39 cm instead of 40 cm). This can be explained as follows: when this test was performed at a water level of 40 cm an amount of waves that wasn't negligible was overtopping the sloping beaches. To solve this problem the water level was reduced with one centimetre and the test was redone. In this new version of test 4, hardly any wave overtopped the sloping beaches. To maintain perfect comparability between the different wave absorbers, test 4 was also executed at a water depth of 39 cm for the other configurations in the test program.

In order to determine the repeatability of the tests, a test (test 4 executed on the sloping beach with large stones) was performed more than once, under the exactly same conditions. Some other tests were also repeated under the same conditions with the only difference that the amount of wave gauges used to measure the water surface elevations was changed. The standard number of wave gauges used was three, but some tests were redone with 4 and 5 gauges in order to determine the differences in accuracy caused by the use of different numbers of wave gauges. Besides all these tests, the thirteen above-mentioned tests were also executed in an empty wave flume. This was done in order to determine the absorbing capacities of the wave flume itself, because even without wave absorbing structure in the flume, some wave energy is inevitably lost due to for example friction or deviations from the straight course of the side walls of the flume which cause reflections perpendicular to the propagation direction of the incident waves and as a consequence also energy loss. Finally, there were also some tests performed with regular waves. This was done for comparison with the test results of the irregular wave-tests. Tests executed with regular waves were always performed with the characteristics of one of the tests performed with irregular waves, with the only difference of course that the values of the significant wave height, the peak wave steepness, the peak wavelength and the peak wave period of the irregular wave test were used as values of the wave height, wave steepness, wavelength and wave period, respectively, in the regular wave test. The extra tests that were executed, besides the 13 tests mentioned in Table 3-1 that were performed for every configuration and with an empty flume, have been summarized in Table 3-2. All the parameters of the AWASYS system used for the different tests can be found in Annex B.

Table 3-2: Extra tests

Test	Information about the test
Test 2-A	Second run of test 4 on the sloping beach with large stones; exactly the same characteristics used
Test 2-B	Third run of test 4 on the sloping beach with large stones; exactly the same characteristics used
Test 2-C	Second run of test 6 on the sloping beach with large stones, however, this time with regular waves
Test 2-D	Second run of test 7 on the sloping beach with large stones, however, this time with regular waves
Test 2-E	Second run of test 8 on the sloping beach with large stones, however, this time with regular waves
Test 3-A	Second run of test 5 on the SIPWA, however, this time with 4 wave gauges
Test 3-B	Second run of test 6 on the SIPWA, however, this time with 4 wave gauges
Test 3-C	Second run of test 7 on the SIPWA, however, this time with 4 wave gauges
Test 3-D	Second run of test 8 on the SIPWA, however, this time with 4 wave gauges
Test 3-E	Second run of test 9 on the SIPWA, however, this time with 4 wave gauges
Test 3-F	Third run of test 8 on the SIPWA, however, this time with 5 wave gauges
Test 3-G	Third run of test 9 on the SIPWA, however, this time with 5 wave gauges
Test 8-A	Second run of test 9 on the hexablock, however, this time with 4 wave gauges
Test 8-B	Third run of test 9 on the hexablock, however, this time with 5 wave gauges
Test 9-A	Second run of test 1 in an empty flume, however, this time with regular waves
Test 9-B	Second run of test 5 in an empty flume, however, this time with regular waves
Test 9-C	Second run of test 6 in an empty flume, however, this time with regular waves
Test 9-D	Third run of test 6 in an empty flume, however, this time with regular waves
Test 9-E	Second run of test 7 in an empty flume, however, this time with regular waves
Test 9-F	Second run of test 8 in an empty flume, however, this time with regular waves
Test 9-G	Second run of test 9 in an empty flume, however, this time with regular waves

An important question that is still unanswered up to now, is: "What should the duration of the different tests be?" The answer is that the duration of the tests varies for each test. In order to obtain very reliable estimates of the reflection coefficients, reflection spectra and other results of the reflection analysis, there was decided to set the length of the different tests equal to 1000 times the average incident wave period plus an additional ten percent to compensate for waves that are not taken into account in the analysis at the beginning and at the end of the test. As the average wave period equals the peak period divided by 1.2, the test length boils down to the following formula:

$$T_0 = 1100 \cdot \frac{T_p}{1.2} \qquad (3.3)$$

in which T_0 denotes the duration of the test.

The 'duration of the test' means the duration of the actual time-series in which the waves are running through the wave flume. The time between the actual start of the engine commanding the wave paddle and the moment at which the wave paddle stops moving is somewhat larger. This is a consequence of the fact that some time is provided between the activation of the engine and the start of the movement of the paddle (5 seconds in this test program) and the fact that at the end of the test program, when the actual test is finished, the active absorption system is still working for some time in order to remove the swell that is still present on the water. This last time was chosen to be equal to 1 minute and this was enough in most cases. Table 3-3 gives an overview of the durations of the 13 different tests shown in Table 3-1. T_t represents the total running time of the test.

Table 3-3: Durations and total running times of the different tests in the test program

Test number	**T_0 [s]**	**T_t [s]**
1	569	634
2	816	881
3	892	957
4	1463	1528
5	569	634
6	827	892
7	910	975
8	1531	1596
9	1168	1233
10	571	636
11	865	930
12	966	1031
13	1721	1786

The final issue that needs to be solved, is the issue of determining appropriate positions for the wave gauges. As already mentioned earlier, the standard number of gauges equals three. In this case one can use the method of Mansard and Funke with three wave gauges. For the positioning of the wave gauges the following conditions (3.4)-(3.8) need to be fulfilled [11]. The different variables are clarified in Figure 3-19.

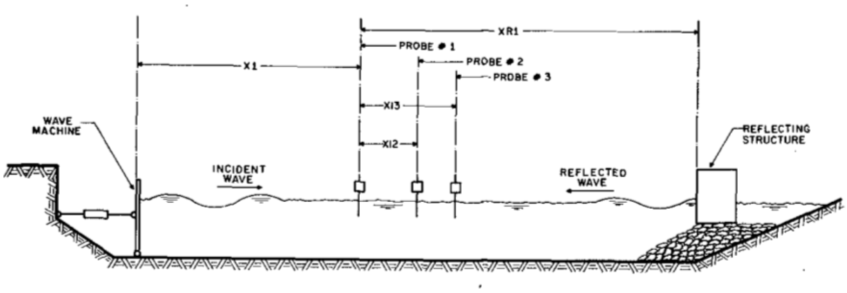

Figure 3-19: Distances x_1, $x_{1,2}$ and $x_{1,3}$ [11]

$$x_1 \geq L_p \tag{3.4}$$

$$x_{1,2} = \frac{L_p}{10} \tag{3.5}$$

$$\frac{L_p}{6} < x_{1,3} < \frac{L_p}{3} \tag{3.6}$$

$$x_{1,3} \neq \frac{L_p}{5} \tag{3.7}$$

$$x_{1,3} \neq \frac{3 \cdot L_p}{10} \tag{3.8}$$

Using these conditions good values for the relative positions of the second and third wave gauge with respect to the first one can be determined. These positions are summarized in Table 3-4 for each test. However, one can see that condition (3.5) is not fulfilled for tests 1, 5 and 10. According to this condition $x_{1,2}$ should equal 0.06 m for these three tests and not 0.10 m as is indicated in Table 3-4. This difference can be explained by the simple fact that it is difficult to place two wave gauges at only 6 cm from each other. Working with a spacing of 10 cm is much easier and with this spacing it was still possible to obtain a digital filter for the active wave absorption with a very good performance.

Table 3-4: Relative positions of the second and third wave gauge

Test number	**$x_{1,2}$ [m]**	**$x_{1,3}$ [m]**
1	0.10	0.20
2	0.12	0.30
3	0.14	0.35
4	0.28	0.70
5	0.10	0.20
6	0.12	0.30
7	0.14	0.35
8	0.28	0.70
9	0.20	0.50
10	0.10	0.20
11	0.12	0.30
12	0.14	0.35
13	0.28	0.70

As (3.4) indicates the first wave gauge should be placed at least one wavelength away from the paddle. However, if this first wave gauge is placed too far, this was found to be bad for the performance of the digital filter used for the active wave absorption system of the wave flume. For this reason two different positions of the first wave gauge were used during the test program. Tests 1, 5 and 10, which are running the shortest waves in the test program, were always performed with a distance between the wave paddle and the first wave gauge of 2.3 m. Tests 4, 8 and 13, which are running the longest waves in the test program, were always executed with x_1=3 m. Using x_1=2.3 m is indeed not allowed for these tests as they have a wavelength of 2.8 m. The other tests can be performed with both x_1=2.3 m and x_1=3 m. As a consequence, the position of the first wave gauge used during the previous test was maintained when one of these tests was executed as in this way a minimal amount of movements of the first wave gauge were necessary.

As already mentioned before, there were also some tests performed with more than three wave gauges. In this case one can use the method of Zelt and Skjelbreia to do the reflection analysis and one should space the wave gauges accordingly. The Zelt and Skjelbreia method is an N-gauge extension of the method of Mansard and Funke. However, in the software that is used to perform the reflection analysis (WAVELAB 3.675), these methods is only used to analyse irregular waves. For the analysis of regular waves the non-linear Lykke Andersen method is used [2].

In the article of Zelt and Skjelbreia (1992) handling their method for wave reflection analysis, the following information is given concerning the spacing of the wave gauges [27]. Two things are said to be undesirable. Firstly, the spacing between two random gauges p and q shouldn't approximate a multiple of one-half the wavelength. Secondly, the spacing between the gauges p and q of a random pair of wave gauges shouldn't be too large with respect to the wavelength. To take both effects into account, Zelt and Skjelbreia proposed a 'goodness' function $G(\Delta\phi_{j,pq})$. If one maximizes this function for a certain pair of wave gauges pq one obtains the optimal spacing between these two gauges. The 'goodness' function is given by the following formula:

$$G\left(\Delta\phi_{j,pq}\right) = \frac{\sin^2\left(\Delta\phi_{j,pq}\right)}{1+\left(\frac{\Delta\phi_{j,pq}}{\pi}\right)^2} \tag{3.9}$$

with $\Delta\phi_{j,pq}$ the phase difference associated with the spacing between the gauges p and q for the angular frequency ω_j corresponding to the wavelength L, which is given by the following formula:

$$\Delta\phi_{j,pq} = \frac{2\pi}{L}\left(x_p - x_q\right) \tag{3.10}$$

in which x_p and x_q denote the positions of wave gauges p and q with respect to the wave paddle.

When several wave gauges are present in the flume, it is of course impossible to find a positioning that makes the spacing between every pair of gauges optimal. For this reason there has been tried, when drawing up this test program, to make the sum of the "goodness" functions for the different pairs of gauges as high as possible without allowing the values of the individual pairs to become too low (0.2 was used as lower limit). In this way the spacings shown in Table 3-5 have been obtained. $x_{1,4}$ denotes the spacing between wave gauges 1 and 4 and $x_{1,5}$ denotes the spacing between wave gauges 1 and 5. If a '/' has been placed instead of a value for $x_{1,5}$, this means that only four wave gauges were used for this test and that there is, logically, no value for $x_{1,5}$. The tests have the same characteristics as tests that were performed with three gauges. For test 3-A, executed with four wave gauges, the distance between gauges 2 and 3 was reduced to 6 cm. It is quite difficult to obtain this very small spacing, but for this single test it was done. The first wave gauge should again be placed at least one wavelength separated from the wave paddle. The same principle for the placement of the first wave gauge as in the case of three wave gauges was used.

Table 3-5: Relative positions of the wave gauges for tests with four and five gauges

Test	**$x_{1,2}$ [m]**	**$x_{1,3}$ [m]**	**$x_{1,4}$ [m]**	**$x_{1,5}$ [m]**
Test 3-A	0.09	0.15	0.24	/
Test 3-B	0.18	0.28	0.46	/
Test 3-C	0.21	0.33	0.54	/
Test 3-D	0.42	0.66	1.08	/
Test 3-E	0.30	0.47	0.77	/
Test 3-F	0.30	0.57	0.79	1.12
Test 3-G	0.21	0.41	0.56	0.80
Test 8-A	0.30	0.57	0.79	1.12
Test 8-B	0.21	0.41	0.56	0.80

Finally, also some tests with regular waves were performed. For these tests the wave gauges should be spaced according to the non-linear method of Lykke Andersen. However, the paper in which this method will be described is not yet published. Nevertheless, Lykke Andersen was contacted and the author pointed out that the spacing of the gauges is not of great importance. For this reason the spacing used with the method of Zelt and Skeljbreia was maintained for some tests with regular waves (Tests 2-C, 2-D, 2-E and 2-F). For the other tests a spacing of 0.15 times the wavelength is used as Lykke Andersen thought that all pair combinations with spacings between 0.05 and 0.45 times the wavelength could result in good gauge spacings. Table 3-6 shows the spacings of the wave gauges used for the different tests with regular waves. Four gauges were used because this is the minimum number of gauges that may be used in the non-linear Lykke Andersen method.

Table 3-6: Relative positions of the wave gauges for tests with regular waves

Test	**$x_{1,2}$ [m]**	**$x_{1,3}$ [m]**	**$x_{1,4}$ [m]**
Test 2-C	0.18	0.28	0.46
Test 2-D	0.21	0.33	0.54
Test 2-E	0.42	0.66	1.08
Test 2-F	0.42	0.66	1.08
Test 9-A	0.09	0.18	0.27
Test 9-B	0.09	0.18	0.27
Test 9-C	0.18	0.36	0.54
Test 9-D	0.18	0.36	0.54
Test 9-E	0.21	0.42	0.63
Test 9-F	0.42	0.84	1.26
Test 9-G	0.30	0.60	0.90

3.4. Some observations and complications

Some observations were made during the execution of the test program. These are discussed below together with some complications which had to be dealt with.

During the tests performed on the sloping beach with small stones, movements of the stones were observed. It was clear that these movements were caused by the breaking of the waves. In the zone of wave breaking the stones were eroded and were moved downwards. As such a depression in the beach with respect to the original profile is created in the zone of wave breaking. Just beneath this zone an elevation in the profile is formed as can be seen in Figure 3-20. As a consequence, a certain S-profile is created. However, in Figure 3-20 the slope is shown from the side from which one should read the S in mirror writing. When the water level was changed, the movements of the stones were big, forming a new S-profile. After some time the movements became considerably smaller and the new S-profile was more or less formed. However, still some movements kept on occurring, making the S more pronounced. This deformation of the slope is certainly an element that will have to be taken into account during deciding which wave absorber one should preferably use when designing a laboratory testing facility. When the deformation is too severe, it will probably be necessary to reshape the beach in order to regain the original profile.

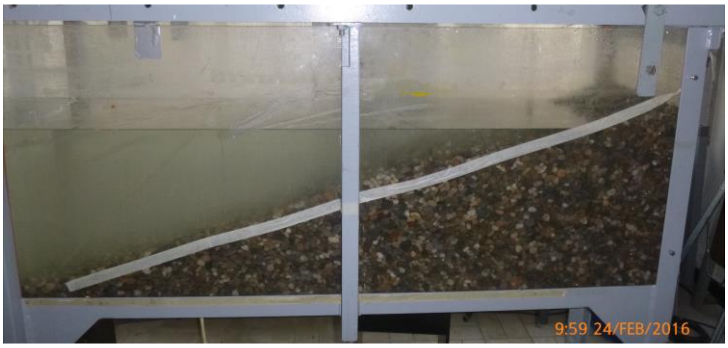

Figure 3-20: S-profile observed in the profile of the sloping beach with small stones

With the sloping beach with large stones the formation of an S-profile wasn't observed. Sometimes rocking of stones was noticed. Very rarely also displacement of an individual stone was observed, but the few stones that moved, moved over very short distances and didn't significantly change the profile of the beach. This is of course caused by the fact that the stones used in this configuration are much harder to move than the ones used in the previous configuration, which are a lot smaller. To illustrate this large difference in stone-sizes the photograph depicted in Figure 3-21 was taken. This photograph shows an average sized stone from both beaches next to each other.

Figure 3-21: Comparison between a stone of the sloping beach with small stones and a stone of the sloping beach with large stones

The SIPWA as well as the vertical wall of polyether foam showed a lot of reflection. This was already clear with eye-observation. The reflection analysis should confirm this. Probably it is not advisable to use one of these configurations as a spending beach in a wave flume or a wave basin or at least not if they are constructed in the exact same way as they have been constructed during this test program. Concerning the vertical wall of polyether foam, it was the idea of the author that the polyether foam with a rough texture used at the front face (see Figure 3-13) was not permeable enough and was the origin of the high reflection that was observed in the flume.

The porous parabola with blue foam showed quite low reflected waves according to eye-observation. However, the parabola itself didn't seem to contribute much to the absorbing capacity of the complete configuration. It was the idea that the waves would break on the parabola, but this wave breaking was hardly ever observed. There are probably two reasons for this. The first reason is that the openings of the parabola were too big and that it is consequently possible that the water particles were not influenced by the presence of the parabola while performing their orbital motions. Another option is that the parabola was too thin and not stiff enough. It is indeed the opinion of the author, who observed lots of tests and even much more waves attacking a structure during this test program, that structures need to have a certain mass and stiffness before a wave will break on it. The parabola was also was observed to move a bit with the motion of the water.

The vertical mesh and the parabola of polyether foam seemed to perform rather well. The performance of the hexablock seemed to be better than the performance of the SIPWA. However, it did still show quite some reflection.

A final problem that was encountered during the test program was the problem of the sticking of the wave paddle. This happened every now and then with the longer tests (longer than 940 s). For this reason some of the tests in the program were limited to a duration of 950 s. With such a duration still a considerable amount of waves was present in the time-series still allowing to do a proper reflection analysis. In other cases this shortening wasn't done but if the sticking took place after a sufficient amount of time had passed by since the beginning of the test, there was no need to repeat the test. Of course the final seconds of the test in which the wave paddle got stuck weren't considered in the reflection analysis. This problem could have been caused by the computer that after some running time of the test didn't send the desired time-series in time to the engine commanding the paddle.

3.5. Data acquisition

The link between the test program and the data obtained from this program is of course the acquisition of data during the tests. This data acquisition is performed by the wave gauges. The wave gauges, which are used in this flume (wave gauges of the resistive type) consist of two poles, which are positioned very close to each other by means of a metal bearing structure with wooden cover plates located at the top of the poles. At the lower end a reference electrode is mounted to avoid influences of the water's conductivity fluctuations (see Figure 3-23). The poles are positioned partly beneath the water surface. Optimally, one third of their length is submerged. The difference in conductance between the two poles is measured. The surface elevation can be calculated using this difference in conductance, as there exists a linear dependency between both. Each Volt difference in conductance corresponds to a surface elevation 0.025 m. The measurements are done by a measuring device to which the wave gauges are connected (see Figure 3-22). In this test program there was worked with a sampling frequency of 40 Hz, which means that 40 times a second a measurement is send to the computer to which the measuring device is connected. It is also important that the wave gauges are calibrated before the start of each test. This is done in a low and in a high position. The shift between the low and the high position can be done automatically making use of a compressor [1], [25].

Figure 3-23: A wave gauge

Figure 3-22: Measuring device for wave gauges

Chapter 4

Reflection Analysis and Results

At the end of the previous chapter there was explained that during the test program the differences in conductance between the two poles of the wave gauges were measured and that a simple linear relationship existed between the measured conductance and the surface elevation at the position of the wave gauge. As a consequence, one obtains time-series of surface elevations at the positions of the different wave gauges. The question is now how these time-series can be converted into useful information that can be used in order to reach the objectives of this Master's Dissertation and more specifically, if one thinks about the first objective, in order to determine the performance of the different configurations investigated in the test program. This is done by performing the reflection analysis. Although the reflection analysis is executed using a computer program (WAVELAB 3.675), it is interesting to have some primary insides in the background of this analysis. This background is given in the next section.

4.1. Theoretical background of the reflection analysis

For the execution of the reflection analysis, different methods exist. Some of them were already mentioned earlier in this thesis as the gauge spacing is influenced by the used method for the reflection analysis. The easiest method is the method of Goda and Suzuki, which uses only two wave gauges. An already more sophisticated method is the method of Mansard and Funke. This method uses three wave gauges. An extension of the method of Mansard and Funke is the method of Zelt and Skjelbreia. The method of Zelt and Skjelbreia can be used for an arbitrary number of wave gauges [4]. These methods can be used for both regular and irregular waves, but in WAVELAB 3.675 another method is used in order to analyse tests executed with regular waves. This method, the non-linear method of Lykke Andersen, is based on the method of Lin and Huang and takes into account the presence of higher harmonics in the wave field. Higher harmonics are waves with frequencies higher than the frequency of the original wave and may be produced when waves interact with structures. In order to perform the analysis with this last method at least four wave gauges must be present in the wave flume [10]. These different methods are all performing the reflection analysis following more or less the same canvas. This canvas is sketched below. The main objective is always to determine the reflection coefficient.

As the reflection analysis for irregular waves is partly based on the reflection analysis for regular waves, the different methods do all start with the reflection analysis for regular waves. First an expression for the water surface elevation η with respect to the still water level is written. The surface elevation is the superposition of the surface elevation caused by the incident wave and the surface elevation caused by the reflected wave, denoted with η_i and η_r respectively. If the surface elevations are described using the linear wave theory, the following can be written:

$$\eta(x,t) = \eta_i(x,t) + \eta_r(x,t) = a_i \cos(k \cdot x - \omega \cdot t + \Phi_i) + a_r \cos(k \cdot x - \omega \cdot t + \Phi_r) \qquad (4.1)$$

in which a_i and a_r are the amplitude of the incident and reflected wave, respectively. Analogous, Φ_i and Φ_r are the phase-angle of the incident and reflected wave, respectively. k and ω are the wave number and the angular frequency, respectively [5]. These are the same for the incident and reflected wave, as the wavelength and wave period don't change when the incident wave reflects against a certain structure. This is indeed a basic physical law [26]. x denotes the position in the longitudinal direction of the flume and t denotes the time. In a physical modelling experiment it is logical to choose the position of the wave paddle before the start of the experiment as the position where x=0 and the moment at which the experiment starts as the moment at which t=0.

In the method of Mansard and Funke and in the method of Zelt and Skjelbreia an error function e(t) is added to (4.1) [11] [27]. This error function is taking noise into account that is probably contaminating the wave signals. This results in the following expression:

$$\eta(x,t) = a_i \cos(k \cdot x - \omega \cdot t + \Phi_i) + a_r \cos(k \cdot x - \omega \cdot t + \Phi_r) + e(t) \qquad (4.2)$$

If higher harmonics are considered too, as is the case in the method of Lin and Huang, (4.2) is extended into:

$$\begin{aligned}
\eta(x,t) = {} & a_i^{(1)} \cos\left(k \cdot x - \omega \cdot t + \Phi_i^{(1)}\right) + a_r^{(1)} \cos\left(k \cdot x - \omega \cdot t + \Phi_r^{(1)}\right) \\
& + \sum_{n \geq 2} a_{i,B}^{(n)} \cos\left(n \cdot (k \cdot x - \omega \cdot t) + \Phi_{i,B}^{(n)}\right) + \sum_{n \geq 2} a_{r,B}^{(n)} \cos\left(n \cdot (k \cdot x - \omega \cdot t) + \Phi_{r,B}^{(n)}\right) \\
& + \sum_{n \geq 2} a_{i,F}^{(n)} \cos\left(n \cdot (k \cdot x - \omega \cdot t) + \Phi_{i,F}^{(n)}\right) + \sum_{n \geq 2} a_{r,F}^{(n)} \cos\left(n \cdot (k \cdot x - \omega \cdot t) + \Phi_{r,F}^{(n)}\right) \\
& + e(t)
\end{aligned} \qquad (4.3)$$

The first two terms of (4.3) are the incident and reflected wave of the first harmonic (denoted with superscript (1)) and are equivalent to the two terms in (4.1). The other terms represent the higher harmonics. Of these higher order frequencies (specific order indicated by number n), two types exist: the bounded frequencies and the free frequencies. Free frequencies correspond to waves that can propagate freely, i.e. waves that can travel on their own frequency-specific speed (wavelength multiplied with frequency). Bounded frequencies, however, correspond to waves that are too long with respect to the water depth to propagate at their own velocity. They are bounded to the celerity of the first harmonic. Whether a certain harmonic is bounded or free is indicated in the notation of the amplitudes and phases by the subscripts 'B' and 'F', respectively. For each harmonic, there exists, logically, an incident and a reflected wave, indicated by the subscripts 'i' and 'r', respectively. e(t) is again an error function [10].

In the next step, the expression mentioned above that one needs to apply for the method that one is using is evaluated at the positions where the wave gauges are present. At these positions the water surface elevation η is known. As a consequence a system of equations of which the number of equations equals the number of wave gauges in the flume, is found. This system can be solved for its unknowns by using Fourier transformations. If only two wave gauges are present in the flume, one has only two equations and only two unknowns (a_i and a_r) can be solved for. Consequently, it is impossible to take noise into account when applying the method of Goda and Suzuki. When more than two wave gauges are present in the flume, it does become possible to account for noise. The error function e(t) is then minimised in a least square sense. As noise isn’t minimised in the method of Goda and Suzuki questions could raise about the accuracy of this method. In the method of Lin and Huang the calculations are a bit more complicated than explained here as also the amplitudes of the higher harmonics need to be determined. A discussion of these calculations would take us too far.

Once the incident and reflected wave amplitude have been calculated one can determine the reflection coefficient by simply applying (4.4) [11]:

$$C_r = \frac{a_r}{a_i} \tag{4.4}$$

or by applying (4.5), if the method of Lin and Huang or the method of Lykke Andersen, which is based on it, is used [10]:

$$C_r = \sqrt{\frac{\left(a_r^{(1)}\right)^2 + \sum_{n\geq 2}\left[\left(a_{r,B}^{(n)}\right)^2 + \left(a_{r,F}^{(n)}\right)^2\right]}{\left(a_i^{(1)}\right)^2 + \sum_{n\geq 2}\left[\left(a_{i,B}^{(n)}\right)^2 + \left(a_{i,F}^{(n)}\right)^2\right]}} \tag{4.5}$$

This finishes the reflection analysis for regular waves as an expression for the reflection coefficient is obtained. For irregular waves the above calculation can be done for every wavelength present in the wave spectrum. As such a so-called reflection spectrum is obtained, showing the reflection coefficient for every element of the wave spectrum. To obtain a single value for the reflection coefficient of the whole irregular wave field the incident and reflected wave amplitude are calculated for every element of the spectrum. Consequently, the incident and reflected energy spectral density, $S_i(f)$ and $S_r(f)$, are calculated using the following formulas [20]:

$$S_i(f) = \frac{\frac{1}{2}a_i^2}{\Delta f} \qquad S_r(f) = \frac{\frac{1}{2}a_r^2}{\Delta f} \tag{4.6}$$

in which f is the frequency for which the energy spectral density is calculated. Δf is the frequency bandwidth (the thickness of the different beams in the spectrum).

As such the incident and reflected wave spectrum are obtained (see Figure 4-1). The surfaces beneath these spectral curves equal the incident and reflected wave energy, denoted with E_i and E_r, respectively. These are calculated between the singularities in the spectrum, which are always present. This zone is called the effective range of resolution. Of course, the boundaries of this range (f_{min} and f_{max}) aren't chosen equal to the singularities their selves but are chosen a little bit greater (for f_{min}) or a little bit smaller (for f_{max}). The eventual calculation of E_i and E_r comes down to the evaluation of the following integrals:

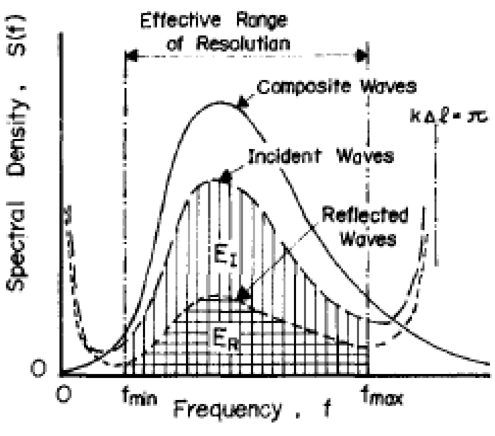

Figure 4-1: Incident and reflected wave spectrum [5]

$$E_i = \int_{f_{min}}^{f_{max}} S_i(f)df \qquad E_r = \int_{f_{min}}^{f_{max}} S_r(f)df \tag{4.7}$$

As the wave energy is proportional to the second power of the wave height, the reflection coefficient for irregular waves can be calculated as follows:

$$C_r = \sqrt{\frac{E_r}{E_i}} \tag{4.8}$$

As such the final result of the reflection analysis, the reflection coefficient, is found. As a check, one can compare the value of the reflection coefficient C_r with the value of the reflection spectrum at the peak frequency. In most cases both are more or less the same [4] [5] [10] [11].

4.2. Results of the reflection analysis

4.2.1. Repeatability of the tests

In section 4.2., the results of the reflection analysis are presented. However, before any result can be discussed one should know how reliable the obtained reflection coefficients are. This reliability is expressed by the repeatability of the tests. The repeatability is determined by performing a certain test more than once and by comparing the reflection coefficients obtained from the different repetitions. If these reflection coefficients are similar, the repeatability is high and the reflection coefficient determined for this test is reliable. If this is the case, one can assume that also the other tests will be reliable. In the test program, test 4 was executed three times on the sloping beach with large stones. The first execution is just the regular test 4, the second and third execution are referred to as test 2-A and test 2-B in Table 3-2. The characteristics of test 4 are given in Table 3-1. The reflection coefficients determined using these three repetitions are shown in Table 4-1. As one can see in this table, the differences between the three reflection coefficients are very small. One can conclude that the repeatability is very good and that the reflection coefficients determined during the test program will most probably be all very reliable.

Table 4-1: Reflection coefficients for the different repetitions of test 4 executed on the sloping beach with large stones

	C_r
Test 4	0.2251
Test 2-A	0.2279
Test 2-B	0.2336

4.2.2. Comparison of tests with different number of wave gauges

Something else that one should know, is whether it was a right choice to use three wave gauges as standard number of wave gauges. During the test program, tests were performed with different numbers of gauges in order to be able to compare the results of the different methods for reflection analysis. Tests executed with three wave gauges can be analysed using the method of Mansard and Funke. If only two of the three gauges are used to perform the analysis, the wave signals can be analysed using the method of Goda and Suzuki. Some other tests were executed with four or with five wave gauges (see Table 3-5) and can be utilised to perform the reflection analysis with the method of Zelt and Skjelbreia and to determine the differences in accuracy of this method when five gauges are installed in the flume with respect to the case in which only four gauges are installed in the flume.

On basis of the different tests, it is possible to make Table 4-2, which gives the reflection coefficient obtained with the different reflection analysis methods for a certain configuration, water depth and certain wave characteristics. The method of Goda and Suzuki is indeed cited twice, as it is applied once on the first two wave gauges and once on the last two wave gauges in tests with three wave gauges.

Table 4-2: Overview of reflection coefficients determined with different analysis techniques for different test parameters

Configuration	h [m]	H_s [m]	S_p [-]	T_p [s]	$C_{r,\ ZS\ 5}$ [-]	$C_{r,\ ZS\ 4}$ [-]	$C_{r,\ MF\ 3}$ [-]	$C_{r,\ GS\ F2}$ [-]	$C_{r,\ GS\ L2}$ [-]
SIPWA	0.34	0.03	0.05	0.6204	/	0.3223	0.3617	0.3737	0.3779
SIPWA	0.34	0.03	0.25	0.9020	/	0.5680	0.5885	0.5775	0.6469
SIPWA	0.34	0.07	0.05	0.9928	/	0.5281	0.5269	0.5368	0.5587
SIPWA	0.34	0.07	0.25	1.6703	0.3537	0.3598	0.3630	0.3859	0.4023
SIPWA	0.34	0.1	0.05	1.2744	0.4124	0.4218	0.4403	0.4619	0.4796
Hexablock	0.34	0.1	0.05	1.2744	0.3418	0.3841	0.3664	0.3783	0.3991

In this table $C_{r,\ ZS\ 5}$ and $C_{r,\ ZS\ 4}$ denote, respectively, the reflection coefficient determined with the method of Zelt and Skjelbreia using 5 gauges and the reflection coefficient determined with the method of Zelt and Skjelbreia using 4 gauges. $C_{r,\ MF\ 3}$ represents the reflection coefficient calculated with the method of Mansard and Funke, obviously using three wave gauges, and finally, $C_{r,\ GS\ F2}$ and $C_{r,\ GS\ L2}$ denote, respectively, the reflection coefficient determined with the method of Goda and Suzuki using the first two wave gauges in a test with three wave gauges and the reflection coefficient determined with the method of Goda and Suzuki using the last two wave gauges in a test with three wave gauges. The test conditions mentioned on the first three lines of Table 4-2 haven't been tested using five wave gauges. As a consequence $C_{r,\ ZS\ 5}$ cannot be calculated. This is denoted by a '/' in Table 4-2.

Out of Table 4-2, it can be concluded that the methods with different number of wave gauges give similar reflection coefficients. One could think that the reflection coefficient decreases when more wave gauges are used, but also this decrease is small and even not always present. We can conclude that the number of used gauges and the related analysis technique don't have a big impact on the results. Working with three wave gauges, as is done in most of the tests of the test program of this study, is a good choice. The use of two wave gauges would even be possible too, but this is probably not such a good idea, as noise cannot be taken into account if only two gauges are used as the theoretical background of the reflection analysis learns us.

4.2.3. Comparison of the different configurations on basis of the tests with 3 gauges and irregular waves

In this section the different configurations are compared with each other in order to determine which configuration(s) are showing the best performance. The most important parameter in this configuration is the reflection coefficient. The reflection coefficients obtained from the 13 standard tests executed with three wave gauges and irregular waves mentioned in Table 3-1 are used. Besides the reflection coefficient, some other parameters such as cost price and length of the absorber will be taken into account. Figure 4-2, Figure 4-3 and Figure 4-4 show graphs of the reflection coefficients of the different configurations at water depths of respectively 40 cm, 34 cm and 25 cm. Also the reflection coefficients found for an empty flume (indicated as vertical wall in the graphs) are added. For test 4 executed on the sloping beach with large stones, the average of the reflection coefficients shown in Table 4-1 is used in these graphs. The exact values of the reflection coefficients can also be found in Annex C.

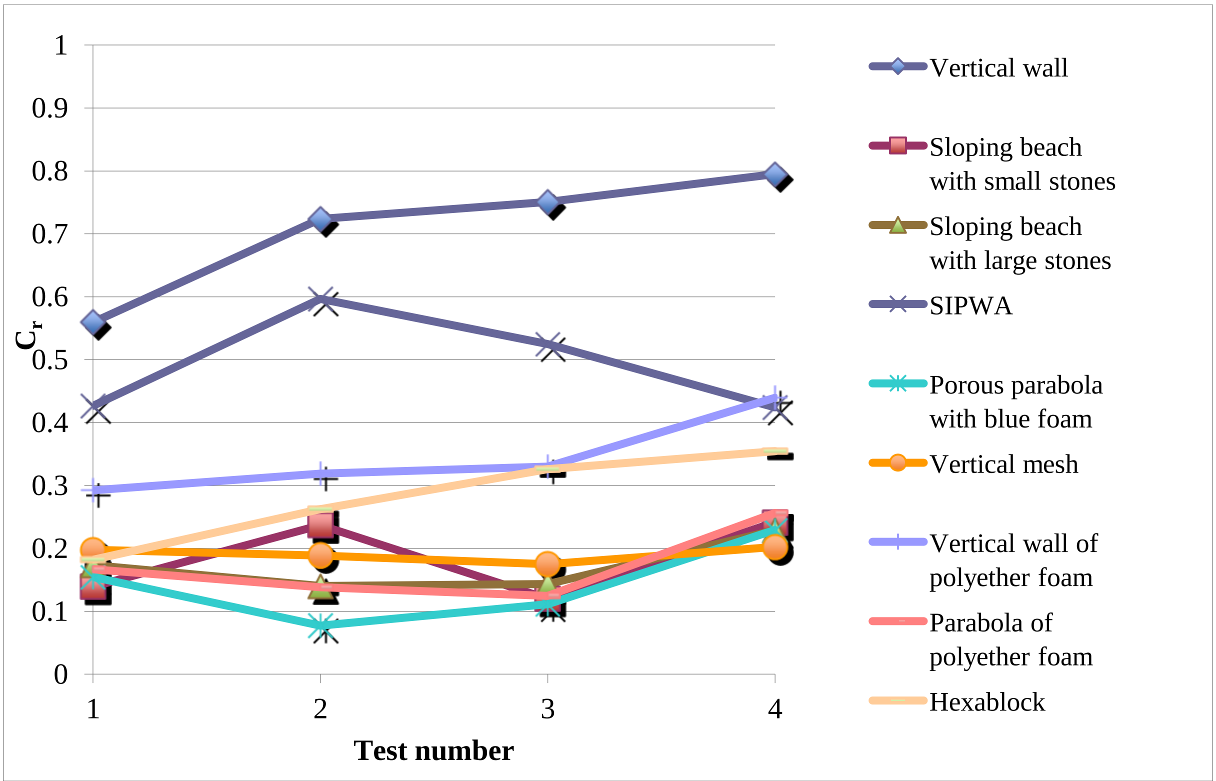

Figure 4-2: Reflection coefficients at a water depth of 40 cm

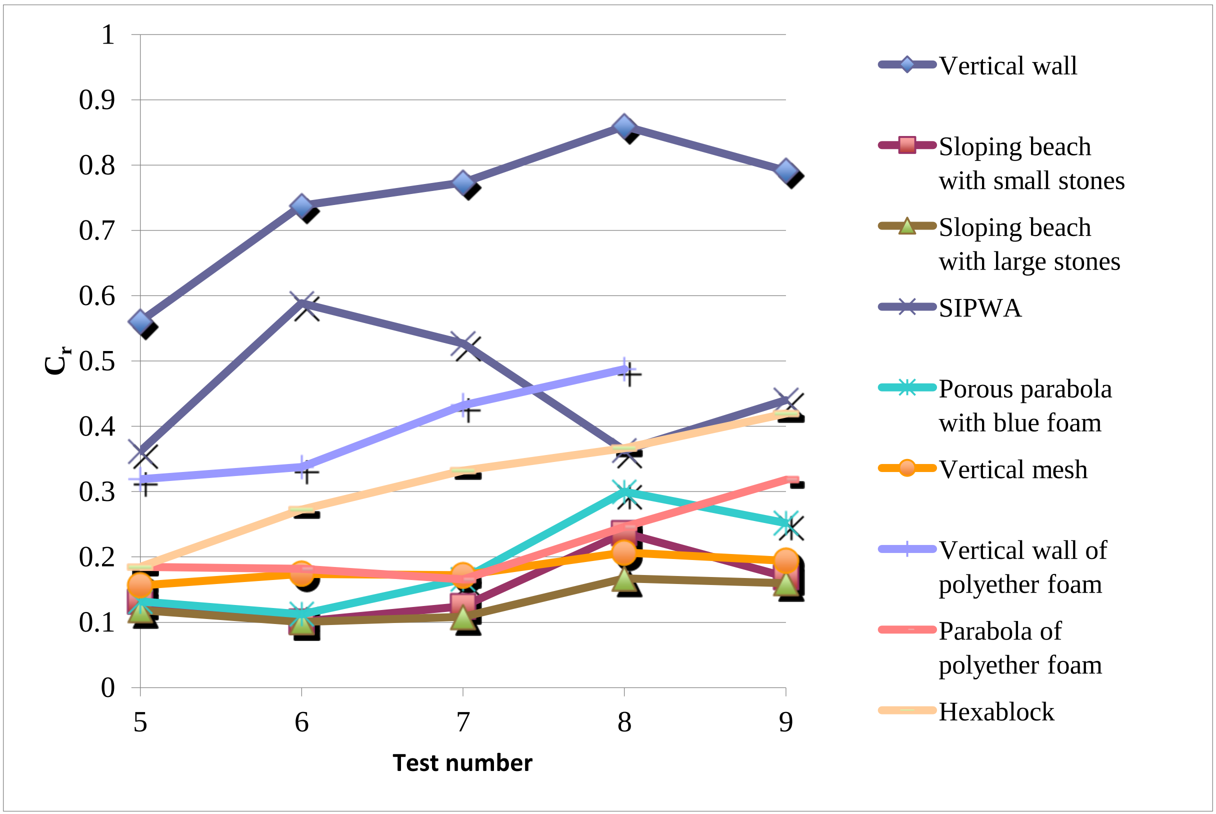

Figure 4-3: Reflection coefficients at a water depth of 34 cm

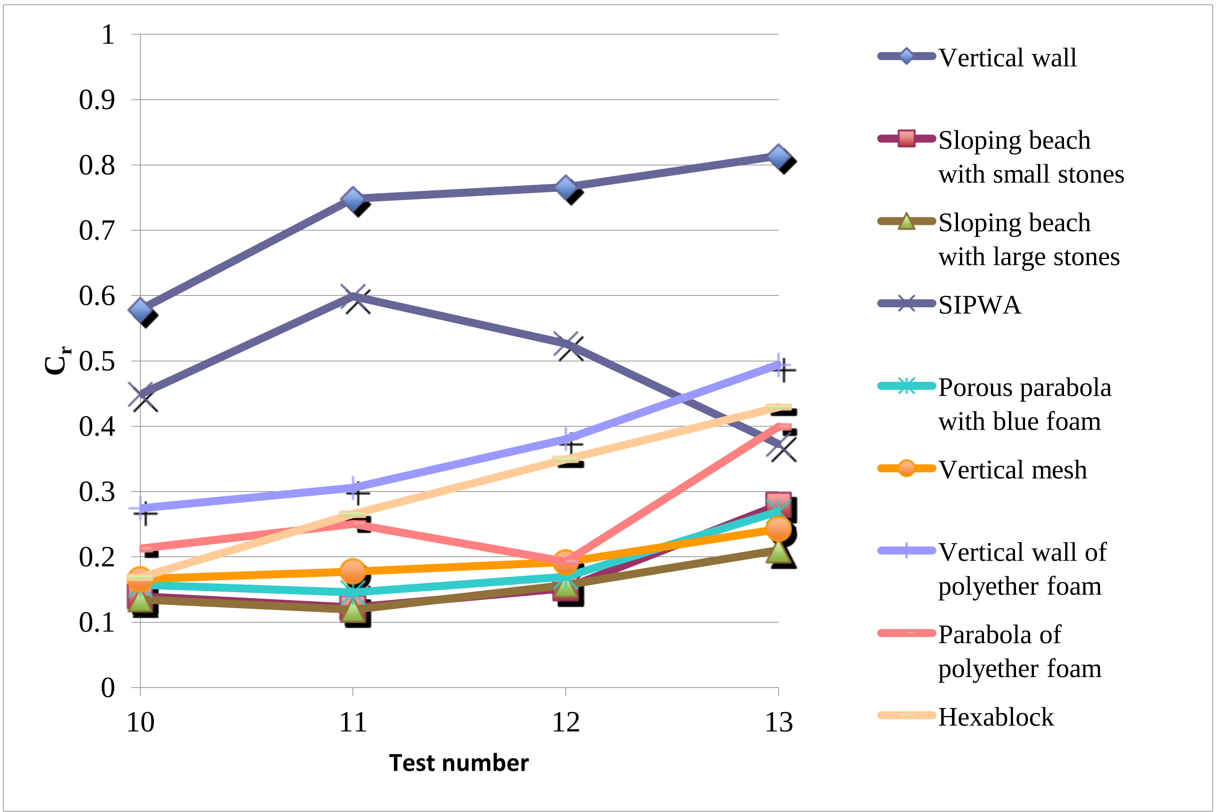

Figure 4-4: Reflection coefficients at a water depth of 25 cm

At all three depths, it is clear that the performance of certain wave absorbers is considerably worse than the performance of the other wave absorbers. These absorbers are, ordered from worst to least bad performance: the SIPWA (reflection coefficients ranging around 50%), the vertical wall of polyether foam (reflection coefficients ranging around 40%) and the hexablock (reflection coefficients ranging around 30%). Of course the vertical wall of Plexiglas (back wall of the flume) performs even worse, but this ‘configuration’ wasn't really used as a serious option for a wave absorber. It was simply tested in order to determine the wave damping capacities of the flume itself. Remark that these capacities are not negligible as for most tests, performed with an empty flume, reflection coefficients between 70% and 80% were found, which means that the reflected wave height is more or less 25% smaller than the incident wave height. As the three above-mentioned configurations are clearly worse than the other ones, they can impossibly be chosen as best wave absorber and are therefore excluded in the sequel of this comparison. The bad performance of these three configurations is also in agreement with the observations done during the test program, which are described in section 3.4. of chapter 3.

The performance of the other configurations is clearly better than the above cited ones. However, at water depths of 34 cm and 25 cm, one can see that the parabola of polyether foam is performing less good than the other four remaining absorbers. Also at a water depth of 40 cm, the performance of this wave absorber isn't very good with respect to the other four. For this reason there is decided to exclude also this configuration. If one compares the three graphs with each other, one can clearly see that the performance of the configuration that was just excluded is decreasing with decreasing water depth. This is caused by the fact that the parabola is steeper at lower positions and less steep at higher positions (see Figure 3-15).

Of the four still remaining configurations the reflection coefficients of the sloping beach with large stones are in general lower than those of the other configurations at water depths of 34 cm and 25 cm. At a water depth of 40 cm, this isn't the exact case, but the sloping beach with large stones is still performing very good at this water depth too. For this reason, there can be stated that, in general, the sloping beach with large stones is performing the best of all wave absorbers tested in the test program of this Master's Dissertation. However, this wave absorber has one disadvantage, namely the fact that it is taking quite some space. In the small wave flume of the department of Civil Engineering, it was taking a length of 1.52 m, which is quite large in comparison with the other configurations. As a consequence, the following advice concerning the selection of a wave absorber for a laboratory testing facility can be formulated: if the space is available, one should certainly choose a sloping beach with stones with a diameter of 30-35 mm and further characteristics as described in section 3.2.2. of chapter 3 (scaled to the dimensions of the facility in question, of course) as wave absorber.

However, if the space for this absorber isn't available one should use another absorber with a shorter length. In this case, two absorbers are possible, namely the porous parabola with blue foam and the vertical mesh. The sloping beach with small stones is excluded as it has the same length as the sloping beach with large stones. Besides this, it does also need more maintenance due to the fact that the profile of the slope needs to be reshaped every now and then as the stones are eroded under wave attack as was already mentioned in section 3.4. of chapter 3. As was also mentioned in this section, it was observed that the parabola of the porous parabola with blue foam was of hardly any use. It was the blue foam beneath it that was absorbing the waves. For this reason, one can simply install the blue foam in the facility without the parabola when one chooses to use this wave absorber. As such a quite short wave absorber with a maximal length of 65 cm is obtained. Detailed plans of this wave absorber are depicted in Figure 4-7, Figure 4-6 and Figure 4-5 for water depths of 40 cm, 34 cm and 25 cm, respectively.

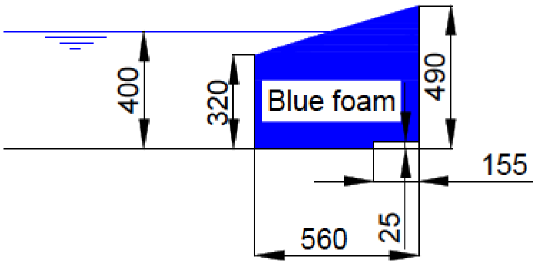

Figure 4-7: Side view of the blue foam absorber for a water level of 40 cm

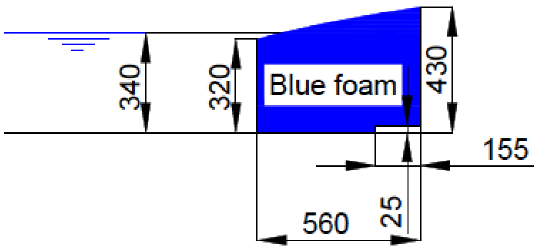

Figure 4-6: Side view of the blue foam absorber for a water level of 34 cm

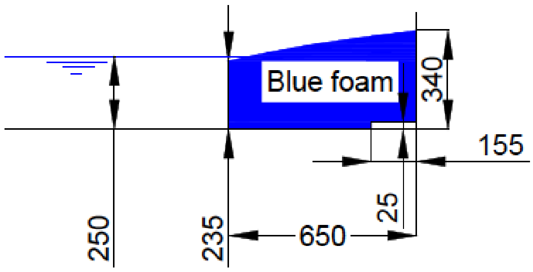

Figure 4-5: Side view of the blue foam absorber for a water level of 25 cm

In order to decide whether one should choose the blue foam or the vertical mesh if the space isn't available to install a sloping beach with stones of diameter 30-35 mm a comparison of the cost prices of both absorbers is done. The cost prices of the different configurations tested in this study are shown in Table 4-3. The prices are shown for the amounts that were needed for installation of these configurations in the small wave flume.

Table 4-3: Cost prices of the different configurations

Configuration	Cost price (€)
Sloping beach with small stones	15
Sloping beach with large stones	15
SIPWA	60
Porous parabola with blue foam	135 (100 for the blue foam and 35 for the parabola itself)
Vertical mesh	120
Vertical wall of polyether foam	125
Parabola of polyether foam	145
Hexablock	29.17

As one can see in this table, the blue foam used in beneath the porous parabola is considerably cheaper than the vertical mesh. The first one costs €100 while the second one has a cost price of €120. Consequently, the blue foam is 16.7% cheaper than the vertical mesh. One can also remark that the sloping beaches are, besides the fact that they are showing good wave absorbing capacities (especially the sloping beach with large stones), also very cheap (only €15). Also the SIPWA and the hexablock are quite cheap in comparison with the other configurations, but this difference in price cannot compensate the worse performance of these configurations.

On this basis, it seems suitable to use the blue foam absorber. However, the disadvantage of this blue foam is that the geometry needs to be changed whenever the water level changes in order to have a curved surface at the still water level (see Figure 4-7, Figure 4-6 and Figure 4-5). This takes time, but it has also a cost due to the working hours that have to be spend on it. However, another advantage of the blue foam is that it performs a bit better than the vertical mesh at a water level of 40 cm (see Figure 4-2). At the other water levels the performances of both absorbers are more or less the same (see Figure 4-3 and Figure 4-4). Also, it is shorter than the vertical mesh.

As a consequence, it isn't perfectly clear whether one should choose the blue foam or the vertical mesh when there is no room to install a sloping beach with slope 2/7. It depends on the project itself. When one really doesn't have a lot of space and one will be performing tests in the facility at high water levels (at which the performance of the blue foam is the best) without changing this level a lot (so that the geometry doesn't need to changed) and if one finds that the slightly better performance of the blue foam is important, one should certainly choose to work with the configuration with the blue foam. If one has the intention of changing the water level very frequently, it is probably more convenient to work with vertical mesh.

However, if there is no space to install a sloping beach with a slope of 2/7, one can still opt to build a sloping beach with a steeper slope. When the slope doesn't have to be made much steeper than 2/7, this is probably a better option than placing a wave absorber with blue foam or a vertical mesh as the sloping beach is a lot cheaper than these options and will still perform quite well.

This finishes the comparison of the different configurations. Two remarks can be made. In Figure 4-2, Figure 4-3 and Figure 4-4 one can see that the sloping beach with small stones is performing worse than the sloping beach with large stones. One could wonder what is causing this difference in performance. Two reasons can be brought forward. The first one is that the sloping beach with small stones is probably not porous enough as not much pores are present between the small stones. The second reason is that the sloping beach with small stones was reshaped under wave attack and that as such a steeper slope was created just beneath the still water level. A second remark that can be made is the following: more than once, there has been said that the choice of the wave absorber is dependent on the space in the wave flume or basin that one is designing. However, what is this space? Physically, there are no objections against building large wave absorbers. However, every centimetre that is taken by a wave absorber is a centimetre less that can be used for hydraulic model tests in the laboratory testing facility. So, before the design of the wave flume or basin can even start, the management should decide which space it wants to foresee for hydraulic model tests and which space it can sacrifice for the placement of a wave absorber. Once this decision has been made, the designer of the wave absorber can start with his work within the space that has been allocated to the building of a wave absorber.

4.2.4. Correlation between the reflection coefficient and some important parameters

For the tests from the standard test program (see Table 3-1) executed on the best performing wave absorbers, i.e. the sloping beach with large stones, the porous parabola with blue foam and the vertical mesh, the correlation between the reflection coefficient and the following important parameters is investigated: the peak wave period, the peak wave steepness, the significant wave height and the water depth. The correlation, which is calculated using a simple linear regression analysis, between the reflection coefficient and the peak wave period is quite good. What is striking is that this correlation is almost equal for both the porous parabola with blue foam and the vertical mesh (0.8152 and 0.8194, respectively). For the sloping beach with large stones, the correlation is a bit smaller and equals 0.6964. The fact that the reflection coefficient is quite well correlated with the peak wave period can also be seen in Figure 4-8, Figure 4-9 and Figure 4-10 for the sloping beach with large stones, the porous parabola with blue foam and the vertical mesh, respectively. As the correlation is positive, the reflection coefficient is increasing with increasing peak period. As a consequence, very long waves, which are having very high wave periods, will lead to very high reflection coefficients and will as a consequence be very difficult to damp. This is in correspondence with the first conclusion of the research of Twu and Liu (see conclusion 1) in the section handling about standard sloping beaches in the Literature review) and is also a well-known phenomenon in physical modelling.

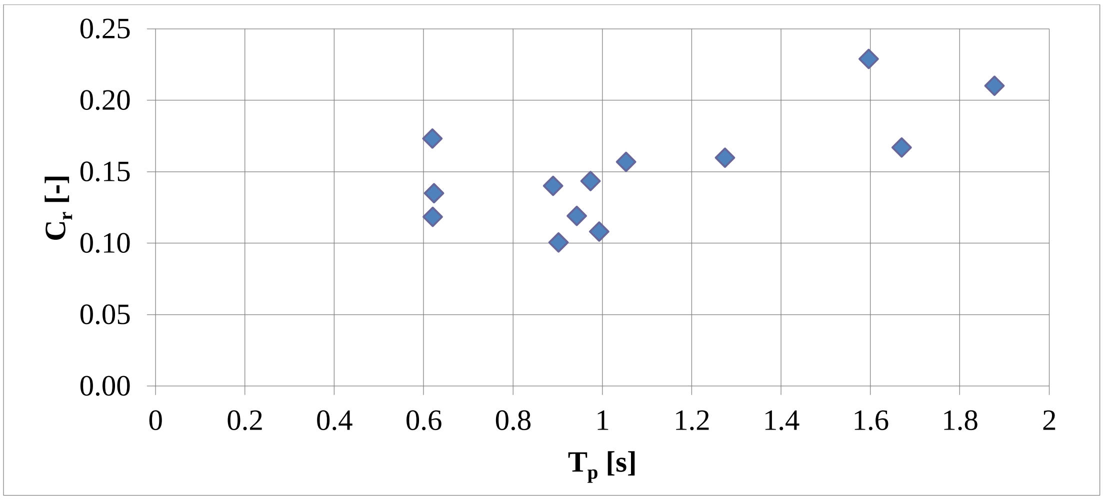

Figure 4-8: Reflection coefficient in function of peak wave period for sloping beach with large stones

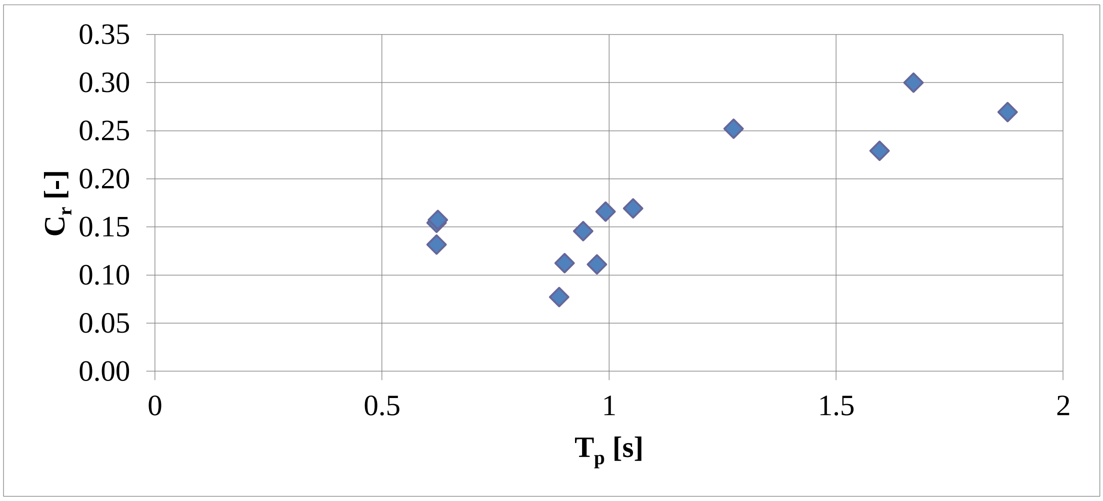

Figure 4-9: Reflection coefficient in function of peak wave period for the porous parabola with blue foam

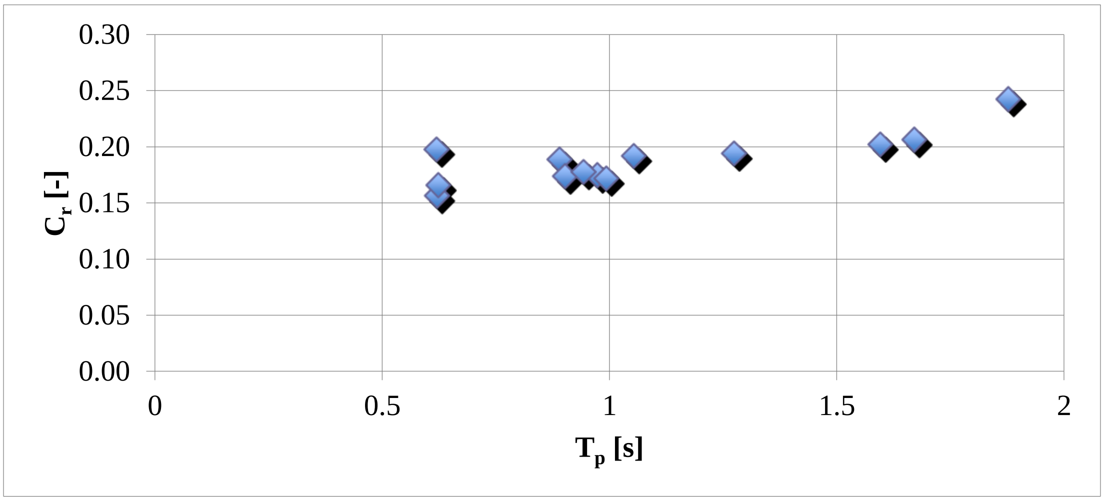

Figure 4-10: Reflection coefficient in function of peak wave period for the vertical mesh

Concerning the correlation of the peak wave steepness, significant wave height and water depth with the reflection coefficient, no clear conclusions can be drawn out of the test results. This can be seen in Figure 4-11, Figure 4-12 and Figure 4-13 for the peak wave steepness, the wave height and the water depth of the sloping beach with large stones. For the other configurations similar graphs can be obtained. The fact that no clear conclusions can be drawn is caused by the fact that only two different peak wave steepnesses and only three different significant wave heights and water depths have been used during the test program. This is insufficient to draw conclusions about the relationship between the reflection coefficient and the peak wave steepness, significant wave height or water depth.

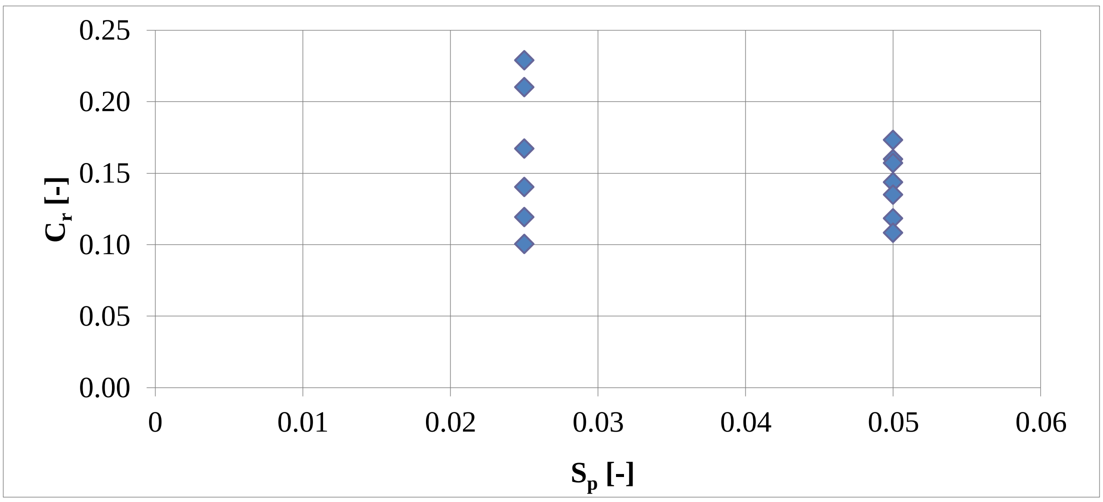

Figure 4-11: Reflection coefficient in function of peak wave steepness for sloping beach with large stones

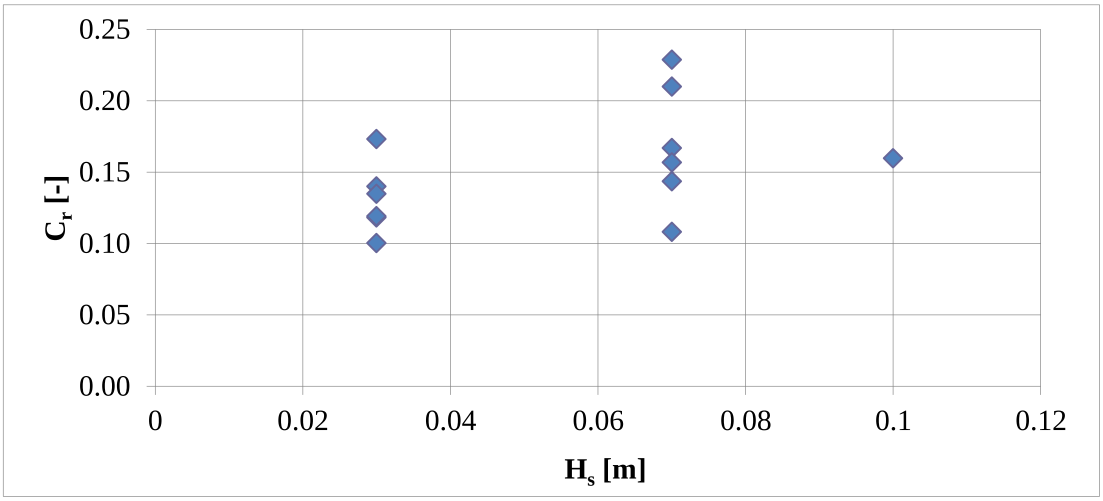

Figure 4-12: Reflection coefficient in function of significant wave height for sloping beach with large stones

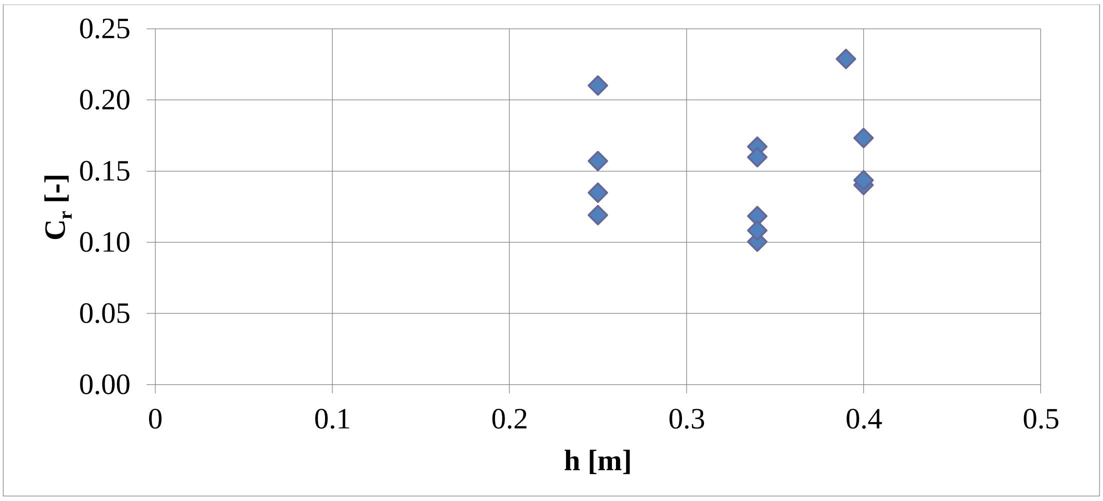

Figure 4-13: Reflection coefficient in function of water depth for sloping beach with large stones

4.2.5. Discussion of the results of the tests with regular waves

As already mentioned in chapter 3, some tests with regular waves were carried out too. The first objective of these tests was to compare the results of the irregular and regular wave tests. On the sloping beach with large stones three tests were performed with regular waves (tests 2-C, 2-D and 2-E in Table 3-2). The reflection coefficients obtained from these tests are summarized in Table 4-4 together with the reflection coefficients of the equivalent tests executed with irregular waves (tests 6, 7 and 8 performed on the sloping beach with large stones).

Table 4-4: Comparison of the reflection coefficients obtained with regular wave tests and with equivalent irregular wave tests

	$C_{r,\ regular}$	$C_{r,\ irregular}$
Tests 2-C and test 6	0.1159	0.1005
Tests 2-D and test 7	0.1972	0.1082
Tests 2-E and test 8	0.1617	0.1671

$C_{r,\,regular}$ and $C_{r,\,irregular}$ denote, respectively, the reflection coefficient found with regular and with irregular wave tests. Out of Table 4-4 one can conclude that the reflection coefficients found for regular and irregular waves are quite similar. Only between test 2-D and test 7 the difference is considerable.

Similar tests were performed in the empty flume (tests 9-A, 9-B, 9-C, 9-D, 9-E, 9-F and 9-G). However, during these tests problems with sloshing occurred. These problems influence the measured wave signals and make them very unreliable. Wave signals of one of these tests (test 9-A) are visualized in Figure 4-14. It isn't possible to perform a good reflection analysis with these wave signals.

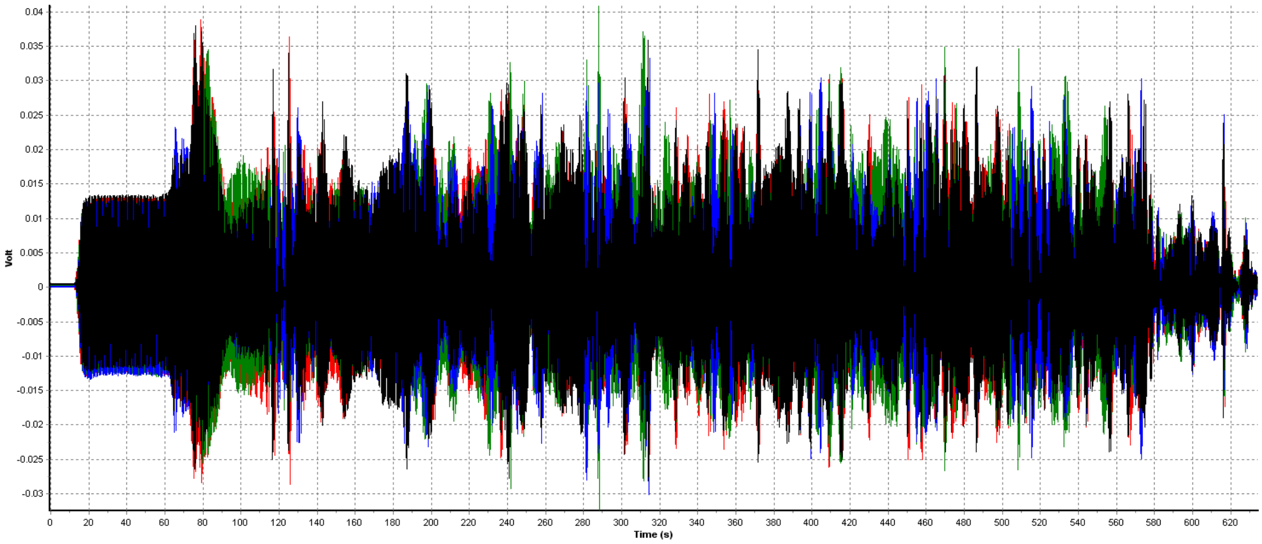

Figure 4-14: Wave signals of test 9-A

However, when observing wave signals of tests with regular waves executed on the sloping beach with large stones (the above mentioned tests 2-C, 2-D and 2-E) one can see that these signals do look very good. Also, no sloshing was observed during these tests. One can conclude that no problems with sloshing occur as long as a good wave absorber is present in the wave flume and, as it is the intention of this Master's Dissertation to look for good wave absorbers, one shouldn't worry about sloshing too much.

The wave signals of test 2-E are shown in Figure 4-15. These wave signals are much nicer than the wave signals visualized in Figure 4-14. This is intuitively clear, if one looks to the shape of both groups of wave signals. However, the reason why the signals depicted in Figure 4-15 are far superior with respect to those depicted in Figure 4-14 can be explained in a more scientific way too. When a regular wave is generated, a wave train of waves with equal wave amplitude travels through the flume. As a consequence, the surface elevation shows a constant sinusoidal movement through time and, as the conductance (expressed in Volt) measured by the wave gauges is proportional with the surface elevation (see 3.5. Data acquisition), the conductance follows this same sinusoidal profile. It is this conductance that is shown on the vertical axis of the graphs in Figure 4-14 and Figure 4-15. When the wave train reaches the reflecting structure at the other side of the flume, it is partly reflected. The reflected wave propagates through the wave flume in the inverse direction and causes an amplitude shift. Once this amplitude shift has taken place, a uniform wave elevation pattern is measured once again. However, the amplitude shift cannot be seen very clearly in Figure 4-15. This is a consequence of the fine wave absorbing capacities of the sloping beach. When sloshing occurs, unusual peaks and depressions in the time signal can be observed as one can see in Figure 4-14.

In total four wave signals are depicted in both Figure 4-14 and Figure 4-15. Each of these signals is measured at one specific wave gauge and as mentioned earlier a minimum of four wave gauges is needed in the method of Lin and Huang for the analysis of regular waves. If a big reflected wave is present in the flume, the differences between the amplitudes of the different wave signals will be great. If, however, the reflected wave is small, the differences in amplitude will be small. It is not that clear, but this is the case in Figure 4-15, which does also correspond with the rather small reflection coefficient of 0.1617 found in the reflection analysis (see Table 4-4). As such, this simple observation in the plot of wave signals can be used as a check for the complicated calculations of the reflection analysis.

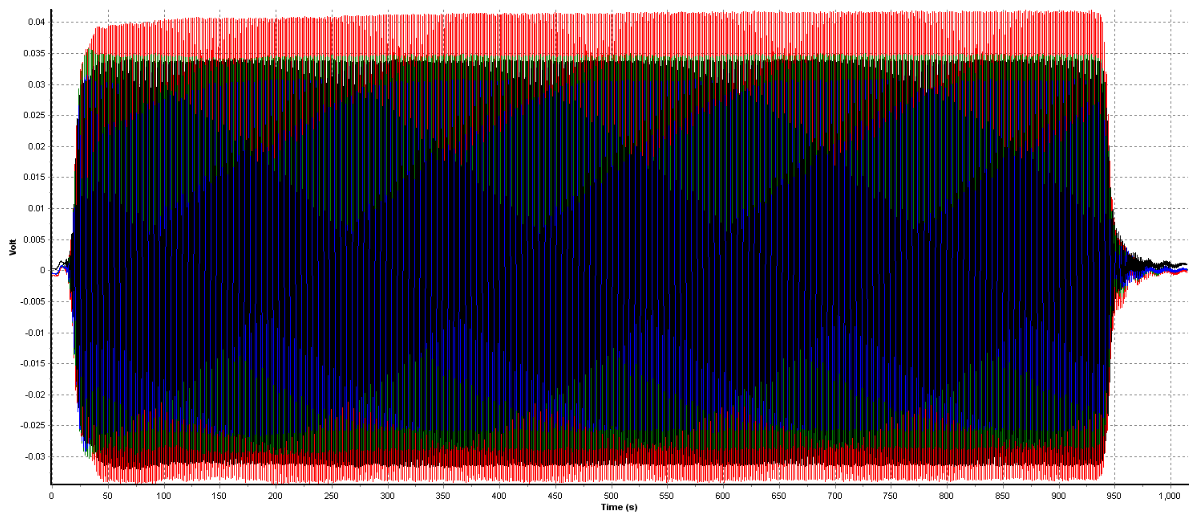

Figure 4-15: Wave signals of test 2-E

It is also important to say that one shouldn't forget to disregard the start and stop of the wave signals while performing the analysis. In these parts of the signals no proper waves are generated as one can see in both Figure 4-14 and Figure 4-15.

Finally, Figure 4-16 is incorporated in this section. This figure shows the incident wave spectrum of a test performed with regular waves (test 2-E). As one can see a large peak at the frequency of the generated regular wave is present in the spectrum but also a much smaller peak can be seen with a higher frequency. This is a higher (second) order harmonic that is produced by the interaction with the back wall of the reflecting structure. It are these kind of higher order harmonics that are taken into account in the method of Lin and Huang.

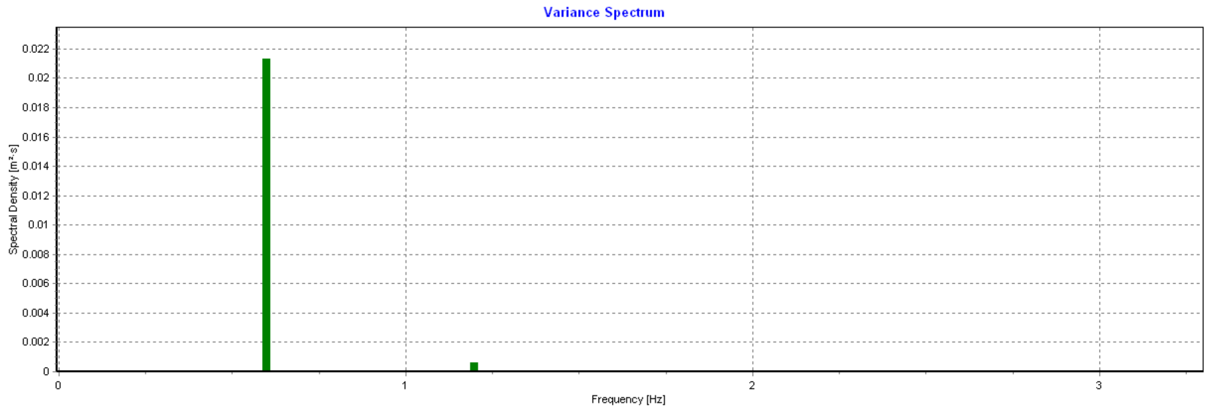

Figure 4-16: Spectrum of a test with regular waves

4.2.6. Additional results of the reflection analysis

Although the reflection coefficient is the major result of the reflection analysis, it isn't the only result. The results of the reflection analysis are broader than that. As already mentioned in section 4.1. also the incident and reflected wave spectrum as well as the reflection spectrum can be calculated. It is certainly appropriate to have also a look to these additional results of the reflection analysis. For every test executed during the test program the above-mentioned spectra can be generated using WAVELAB. However, these spectra are often similar to each other and it is therefore not necessary to talk about all of them in this text. Nevertheless, the spectra of a certain test performed in the test program of this Master's Dissertation will be discussed below.

The spectra are depicted in Figure 4-17 and are the spectra of test 7 performed on the hexablock. The incident wave spectrum is shown in green and the reflected wave spectrum is depicted in blue. The theoretical spectrum, that was intended to be generated, is shown by the black line. As can be seen the incident wave spectrum follows this line quite nicely. The reflection spectrum, which can be calculated out of the incident and reflected spectrum by making use of formula (4.8), is drawn in yellow in Figure 4-17. It should only be considered where it crosses the green incident wave spectrum. Values of the reflection spectrum shown outside the incident wave spectrum are unreliable. It is clear that the reflection spectrum decreases with increasing frequency and as a consequence with decreasing period. This is again logical as shorter waves are damped more easily and consequently result in smaller reflected waves and smaller reflection coefficients. The blue reflected wave spectrum is indeed smaller with respect to the incident wave spectrum for larger frequencies than it is for smaller frequencies. The reflection coefficient that was found with the method of Mansard and Funke for this test equals 0.3321. This more or less equal to the value of the reflection spectrum at the peak frequency as it should be (see section 4.1.).

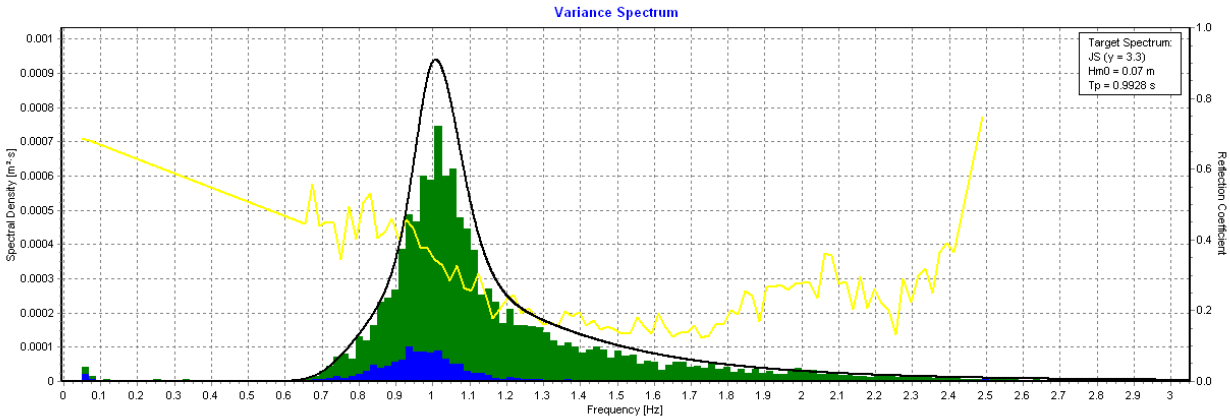

Figure 4-17: Spectra of test 7 executed on the hexablock

4.3. Comparison with previous studies

If one compares the results of the test program mentioned in the previous section with what was found in literature (see chapter 2 Literature review), one comes to the conclusion that the results from the test program are not always as one would expect from the literature review.

For the two configurations using polyether foam and the configuration with the hexablock, it is of course difficult to know whether these setups are performing better or worse than what one should expect, as no information about the performance of these wave absorbers can be found in literature. For the SIPWA, however, the absorbing capacities of the configuration tested during this study were an awful lot worse than what Lebey and Rivoalen (2002) obtained during their test program. During the test program of this study, reflection coefficients ranging around 50%, were indeed found, while Lebey and Rivoalen found a reflection coefficient of no more than 3.5% [9]. Causes of this striking difference can be found in the fact that the model used in the test program of this study had other dimensions than the model used in the test program of Lebey and Rivoalen, because Lebey and Rivoalen worked with a smaller wave flume and as consequence with a smaller model. Another issue that might have caused this difference is the possibility that the model of Lebey and Rivoalen was tested with waves with other characteristics than the model used in this Master's Dissertation. It is indeed not known which wave period, wave height or wave steepness Lebey and Rivoalen used in their test program (see Table 2-2).

Also for the porous parabola with blue foam, which was designed after the idea of the parabola of Tiedeman [19], the reflection coefficients found in this study, which range between 10% and 20% and which are sometimes even higher than 20%, are significantly larger than what was found by Tiedeman. Tiedeman did indeed find reflection coefficients ranging around 5%. For particular periods, reflection coefficients of only 1% were even found. This difference is probably caused by the fact that the parabola built in the small wave flume of the department of Civil Engineering is certainly not a perfect replica of the parabola tested by Tiedeman. This was impossible, as Tiedeman didn't give much detailed information about the parabola constructed during his test program.

Concerning the two sloping beaches tested in the test program, it was already mentioned in Table 2-2 that a high variety on reflection coefficients is possible. However, two methods were found in literature that can be used in order to predict the reflection coefficient for a certain sloping beach and a wave with certain characteristics. The first method is the method of Miche and makes use of the graph depicted in Figure 2-2, which is actually valid for crushed stones. However, the stones used for the sloping beach with small stones were still intact. Nevertheless, the graph can also for this configuration still be used to obtain an estimation of the reflection coefficient. One finds, after linear interpolation between the different lines depicted in the graph, a reflection coefficient of 0.035 for tests executed with an incident wave steepness of 0.05 and a reflection coefficient of 0.07 for tests executed with an incident wave steepness of 0.025. 0.05 and 0.025 are indeed the two wave steepnesses used in the tests program (see Table 3-1).

The second method is the method of Twu and Liu and uses formulas (2.4)-(2.8) in order to obtain an estimation of the reflection coefficient. These formulas do actually assume that the slope is impermeable, but can be used to obtain an estimation of the reflection coefficients that one can expect for a permeable slope too. The Maple file used to calculate the estimations according to this method can be found in Annex D together with the exact values of the predicted reflection coefficients for the 13 tests performed in the standard test program. As both methods don't incorporate the grain-size in their calculations, the predictions of the reflection coefficient are the same for both sloping beaches tested in the test program.

The graph depicted in Figure 4-18 shows the reflection coefficients deduced from the wave signals measured during the tests performed on both sloping beaches in the test program together with the predictions for the reflection coefficients according to both above-mentioned methods. One sees immediately that the method of Twu and Liu gives estimates of the reflection coefficient that lie much closer to what was measured in reality. This method is indeed published much more recent than the first method and is already much more sophisticated. This compensates the shortcoming that the sloping beach is assumed to be impermeable amply. One can conclude that, if one wants to estimate the reflection coefficients for a certain sloping beach, the method of Twu and Liu should be preferred. However, both methods don't give perfect estimations, which makes it advisable to keep on performing physical model tests.

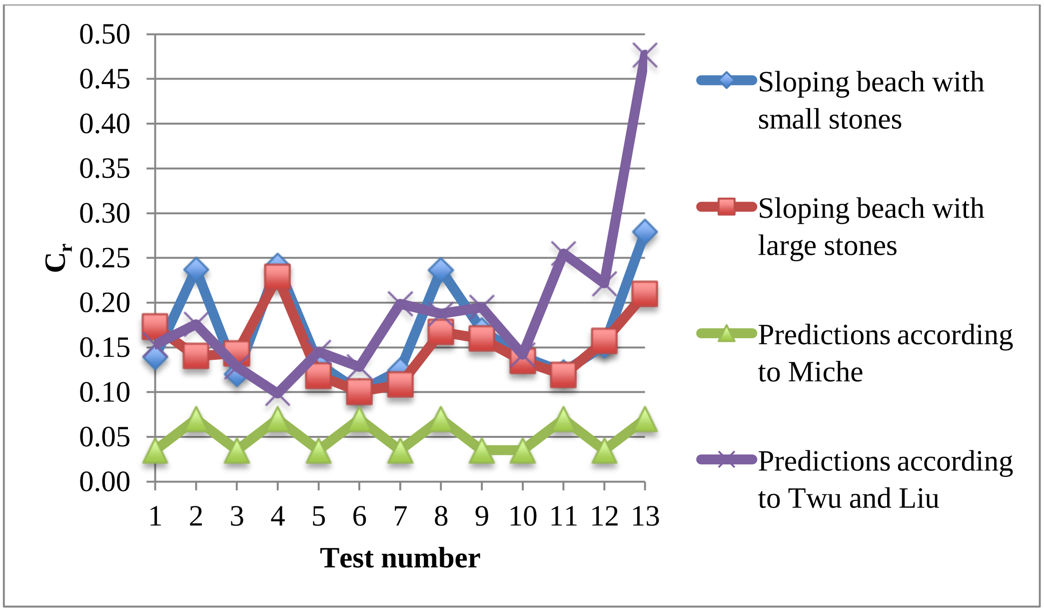

Figure 4-18: Comparison between measured and predicted reflection coefficients

4.4. Gaps in the knowledge

At the end of this work there are still some gaps in the knowledge which should be the subject of further research. These gaps are listed here.

The first gap in the knowledge concerns the following: in section 4.2.3. it has been said that, in general, the sloping beach with large stones is performing the best of all wave absorbers tested in the test program of this Master's Dissertation. However, one could wonder whether, for example, stones of diameter 45-50 mm or 20-25 mm show maybe even better wave absorbing capacities. This wasn't investigated in this study. The only thing that is known is that a sloping beach with stones of diameter 10-16 mm is performing worse. Consequently, one can reasonably assume that sloping beaches with stones of diameter smaller than 10-16 mm are performing worse too. So, a first gap in the knowledge is the answer to the following question: "What is the optimal stone-size that gives the best possible wave damping performance that can be achieved with a sloping beach?"

A second gap in the knowledge concerns the problem that the sloping beach with large stones has a superior performance, but that it is unknown up to which higher value of the slope one may go in order to still achieve wave absorbing capacities that are better than the capacities of any other possible wave absorber. Also, it is unknown at which value of the slope the performance of the sloping beach has become that worse that its lower cost price can impossibly compensate for this. In question format this gap in the knowledge can be formulated as follows: “What is the highest value of the slope that still guarantees superior wave damping properties and at which value of the slope does it become impossible to compensate the worse wave damping properties of the slope by its lower cost price?” This problem and the previous one are both issues that can probably be tested quite efficiently using numerical modelling, as it is in a numerical model easier to change stone-sizes and slopes than it is in a physical modelling set-up.

The third gap in the knowledge feeds back to chapter 3. It was mentioned in this chapter that the sloping beaches were added to the test program as a reference case. Although they were discussed in the literature review, they didn’t came out of it as the best performing absorbers (see section 2.21. Comparison of the different wave absorbers). Consequently, it is quite remarkable that the sloping beach with large stones is found to be the best performing wave absorber. As a consequence one could also wonder if there would exist other wave absorbers cited in the literature review that could possibly perform even better. This is hard to say and some extra model tests on other wave absorbers mentioned in the literature review wouldn’t certainly be superfluous. A wave absorber that would certainly need to be investigated is the Marcou wave absorber which couldn’t be investigated during the test program of this Master's Dissertation but which is showing very nice wave damping capacities according to literature (average reflection coefficient in the optimal configuration of 4.3%).

A fourth and last point on which further research could be done is the amelioration of some of the configurations which were already tested in the test program. For the SIPWA, for example, the very small length of the absorber was maybe a bit too ambitious. It could be an idea to elongate the different superposed planes. Another idea could be to play with the spacings between the planes and see whether or not the used 3 cm is optimal and if not which spacing would be optimal instead. One could also change the slope-angle of the planes, but Lebey and Rivoalen (2002) found in an experimental study that 35° would be the optimal value for this greatness and one can probably assume that this is correct. For the vertical mesh tests could be performed with smaller openings (as the openings with diameter 2 cm were maybe a bit on the large side), other porosities and other spacings. For the porous parabola with blue foam, tests could be performed without the parabola and with maybe slightly changed cross-sections of the blue foam so that the vertical front surface becomes smaller. Another option would be to do tests with a thicker parabola and smaller openings in order to obtain a parabola which dissipates the wave energy in a better way. Concerning the vertical wall of polyether foam, it would be an idea to execute tests with a more porous material as front face, as the polyether foam with a rough texture was found to be not permeable enough. A material that could certainly be taken in consideration would be the at the department of Civil Engineering well-known blue foam. This material is indeed quite more porous than the rough textured polyether foam. The different materials are shown in Figure 4-19. Bottom right the blue foam is depicted. Top right polyether foam with a rough texture is shown. The material at the left side is polyether foam with a fine texture. The differences in porosity can be seen clearly. The parabola of polyether foam could be improved by making the parabola a bit less steep or by changing the polyether foam by the more porous blue foam, but if this last option is chosen this configuration becomes very similar to the blue foam absorber. For the hexablock no improvements are possible as the hexablock is a prefabricated item.

Figure 4-19: Different types of foam used as an absorbing material in the test program

Chapter 5

Conclusions

This Master's Dissertation focuses on the topic of passive wave absorbers in laboratory testing facilities. It has four research objectives of which the first one, namely determining which absorber one should use when designing a wave flume or a wave basin in order to achieve the best wave absorbing characteristics, is the most important one. An extensive literature review was performed in which a lot of wave absorbers mentioned in literature were described. According to what was found in this literature review four wave absorbers were showing superior wave absorbing capacities. These wave absorbers were the SIPWA, the vertical mesh, the Marcou wave absorber and the parabolic slope with a front wall. Except the Marcou wave absorber, which couldn’t be installed properly in the small wave flume of the department of Civil Engineering where the tests were executed, these absorbers were tested in a test program. However, in order to make it compatible with the wave flume the design of the parabola was changed a bit with respect to the original design found in literature. Also blue foam was added beneath the parabola. In this test program also two materials which were not yet tested in earlier research were incorporated. These materials are polyether foam and hexablocks. Two configurations were tested with polyether foam, one with a vertical wall and one with a parabolic shaped surface. Finally, two standard sloping beaches, one with small stones (diameter of 10-16 mm) and one with large stones (diameter of 30-35 mm) were tested. Once the test program was finished the reflection analysis was performed. Using the results of the reflection analysis the objectives of this Master’s Dissertation can be reached and conclusions can be drawn. Each objective is recapitulated below and the corresponding conclusion is formulated.

The first and by far the most important objective of this Master's Dissertation was the following:

1) To determine which wave absorber one should use when designing a wave flume or a wave basin in order to achieve the best wave absorbing characteristics.

When designing a wave absorber for a wave flume or wave basin, it is found that one should choose a sloping beach with stones of diameter 30-35 mm in order to achieve the best wave absorbing capacities. The size of the stones is on the scale of the small wave flume of the department of Civil Engineering of the Faculty of Engineering and Architecture of Ghent University; of course one should scale this to the dimensions of the facility that one is designing. With a slope of 2/7 the superior wave damping properties of this absorber are guaranteed. In this case one can expect to find reflection coefficients ranging between 0.1 and 0.2. Reflection coefficients higher than 0.2 will be found rarely. Reflection coefficients close to 0.1 will be found for the smaller periods. Nevertheless, if the space is available in the laboratory testing facility, one can of course opt to use even smaller slopes in order to obtain an even better performance. However, if the slope of 2/7 takes too much place, one cannot choose any more for a sloping beach with the warranty that the wave absorbing capacities will be superior to any other wave absorber. If the space is indeed not available the designer has the following three options:

a) The first option is to place a sloping beach with a steeper slope. This solution can only be used successfully if the space limitation isn’t too strict and a quite mild slope that still shows nice wave damping properties can still be installed. This option has also the advantage that it is 85% cheaper than option b and 87.5% cheaper than option c.
b) The second option is to build a wave absorber consisting of blue foam with geometrical characteristics as depicted in Figure 4-7, Figure 4-6 and Figure 4-5 (scaled to the right scale). This wave absorber will show very nice wave absorbing properties which will, however, not equalize the performance of a sloping beach with stones of diameter 30-35 mm and a slope of 2/7. Also, it has a maximal length of only 62 cm (in the scale of the small wave flume of the department of Civil Engineering) and it is 16.7% cheaper than option c. An extra advantage is that it performs slightly better than the option c at a high water level. Disadvantageous is, however, that the shape of the slope needs to be changed every time the water depth changes in order to have a curved surface at the still water level.
c) The third option is to place a vertical mesh consisting of 6 subsequent vertical porous plates in the laboratory testing facility by means of wave absorber. If one chooses the porosities and spacings as shown in Figure 3-10 quite nice wave absorbing capacities will be obtained.

Which one of these three options should be chosen in case no space is available to build a slope of 2/7 differs from project to project. If the space is available, one should choose for a sloping beach with a slightly steeper slope. However, if this isn't the case one should choose between the blue foam and the vertical mesh. When one really doesn't have a lot of space and one will be performing tests in the facility at high water levels (at which the performance of the blue foam is the best) without changing this level a lot (so that the geometry doesn't need to changed) and if one finds that the slightly better performance of the blue foam is important, one should certainly choose to work with the configuration with the blue foam. If one has the intention of changing the water level very frequently, it is probably more convenient to work with vertical mesh.

The second objective was the following:

2) To identify the gaps in the knowledge related to passive wave absorption.

Four gaps in the research which should be the subject for further research were found. These gaps can be presented by the following research questions:

- What is the optimal stone-size that gives the best possible wave damping performance that can be achieved with a sloping beach?
- What is the highest value of the slope that still guarantees superior wave damping properties and at which value of the slope does it become impossible to compensate the worse wave damping properties of the slope by its lower cost price?
- Do there exist wave absorbers cited in the literature review that weren't tested in the test program, which could perform better than a sloping beach with large stones and is the Marcou wave absorber one of them?
- Is it possible to improve the performance of the configurations already tested in the test program by modifying their designs?

In response to the objective:

3) To find how the accuracy in the analysis is affected by the use of different numbers of wave gauges.

It was found that the differences in accuracy caused by the use of a different number of wave gauges are very limited. Only, the use of two wave gauges isn't advised, because in this case it is impossible to take the noise, contaminating the wave signal, into account. As a consequence, using three wave gauges is certainly enough. Only for tests with regular waves, one is obliged to use four wave gauges when one is using WAVELAB 3.675 for the reflection analysis as this program is working with the non-linear Lykke Andersen method, which needs a minimum number of four wave gauges in order to be able to perform the reflection analysis.

The final objective:

4) To determine whether the method of Miche or the method of Twu and Liu is giving the best estimations for the reflection coefficients of sloping beaches

The method of Miche is systematically overestimating the performance of the sloping beaches and therefore the use of this method isn't advised. However, the results of the method of Twu and Liu are clearly better than the method of Miche, giving reflection coefficients which are much more in the range of what's found in practice. However, there is certainly no perfect correspondence between the results of the method of Twu and Liu and the real test results. For this reason it is of importance to keep on doing physical model tests. Both methods do also not take into account the influence of the size of the stones used for the construction of the sloping beach.

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Annex A

Extra information on wave absorbers used around the world

Table A.1: Standard sloping beaches

Research centre	Slope	Material	Permeability	C_r
Hydraulic laboratory of the Dauphiné	2/1-1/30	Cement	Non permeable	0.2 for 1/10 and milder slopes
St. Anthony Falls Hydraulic Laboratory	1/1-1/3.7	Rock	Permeable (50%)	0.2
St. Anthony Falls Hydraulic Laboratory	1/1-1/3.7	Corrugated wire mesh	Permeable (92,3%)	0.35
St. Anthony Falls Hydraulic Laboratory	1/1.7	Corrugated wire mesh	Permeable (92.3%)	0.02-0.5
University of Iowa	1/6	Wooden laths	Permeable	No info
HRD Burlington	1/8	Horse hair	No info	0.1
LIT Haifa	1/10	Wire screen+horse hair+sand, gravel and stones	Permeable	No info
FIWKW, Hannover	1/7.5	Wire screen+ripples	Non permeable	0.025-0.1
IV Stockholm	1/6	Wooden laths	Permeable	0.1
Ontario Hydro	1/6	Wire screen+horse hair	Non permeable	0.08-0.1
Empresa de Portos	1/5	Sand, gravel and stones+Cages filled with porous material	Non permeable	No info
MIT Cambridge	No info	Shavings	Non permeable	No info
IBW Gdansk	1/3-1/8	Sand, gravel and stones+Cages filled with porous material	Permeable	No info
DPRI Kyoto	No info	Sand, gravel and stones	Permeable	0.2-0.25
OTC Escondido	1/3	Shavings	Non permeable	0.05
Monash University	1/6.5	Transversal bars	Non permeable	No info
PHRI Yokosoka	1/2.33	Wire screen+transversal bars+sand, gravel and stones+cages filled with porous material	Non permeable	No info

HRS Wallingford	No info	Cages filled with porous material	No info	No info
HSL New South Wales	1/5	Horse hair+sand, gravel and stones	No info	No info
University of Grenoble	1/6	Wire screen	No info	No info
SMEC Coma	No info	No info	Permeable	No info
University of Bristol	1/11	Horse hair	Permeable	<0.04
Universtiy of California	No info	Horse hair	Non permeable	No info
HD Goeborg	1/6	Wire screen	Non permeable	>0.1
HERI Romania	1/5	Sand, gravel and stones	Permeable	No info
University of Washington	1/10	No info	Non permeable	No info

Table A.2: Sloping beaches that don't reach the bottom

Research centre	Slope	Material	Permeability	C_r
MWD New Zealand	No info	Concrete	Non permeable	No info
WINA, Glen Cove, N.Y.	No info	Horse hair+perforated plywood	Permeable	No info
CBI, Chicago	1/3.7	Sand, gravel and stones	Permeable	0.02-0.1

Table A.3: Sloping beaches with meshes in front

Research centre	Slope of the beach	Material of the beach	Permeability	C_r
Arctec Canada	1/4-1/2	Wire screen+horse hair+sand, gravel and stones	Permeable	0.3-0.4
AMTE, United Kingdom	1/6	Transversal bars	Non permeable	0.1
AMTE, United Kingdom	1/7	Transversal bars	Non permeable	0.05-0.25

Table A.4: Broken slopes

Research centre	Slope	Material	Permeability	Cr
University of Hamburg	1/10->1/67	Plastic impregnated cocos fibre	Non permeable	0.05
University of Stellenbosch	1/20->1/50	Cages filled with porous material	Permeable	<0.1
NRCC Ottawa	1/6->1/2	Perforated plywood	Permeable	0.02-0.1

Table A.5: Broken slopes that don't reach the bottom

Research centre	Slope	Material	Permeability	C_r
DHI, Horsholm	1/8->1/11->1/27	Ripples+perforated plywood	Permeable (70%)	0,08-0,1

Table A.6: Slope with a front wall

Research centre	Slope	Material	Permeability	C_r
St. Anthony Falls Hydraulic Laboratory	1/4.7	Layers of concrete bars	Permeable (67%)	≤0.09

Table A.7: Standard parabolic slopes

Research centre	Height [m]	Length [m]	Material	Permeability	C_r
BSHC, Varna	6.5	12	Wire screen	No info	0.1
LV, Delft	0.3-0.8	2.5	Transversal bars	Non permeable	0.05
HSB, Hamburg	6	0.8	Wooden laths	Non permeable	No info
LNEC, Lisboa	0.4	2.74	Sand, gravel and stones	Permeable	0.02-0.1
HD Goeborg	1.2	3	Sand, gravel and stones	No info	>0.1
NRCC, St. John's	8	8	Transversal bars	No info	No info
Laval University	No info	6.4	Perforated steel sheet+horse hair+plywood	Permeable	≤0.2

Table A.8: Parabolic slopes that don’t reach the bottom

Research centre	Height [m]	Length [m]	Material	Permeability	C_r
University of Tokyo	2.5	6	Transversal bars	Non permeable	0.2
DSL, Delft	1.6	6.6	Transversal bars	Non permeable	No info
SDR, Gdansk	3.25	8	Transversal bars	Non permeable	0.1

Annex B

Parameters chosen for the digital filters of the AWASYS

Test	Top b	Low cut off [Hz]	High cut off [Hz]
Test 1	1.05	1.2	1.9
Test 2	3.60	0.7	1.4
Test 3	3.10	0.7	1.4
Test 4	1.00	0.2	1.1
Test 5	1.20	1.2	2.0
Test 6	3.70	0.7	1.4
Test 7	4.40	0.6	1.4
Test 8	6.20	0.3	1.0
Test 9	6.50	0.4	1.1
Test 10	1.30	1.2	1.9
Test 11	3.90	0.7	1.4
Test 12	4.40	0.6	1.4
Test 13	4.00	0.1	0.9
Test 2-A	1.00	0.2	1.1
Test 2-B	1.00	0.2	1.1
Test 2-C	3.00	0.6	1.4
Test 2-D	3.00	0.6	1.4
Test 2-E	5.00	0.3	1.0
Test 3-A	1.00	1.2	2.0
Test 3-B	2.50	0.7	1.4
Test 3-C	2.90	0.6	1.4
Test 3-D	4.70	0.3	1.0
Test 3-E	4.50	0.4	1.2
Test 3-F	6.60	0.3	1.0
Test 3-G	6.00	0.4	1.2
Test 8-A	4.50	0.4	1.2
Test 8-B	6.00	0.4	1.2
Test 9-A	1.20	1.2	1.9
Test 9-B	1.30	1.2	1.9
Test 9-C	3.00	0.6	1.4
Test 9-D	4.90	0.7	1.5
Test 9-E	4.40	0.6	1.4
Test 9-F	6.00	0.3	1.0
Test 9-G	6.50	0.4	1.1

Annex C

Reflection coefficients obtained from the 13 standard tests for each configuration in the test program

In this annex the resulting reflection coefficients for the thirteen standard tests (see Table 3-1) in the test program are summarized for the different configurations. The reflection coefficients were determined by making use of the method of Mansard and Funke and are shown in the table below. The different configurations are numbered in this table. Their numbers correspond to the last number in their section number in chapter 3. Also the reflection coefficients found for the tests executed in an empty flume are added and can be found beneath the cell with as contents 'Empty'. If a '/' is placed in this table, this means that no wave signals were recorded for this test which made it impossible to determine a reflection coefficient.

		CONFIGURATION								
		Empty	1	2	3	4	5	6	7	8
TEST NUMBER	1	0.5782	0.1395	0.1732	0.4266	0.1545	0.1978	0.2925	0.1669	0.1822
	2	0.7481	0.1224	0.1402	0.5968	0.0774	0.1889	0.3191	0.1382	0.2626
	3	0.7660	0.1522	0.1436	0.5249	0.1113	0.1749	0.3303	0.1248	0.3261
	4	0.8137	0.2794	0.2289	0.4242	0.2292	0.2022	0.4396	0.2564	0.3547
	5	0.5605	0.1315	0.1184	0.3617	0.1317	0.1565	/	0.1846	0.1846
	6	0.7379	0.1011	0.1005	0.5885	0.1125	0.1741	0.3191	0.1817	0.2723
	7	0.7733	0.1245	0.1082	0.5269	0.1661	0.1720	0.3377	0.1656	0.3321
	8	0.8597	0.2366	0.1671	0.3630	0.2999	0.2066	0.4323	0.2460	0.3664
	9	0.7915	0.1695	0.1598	0.4403	0.2521	0.1941	0.4877	0.3181	0.4194
	10	0.5782	0.1395	0.1349	0.4489	0.1573	0.1660	0.2744	0.2125	0.1687
	11	0.7481	0.1224	0.1192	0.5991	0.1456	0.1776	0.3056	0.2504	0.2654
	12	0.7660	0.1522	0.1570	0.5266	0.1694	0.1919	0.3802	0.1926	0.3493
	13	0.8137	0.2794	0.2101	0.3727	0.2695	0.2428	0.4942	0.3991	0.4292

Annex D

Predictions of reflection coefficients for both sloping beaches evaluated this study according to Twu and Liu

Used Maple file

> restart;

In this worksheet the parameter q is introduced. q is the ratio of water depth and wave length (h/L). As a consequence the product k*h can be rewritten as 2*Pi*q and the product k*S can be rewritten as 2*Pi*q/slope, as the slope of the sloping beach can be written as h/S. With this adjustment the result of these calculations is only dependent on this one parameter q.

> $A := \frac{a\_i}{R} \cdot sum\left(\mathrm{sqrt}\left(\cosh\left(\frac{2\cdot(i-1)\cdot 2\cdot \mathrm{Pi}\cdot q}{N}\right)\right)\cdot \cos\left(\frac{2\cdot(i-1)\cdot 2\cdot \mathrm{Pi}\cdot q}{N\cdot slope}\right), i=1..N\right);$

$$A := \frac{a\_i \left(\sum_{i=1}^{N} \sqrt{\cosh\left(\frac{2\,(2\,i-2)\,\pi\,q}{N}\right)}\,\cos\left(\frac{2\,(2\,i-2)\,\pi\,q}{N\,slope}\right)\right)}{R} \quad (1)$$

> $B := \frac{a\_i}{R} \cdot sum\left(\mathrm{sqrt}\left(\cosh\left(\frac{2\cdot(i-1)\cdot 2\cdot \mathrm{Pi}\cdot q}{N}\right)\right)\cdot \sin\left(\frac{2\cdot(i-1)\cdot 2\cdot \mathrm{Pi}\cdot q}{N\cdot slope}\right), i=1..N\right);$

$$B := \frac{a\_i \left(\sum_{i=1}^{N} \sqrt{\cosh\left(\frac{2\,(2\,i-2)\,\pi\,q}{N}\right)}\,\sin\left(\frac{2\,(2\,i-2)\,\pi\,q}{N\,slope}\right)\right)}{R} \quad (2)$$

> $a\_r := \mathrm{sqrt}(A^2 + B^2)$:

> $R := sum\left(\mathrm{sqrt}\left(\cosh\left(\frac{2\cdot(i-1)\cdot 2\cdot \mathrm{Pi}\cdot q}{N}\right)\right), i=1..N\right);$

$$R := \sum_{i=1}^{N} \sqrt{\cosh\left(\frac{2\,(2\,i-2)\,\pi\,q}{N}\right)} \quad (3)$$

The exact value of the slope is used in the calculation.

> $N := 30;$

$slope := \frac{44}{152};$

$$N := 30$$

$$slope := \frac{11}{38} \quad (4)$$

Here the value of q needs to be calculated. In this case the value is calculated for test 5 out of the test program.

> $q := \frac{0.34}{0.6};$

$$q := 0.5666666667 \quad (5)$$

> $a\_r;$

$$0.1450335732\,\sqrt{a\_i^2} \quad (6)$$

> $assume(a\_i > 0);$

> $C\_r := simplify\left(\frac{a\_r}{a\_i}\right);$

$$C\_r := 0.1450335732 \quad (7)$$

>

Predictions of the reflection coefficients

Test number	**C_r**
1	0.1531
2	0.1759
3	0.1283
4	0.0985
5	0.1450
6	0.1283
7	0.1988
8	0.1875
9	0.1948
10	0.1418
11	0.2550
12	0.2216
13	0.4770