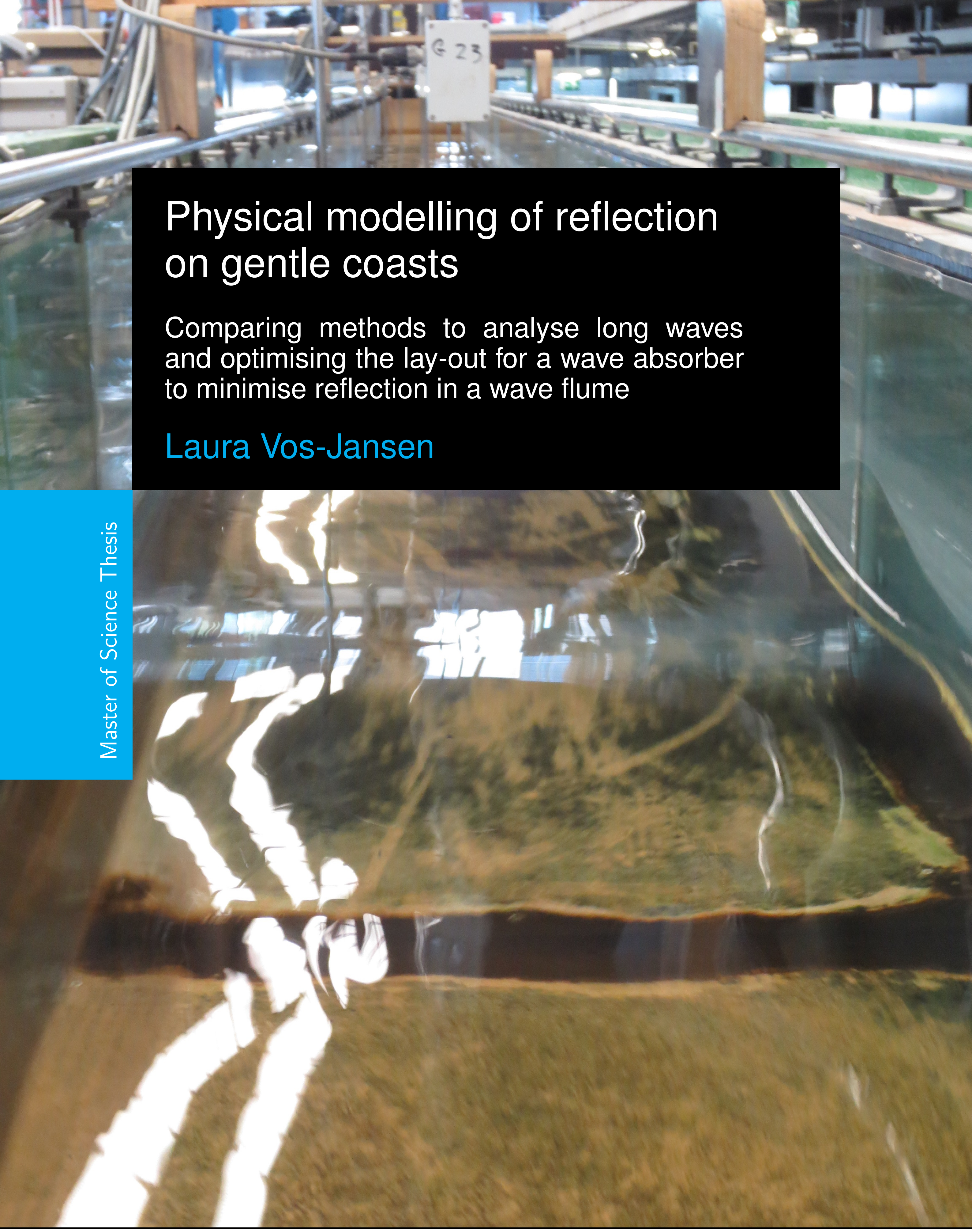

Physical modelling of reflection on gentle coasts

Comparing methods to analyse long waves and optimising the lay-out for a wave absorber to minimise reflection in a wave flume

Laura Vos-Jansen

Master of Science Thesis

TU Delft Delft University of Technology

Civil Engineering and Geosciences

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Abstract

Studying mangroves in the field can be very expensive, difficult, and sometimes even dangerous or impossible. Therefore it is in some situations better to model in a flume, which makes aspects like wave penetration, sediment transport and turbulence easier to measure and changing parameters much quicker and more convenient. The question however is, to what extend are the situation in the field and the situation in the flume comparable with each other? Various aspects need to be taken into account; this study focusses on reflection in the wave flume.

Wave energy in a flume can be damped by placing a wave absorber at the back of the flume. This is a construction that absorbs part of the wave energy; part of the waves is reflected. In this study rock is used to build the wave absorber.

Two aspects are studied: the influence of the lay-out of the wave absorber on the reflection in the flume, with as goal to find an optimal lay-out, fitting on a maximum horizontal length of 3.00 m, to minimise reflection; and the method of measuring the amount of reflection in a wave flume.

There are various ways to measure reflection in a wave flume: with two or more wave gauges (WG; which measure the water level) or with a combination of a wave gauge and an electromagnetic flow meter (EMF; which measures the horizontal velocity). A first step is to determine which implementation of a method is most suitable to use. In the analysis of five reflection implementations accuracy and efficiency are taken into account. It is found that two implementations are unreliable (WG/EMF and MF) and two others give identical results (R3 and R4), which results in two remaining implementations, which both work well (R2 and R3). Both implementations can be used, depending on the user's preference: R2 needs two wave gauges and therefore less measuring devices and length than R3, but R3 gives more usable results. In further analyses the R3-implementation is used in this study.

Various wave absorber slopes are modelled, with the slope as main aspect that changes. The slopes are calculated using theory and chosen such that there is a good distribution between the used steepnesses. Further experiment set-up in the wave flume consists of a foreland bathymetry to model a mangrove coast as could be found in the Mekong Delta (Vietnam). To model the very gentle sloping mangrove foreshore, an elevated bottom profile is created, which is 0.50 m higher than the original bottom. The transition between both bottom levels consists of two sloping parts, with steepnesses of 1:10 and 1:20. The water level is 0.65 m at the front of the flume and 0.15 m after the foreland. Various wave conditions are modelled, focussing on long, low waves but also using shorter, higher waves to make a more complete comparison possible. To obtain the measurement signals use is made of thirteen wave gauges and seven EMF's.

When comparing the amount of reflection (K_r) for different wave absorber slopes, it is found that a more gentle slope results in a lower reflection value. As there is a limited distance available and a minimum wave absorber length at still water level is desired, there is a minimum slope steepness to create in this study. It is possible to create an even more gentle slope by shortening the wave absorber toe. For an absorber with a certain slope, taking away more of the toe results in more reflection. However, using both a toe and a more gentle slope results in less reflection than for a 'complete' wave absorber which fits in the same horizontal distance. Comparing a 1:10 slope with a horizontal length of 3.00 m and a 1:15 slope with toe with equal length, the latter returns less reflection than the first. Another conclusion from the physical modelling is that for the same slope, a larger length doesn't necessarily result in less reflection. As the locations of the measuring devices are fixed, other effects (such as evanescent modes) can be influencing the water level and thus the results.

Not all physically modelled wave conditions gave usable results; possibly due to unstable waves, dispersion or a wave length that does not fit well within the used wave gauge distances. These deviating values are not taken into account in the analysis of the data and results.

Analysing the experimental results shows that the reflection as function of the Ursell number (a measure of linearity of the waves) assumes a relation between these parameters with a trend depending on the wave absorber slope on which the waves break. Reflection as function of the Iribarren number (a measure of the type of wave breaking) shows that the reflection values lie well below the theoretical values for smooth, impermeable slopes and are comparable to the theoretical values of permeable rock slopes (which is indeed used). No trend depending on slope steepness is found. To study the influence of the assumed trend in slope steepness for Ursell, a new relation is sought. With the dimensionless depth and the steepness of the waves near the absorber (both parts forming the Ursell equation) and the wave absorber slope (part of the Iribarren equation) it is found that these three parts combined show the assumed trend for the Ursell number. With this new equation the amount of reflection can be estimated from the wave height and length, local water depth and wave absorber slope.

The experiment set-up and used wave conditions are modelled in SWASH for validation, but it turned out not to be possible to reproduce the experiment results. It is assumed that the foreland bathymetry is not suitable to model the used wave conditions in SWASH. Therefore the bathymetry is changed to a water level of 0.15 m over the whole flume length. This change in set-up gives usable results, although these cannot be compared quantitatively to the experimental results. Qualitatively they can, and the same conclusions as for the physical modelling can be drawn.

Preface

This document is the result of the master thesis, which is executed at the department of Hydraulic Engineering, section Coastal Engineering, as part of the master program Civil Engineering at Delft University of Technology. In this thesis two aspects are studied: the influence of the lay-out of the wave absorber on the reflection in the flume, with as goal to find an optimal lay-out, fitting on a maximum horizontal length of 3.00 m, to minimise reflection; and the method of measuring the amount of reflection in a wave flume.

When asking prof.dr.ir. Marcel Stive to a graduation topic in Coastal Engineering, preferably hands-on and dealing with natural coastal protection, he suggested me to conduct part of the research Linh Phan Khanh MSc was doing on long wave penetration in mangrove forests. She had just started performing experimental runs in the wave flume of the Stevin III laboratory at Delft University, and didn't mind an extra hand to help. Within only a couple of weeks I was building wave absorbers, and the topic that I could study got more shape. It was very nice to start my thesis in such a practical way, although in the months to follow it appeared not always easy to have dived in directly, without a more extensive theoretical preparation. Looking back on this period of time, it has probably cost me more time to formulate my research question, but it also gave me the practical experience of physical modelling, which came in very handy when designing my own experimental set-up.

I would like to thank my supervisors, prof.dr.ir. Marcel Stive, dr.ir. Bas Hofland, Linh Phan Khahn MSc and prof.dr.ir. Stefan Aarninkhof, for their supervision and feedback on my research. They helped me to shape my research questions, to dig deeper in some topics and at the same time to keep the bigger picture in mind. I am also thankful for the help the laboratory staff, Sander, Arno, Jaap and Frank, offered during my experiments: their knowledge and help to practically set up my set-up and keep it running. Also, thanks to all the fellow students who made studying in the graduating room more sociable.

Finally, I would like to thank my family and friends for supporting me during my study; not only in my graduation but also the years before. A special thanks to my parents, who always supported me to keep going, but also at my own pace. And last but certainly not least, a special thanks to my husband, who enjoyed brainstorming with me about my research, for his support, patience and his ongoing confidence in my abilities.

Laura Vos-Jansen
Delft, 16th March 2018

Contents

Nomenclature

Subscripts

x_0	Parameter at deep water
x_{15}	Parameter at a water level of 0.15 m
x_{65}	Parameter at a water level of 0.65 m
x_{in}	Incoming
x_r	Ratio for scaling ($x_r = x_{real}/x_{model}$)
x_{re}	Reflected
x_{real}	Real value used for scaling
x_{model}	Model value used for scaling

Greek symbols

α	Slope (or described as $\tan(\alpha)$)
β_H	Normalised bed slope parameter
η	Wave signal
$\bar{\eta}$	Time-averaged wave signal (wave setup or setdown)
ξ	Iribarren parameter
σ	Standard deviation
σ^2	Variance
ω	Radial frequency ($\omega = 2\pi/T$)

Latin symbols

a	Wave amplitude ($a = \frac{1}{2}H$)
b	Width of a porous media (wave absorber) at still water level (also described as L_{SWL})
F	Factor to calculate the relation between K_r and ξ
Fr	Froude number
f	Frequency ($f = 1/T$)
g	Acceleration of gravity (9.81 $\mathrm{m/s^2}$)
H	Wave height
h	Water level
h_0	Still water level
h_u	Measuring height for horizontal velocity
h_x	Wave absorber slope (originally: bed slope)
K_r	Reflection (calculated output value)

K_u	Velocity response function
k	Wave number ($k = 2\pi/\lambda$)
L	Wave length
L_{SWL}	Wave absorber length at still water level (also described as b)
n	Friction coefficient (used for Manning friction)
R	Reflection (input value)
R_u	Wave run-up on a slope
T	Wave period
U	Ursell number
u	Horizontal water velocity
X	Distance from the beginning of the flume
x_{xx}	Distance between two wave gauge locations

Abbreviations

EMF	Electromagnetic flow meter
G&S	Abbreviation of the method to analyse reflection by Goda and Suzuki, (1976)
Guza	Abbreviation of the method to analyse reflection by Guza et al., (1984)
Ix	Reflection analysis implementation for irregular waves, based on the theory of Zelt and Skjelbreia, (1992), using x WG's
MF	Reflection analysis implementation based on the theory of Mansard and Funke, (1980), using three WG's
M&F	Abbreviation of the method to analyse reflection by Mansard and Funke, (1980)
R2	Reflection analysis implementation based on the theory of Zelt and Skjelbreia, (1992), using two WG's
R3	Reflection analysis implementation based on the theory of Zelt and Skjelbreia, (1992), using three WG's
R4	Reflection analysis implementation based on the theory of Zelt and Skjelbreia, (1992), using four WG's
Re	Regular (waves)
SNR	Signal-to-noise ratio (SNR = 1/noise)
SWL	Still water level
WA	Wave absorber
WG	Wave gauge
WG/EMF	Reflection analysis implementation based on the theory of Guza et al., 1984, using a WG and an EMF
Z&S	Abbreviation of the method to analyse reflection by Zelt and Skjelbreia, (1992)

1 Introduction

1.1 Problem description

Studying mangroves in the field can be very expensive, difficult, and sometimes even dangerous or impossible. Therefore it is in some situations better to model in a measuring flume. Aspects like wave penetration, sediment transport and turbulence can be measured more easily in a flume than in the field. Additionally, in a flume various situations can be modelled to investigate different parameters. The question however is, to what extend are the situation in the field and the situation in the flume comparable with each other? Aspects that need to be taken into account when modelling in the flume are:

- Reflection; which is much higher and behaves differently in a flume than in the field, due to the confining of the flume;
- Set-up; which also occurs in a different way than in the field;
- The transition of the shore bathymetry: on real mangrove coasts the bottom is very gentle, in the order of 1:1000. This is very difficult to model in a flume at a reasonably large scale, as either the flume is too short or the parameters that are modelled are too small to measure. Therefore a (partially) steeper slope is needed in modelling in a flume;
- Scale effects.

In this research the focus will be on reflection.

1.2 Relevance

1.2.1 Wave absorber lay-out

Generally, waves in a flume can be damped by placing a wave absorber at the back of the flume. This is a construction that absorbs part of the wave energy, but not all; part of the waves is reflected. It depends on the lay-out of the wave absorber how much of the wave energy is absorbed, and thus how much reflection occurs. It can easily be imagined that a more gentle slope results in less reflection, but unfortunately the available space at the end of a flume is limited. Therefore the question arises how much reflection reduction is possible for a certain wave absorber length, and whether it is possible to find an 'optimal' lay-out, to reduce the reflection as much as possible for a given available space.

The focus of the waves that are modelled is on regular waves. Different wave conditions are run on several lay-outs of a wave absorber. Long waves as well as intermediate waves are taken into account.

1.2.2 Reflection analysis methods

To measure the reflection in a flume, different approaches can be used. For the measuring equipment use can be made of wave gauges (WG's) to measure the water level (and thus the wave height) at a certain location. Also electromagnetic flow meters (EMF's) can be used, which measure the horizontal velocity.

One way to determine the reflection is by combining the water level (with a WG) and the water velocity (with an EMF) at the same location (described by Guza et al., (1984)). Other methods only use wave gauges: two (Goda and Suzuki, 1976), three (Mansard and Funke, 1980), four (Lin and Huang, (2004)) or an arbitrary number starting with two (Zelt and Skjelbreia, 1992).

Zelt and Skjelbreia, (1992) state that their approach with two wave gauges is similar to that of Goda and Suzuki, (1976), because the used equations can be solved exactly with two gauges. For more than two wave gauges Zelt and Skjelbreia, (1992) use a weighted least squares approach that is valid for any number of gauges. For three WG's Mansard and Funke, (1980) use a least squares approach with uniform weighting, and to determine the reflection with four gauges Lin and Huang, (2004) also use the least squares method.

In the various articles it is stated that for a certain number of wave gauges the method (and outcome) is comparable: for example the method of Mansard and Funke, (1980) is comparable to the three wave gauge method of Zelt and Skjelbreia, (1992). Literature suggests that using more probes gives more reliability as more details can be distinguished. However, it is not pointed out clearly how much better these developments are. It would be interesting to compare the outcomes of the different methods, when used to analyse the reflection of a certain dataset. Are the results of these methods comparable, or do they give significant differences? If so, what could have caused this? And is it more reliable to measure the reflection with more probes, or is a 'simple' method just as good?

1.3 Approach

1.3.1 Research questions

Based on the found unexamined topics, the following question of interest arises:

> *How can the reflection in a flume be minimised by the shape of the wave absorber?*

In order to assess these wave absorber lay-outs, the following question needs to be answered:

> *With what method can the reflection of long waves in a flume best be estimated, for both long and short regular waves?*

As not much research is done to long waves in mangroves, it is interesting to model these in a flume. To get to reliable results, it is desirable to know how the reflection in a flume of these long waves can be analysed, and as there are various methods to use these will be compared. To make the spectrum more complete and comparable to the real situation, also shorter waves can be taken into account.

When it is known how to obtain a reliable reflection parameter, it can be investigated how the reflection can be made as small as possible by varying the shape of the wave absorber.

Combining these two questions results in the main research question:

> *When modelling a mangrove coast in a wave flume (with a bottom profile that is shortened and steepened compared to a field situation), how can the reflection be minimised by the lay-out of a wave absorber and how can the reflection of long, regular waves be measured best?*

1.3.2 Modelling methods

To answer these research questions, use will be made of different modelling methods. With an analytical model the amount of reflection on a wave absorber slope of a certain steepness can be estimated. Physical modelling is executed as experiments in the wave flume in the Stevin III laboratory of TU Delft. The goal of these experiments is to find an optimal wave absorber lay-out for the given available length, and to compare the various reflection implementations with experimental data. For numerically modelling the reflection in a flume, the computer model SWASH (Simulating WAves till SHore) is used. The aspects that are modelled numerically are the wave conditions, bathymetry and scale. Sediment will not be modelled. The goal of the numerical modelling is to study to what extend the physical model can be reproduced in SWASH. Also a quick, qualitative look into scale effects can be taken.

1.4 Outline

To answer the research question, in chapter 2 a theoretical calculation of the wave absorber slopes is given for a first estimation. The different methods and associated implementations to convert a measured wave or velocity signal into a value for reflection are described and analysed in chapter 3. In chapter 4 the experimental set-up for the physical modelling in the wave flume is given, followed by the experiment results in chapter 5 and an analysis of these results in chapter 6. The numerical modelling by SWASH is given in chapter 7. In chapter 8 the discussion of the research can be found, followed by its conclusions and recommendations for further research in chapter 9.

2 Theoretical approach

For a wave absorber at the end of a flume, various options are possible. The most basic option is to use rock: absorber lay-outs are easily constructed or adapted, material is inexpensive and easy to obtain and it is widely used in other studies. Other methods to reduce wave energy are for example perforated plates placed with interspaces of different lengths, a wave paddle that can be actively controlled to produce counterwaves, or a certain type of foam which reduces the wave energy in a comparable way as stones. However, these options are much more expensive than rock, and therefore for this research only wave absorbers constructed of rock are studied. The rock used in this study is estimated to have a porosity around the value of 0.40 and an average stone size of 0.03 m.

In this chapter the preparatory calculations, needed for the experimental set up, are given.

2.1 Determination of wave absorber slopes

In the wave flume, an experimental set up was already present for research on mangroves.[1] A certain length was needed to model these mangroves (which were added to the flume after the experiments for this research), which caused the available space for the wave absorber (WA) to be limited to around 3.00 m.

The equipment nearest to the wave absorber is positioned at approximately 3.35 m from the back of the flume, so a small distance between wave absorber and equipment is present. In general, the wave absorber lay-outs can be presented as in figure 2.1.

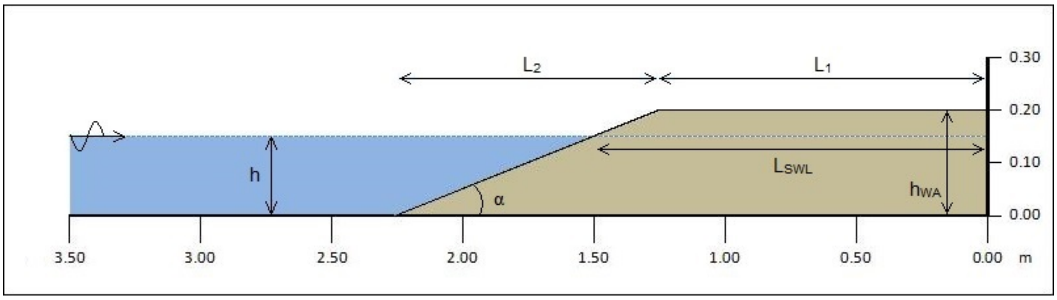


Figure 2.1: General wave absorber shape

The water level h has the value of 0.15 m, which is explained in chapter 4. The wave absorber slope ($\tan(\alpha)$) can vary in steepness and can be calculated by dividing the wave absorber height h_{WA} by the horizontal length of the slope L_2. The horizontal part of the wave absorber (L_1) is chosen to be around 0.20 m high, which is above the 0.15 m of the still water level (SWL). It is assumed that the waves will not get above the wave absorber

[1] PhD research by L. Phan Khanh on long wave penetration in mangroves

height, which is verified during the experiment runs in the flume. In practice, the slope is elongated a little (up to a total wave absorber height between 0.20 m and 0.25 m at the beginning of the horizontal part) to guarantee that there is no wave run-up higher than the slope length. The horizontal length at still water level is denoted as L_{SWL}.

To find appropriate values for the slope steepness, two methods can be used. Firstly the quick method of choosing a wave absorber length at still water level (L_{SWL}) of ¼ of the wave length can be used; the minimum wave absorber length can be calculated as ¼ of the (longest) wave length. In this method the slope can be chosen for a (calculated) horizontal length (at still water level). Secondly, the theory of Van Dongeren et al., (2007) can be used, which starts from the desired amount of reflection, from which the wave absorber slope can be calculated.

2.1.1 Method 1: Length of absorber

The first hypothesis that is tested, is that a longer wave absorber would yield less reflection. As the largest horizontal velocity occurs at ¼ wave length (L) from the back wall, most damping is expected for absorber lengths larger than ¼ wave length. In table 2.1 the wave lengths for each wave period are given for a water depth of 0.15 m, as well as ¼ of this wave length. These cover the range of conditions that are of interest.

Table 2.1: Wave lengths for various wave periods

	T = 1.2 s	T = 1.4 s	T = 1.6 s	T = 2.0 s	T = 4.0 s	T = 10.0 s
L_{15} (m)	1.35	1.61	1.86	2.37	4.82	12.12
¼ L_{15} (m)	0.34	0.40	0.47	0.59	1.21	3.03

It can be seen that for the longest waves (with wave period T = 10.0 s) the wave absorber should horizontally be around 3 m long at still water level to benefit from the wave absorber length in reducing reflection.

2.1.2 Method 2: Slope of absorber

Another hypothesis that is tested, is that a wave absorber with a more gentle slope would yield less reflection than a steeper sloped one.

Battjes, (1974) states that the type of wave breaking depends on the (dimensionless) Iribarren parameter ξ, which consists of the slope ($\tan(\alpha)$) on which the waves break, as well as the steepness of the breaking waves (the ratio between wave height H and deep water wave length L_0). In eq. (2.1) the Iribarren number is given. More details about the Iribarren number can be found in section 6.2.

$$\xi = \frac{\tan(\alpha)}{\sqrt{H/L_0}} \tag{2.1}$$

Although Battjes, (1974) used the deep water wave length and wave height, he found that his theory is also applicable inshore (for shallow water).

Van Dongeren et al., (2007) use the Iribarren number in their theory to calculate the reflection for long waves on various impermeable, smooth slopes. Although in this research permeable, rocky slopes are used, in the remainder of this section the theory of Van Dongeren et al., (2007) is used as a starting point to choose various wave absorber slopes to use in the physical modelling. The reflection for this research is therefore expected to be lower than calculated by the theory of Van Dongeren et al., (2007).

Starting with eq. (2.2) (with the first part from Battjes, (1974)), the amount of reflection R can be calculated from the Iribarren number, which can also be written as a function of the normalised bed slope parameter β_H. The function for β_H is given in eq. (2.3) (from Battjes, (2004)) and describes the relative depth change per wavelength; β_H is dimensionless.

$$R = 0.1\xi^2 = 0.2\pi\beta_H^2 \tag{2.2}$$

$$\beta_H = \frac{h_x}{\omega}\sqrt{\frac{g}{H}} \tag{2.3}$$

In eq. (2.3), h_x describes the bed slope ($h_x = \tan(\alpha)$, see figure 2.1), but is used in this research as the wave absorber slope (the bed slope is zero in the experiment set-up). Note that h_x is indeed a height when calculated with a horizontal length of 1.00 m. H is the incoming long wave height, and is set at 0.05 m for short waves and 0.03 m for long waves. The radial frequency ω of the low-frequency waves can also be written as $\omega = 2\pi/T$, with T the (chosen) wave period in s. For waves with a longer wave period the radial frequency is smaller, which results in a larger normalised bed slope parameter β_H (in which H stands for the wave height of the incoming long wave near the shoreline). A larger β_H-value gives a larger value for the reflection R (a value between 0 and 1). The Iribarren number ξ is calculated with the local wave length L_{15}.

Combining eq. (2.2) and eq. (2.3) gives the relation between the slope h_x and the reflection R, which is given in eq. (2.4).

$$h_x = \omega\sqrt{\frac{H}{g}}\sqrt{\frac{R}{0.2\pi}} \tag{2.4}$$

For a calculation of the slope h_x for all wave periods, the values for R are chosen as 0.1 (10% reflection), 0.3, 0.5 and 1.0 (100% reflection). For each wave length the corresponding slope is calculated and presented in table 2.2. A wave height of $H = 0.05$ m is used for all wave lengths, to make comparison between the results convenient. It can be seen that longer waves need a more gentle slope (and thus a longer wave absorber) to reach a certain maximum reflection value. Also, minimising the reflection leads to a more gentle slope.

Table 2.2: Values for h_x: Calculation of estimated required (smooth, impermeable) slope (h_x) as function of T and R, with H = 0.05 m

	T = 1.2 s	T = 1.4 s	T = 1.6 s	T = 2.0 s	T = 4.0 s	T = 10.0 s
R = 0.1	0.15	0.13	0.11	0.09	0.04	0.02
R = 0.3	0.26	0.22	0.19	0.16	0.08	0.03
R = 0.5	0.33	0.29	0.25	0.20	0.10	0.04
R = 1.0	0.47	0.40	0.35	0.28	0.14	0.06

In table 2.3 the same table can be seen, but here the values are given as the x-value of approximate 1:x slopes (compare the values in table 2.2 (h_x) and table 2.3 ($1/h_x$)). For the intermediate waves (T = 1.2 s to T = 2.0 s) a wave height of H = 0.05 m is taken, for the long waves (T = 4.0 s and T = 10.0 s) a wave height of H = 0.03 m is taken.

Table 2.3: Values for $1/h_x$: Calculation of estimated required (smooth, impermeable) slope ($1/h_x$) as function of H, T and R

	H = 0.05 m				H = 0.03 m	
	T = 1.2 s	T = 1.4 s	T = 1.6 s	T = 2.0 s	T = 4.0 s	T = 10.0 s
R = 0.1	6.71	7.82	8.94	11.18	28.86	72.14
R = 0.3	3.87	4.52	5.16	6.45	16.66	41.65
R = 0.5	3.00	3.50	4.00	5.00	12.91	32.26
R = 1.0	2.12	2.47	2.83	3.53	9.13	22.81

Slopes gentler than 1:15 are not considered as possible to use in the flume; either the total horizontal length needed is too large, or the length at SWL is too small. A solution to use it is to shorten the toe of the wave absorber.

From this analysis, the following slopes are chosen:

- 1:3; this is a very steep slope and absorption is expected to be very low. Most wave energy is reflected, according to the values in table 2.3.
- 1:5; this slope steepness results in much more reduction of the wave energy, especially for the shorter waves.
- 1:10; the wave energy is expected to be damped quite well with this value, especially for the shorter waves.
- 1:15; many waves are expected to be damped to 10% with this value.

The calculated values for h_x apply to impermeable, smooth slopes. In this research the wave absorber is constructed from rock, which makes the slopes rough and permeable; therefore a lower amount of reflection is expected.

2.2 Wave absorber height: run-up

The run-up R_u on a slope can be calculated for smooth slopes as in eq. (2.5) (from Schiereck, (2012)), which is expressed as a function of β_H in eq. (2.6).

$$\frac{R_u}{H} = \xi \tag{2.5}$$

$$R_u = H\xi = H\sqrt{2\pi}\beta_H \tag{2.6}$$

Slopes with a rough surface give values which are approximately half of those found with eq. (2.6). Assuming a reflection of 100% (R=1), the β_H-value calculated with eq. (2.2) is 1.26 and with waves of H = 0.05 m the run-up is 0.16 m for a smooth slope. In reality a rougher, permeable slope is used, so for a water level of 0.15 m a wave absorber height increasing up to 0.20 to 0.25 m is considered sufficient.

Reflection analysis methods

3

Various methods can be used to calculate the reflection in a flume, each with one or more implementations to practically analyse (experiment) data. As these implementations all use a different way to get to results, their outcomes also vary. It is important to know how accurate the outcomes are, so that effectivity (the preciseness of the outcome) and efficiency (the ratio between the reliability of the outcome and the needed length for the equipment set-up, the effort of analysis, etcetera) of the methods can be compared.

The reason for comparing all implementations in such detail is to know whether they are reliable. The initially obtained results from the experiment data (see chapter 5) were odd, which made it necessary to examine the process of data analysis in more detail.

In this chapter the used methods and implementations are discussed and their reliability is evaluated. To do this, a synthetic signal is made, of which the input parameters are known. With the outcomes of the reflection implementations it can be seen whether an implementations is reliable.

3.1 Methods and implementations

There are various methods to calculate reflection. In this section the reflection methods that are used in this research to base implementations on are described. In appendix A more details about these methods can be found.

Guza et al. (WG+EMF)
This method uses a wave gauge and an EMF at one certain location. With the combination of the wave height and the horizontal water velocity the wave signal can explicitly be separated into an incoming and a reflected wave signal. Herewith the amount of reflection can be calculated. The basic method is described by Guza et al., (1984) and its equations are given in appendix A. As only two parameters are measured, there is no possibility to separate noise from the signal. The incoming and reflected waves are assumed to be free waves.

Goda and Suzuki (2 WG)
A method using two wave gauges is developed by Goda and Suzuki, (1976). Using the wave height data from two locations at a certain distance from each other (depending on the wave length), the wave signal can be separated into an incoming and a reflected signal. Also in this method the noise can't be isolated, but is divided over the signals.

Mansard and Funke (3 WG)
A method using three wave gauges is developed by Mansard and Funke, (1980), as an extension to the two wave gauge method of Goda and Suzuki, (1976). The wave height data from the three WG's can be separated into an incoming signal and a reflected signal, using a

least squares method. In comparison with the two wave gauge method, this method has a reduced sensitivity to noise.

Zelt and Skjelbreia (2^+ WG)
A generalised method using two or more wave gauges is developed by Zelt and Skjelbreia, (1992); for its equations see appendix A. Using their method with two wave gauges gives the theory of Goda and Suzuki, (1976); using it with three wave gauges results in the theory of Mansard and Funke, (1980). When this method is used with three or more wave gauges, the sensitivity to noise can be reduced, compared to using only two wave gauges.

3.1.1 Implementations

The methods can be put into practice using various Matlab scripts; each of the scripts is referred to as an implementation. In this research, the following implementations are used:

- The combination of a wave gauge and an EMF, according to the theory of Guza et al., (1984). In further references to this script, it is mentioned as 'WG/EMF'.
- An implementation script written to separate incoming and reflected waves using the data of three wave gauges, according to the method of Mansard and Funke, (1980). In further references to this script, it is mentioned as 'MF'.
- A matlab script designed to separate regular waves into incoming and reflected waves, using the data of two or more wave gauges. With these two parts the reflection can be determined. In further references to this script, it is mentioned as 'Rx', with x the number of wave gauges used. It is based on the theory of Zelt and Skjelbreia, (1992).
- A matlab script designed to separate irregular waves into incoming and reflected waves. With these two parts the reflection can be determined. It is based on the theory of Zelt and Skjelbreia, (1992) and can be used for two or more wave gauges. In further references to this script, it is mentioned as 'Ix', with x the number of WG's used.
- There is no script used specifically for Goda and Suzuki, (1976).

This results into the use of eight implementations in total. An overview can be found in table 3.1, in which the methods mentioned in section 3.1 are abbreviated as 'Guza' for Guza et al., (1984), 'G&S' for Goda and Suzuki, (1976), 'M&F' for Mansard and Funke, (1980) and 'Z&S' for Zelt and Skjelbreia, (1992), which itself is devided into regular (re) and irregular (ir) implementations.

Table 3.1: Reflection implementations for various methods

	Method				
	Guza	G&S	M&F	Z&S	
Equipment				re	ir
WG+EMF	WG/EMF				
2 WG		-		R2	I2
3 WG			MF	R3	I3
4 WG				R4	I4

3.1.2 Equipment for experiments

In combination with the equipment positions used during the experiments (see appendix B and figure 4.1, with more information about the bottom profile in section 4.2.1) the following possibilities of measuring the reflection exist:

- WG/EMF: There are seven EMF's placed next to a wave gauge in the experiments, so there are also seven locations to calculate the reflection with this implementation. Using these combinations along the flume also gives insight into the progression of the amount of reflection along the flume.
- 2 WG: At three locations in the flume wave gauges are spaced such that they are at equal distances (and therefore comparable): at the back of the flume near the wave absorber, at the front of the flume and just after the slope of the bottom profile. For intermediate water depth (intermediate waves) and shallow water depth (long waves) the exact combination of WG's differ: the WG spacing for intermediate water waves can be smaller than that for shallow water waves, so that for each location at least three WG's are necessary. This is the case for all three locations.
- 3 WG: At all three mentioned locations where three WG's are placed, the spacing is adequate to be used for reflection analysis of intermediate waves. However, the long waves need a longer distance, so for these waves it is not possible to use the locations in the middle and at the front of the flume. At the back of the flume an additional WG provides the possibility for adequate spacing for long waves.
- 4 WG: At the back of the flume the method of using four wave gauges can be used, for both intermediate and long waves, which also here require a different spacing. In the middle and at the front of the flume only three WG are present, so that it is not possible to calculate the reflection at these locations.

The focus of the reflection calculation for the experiment data is near the wave absorber. For the other locations no results are given.

3.1.3 Expectations

It is expected that the more measurement signals are used, the more accurate the results are. In this research the maximum number of wave gauges is four, as there is only a limited amount of equipment available to perform experiments in the flume. It is expected that the methods using three or four wave gauges are more accurate than those using two wave gauges or a combination of a WG and an EMF, because for three or more wave gauges the sensitivity to noise can be reduced. Also, Zelt and Skjelbreia, (1992) state that using four or more wave gauges in their approach increases the accuracy of the outcome, which holds for wave data with a wide spectrum in particular. The wave spectra in this research are narrow (regular waves with one wave length; no breaking of the waves but dispersion is in some experiment cases present), it is expected that the results using four WG's will not differ much from the results using three WG's.

It is also expected that the results of the implementations of WG/EMF and R2 are comparable to each other, as both implementations use two measuring instruments to come to an answer, and therein don't have the possibility to separate noise. Also the results of the implementations of MF and R3 are expected to be comparable to each other, as both implementations use three WG's.

3.2 Synthetic signal considerations

The various implementations to analyse the reflection (K_r) in the flume from the data need to be evaluated in their effectiveness and reliability, so that it is known how accurate their results are. Therefore a synthetic signal is made, which consists of a regular wave signal and added random noise. This wave signal consists of a wave height part and a velocity part, just as the data series measured during the experiments. The wave height H, wave period T, percentage of reflection R and signal-to-noise ratio SNR (SNR = 1/noise) can be varied as input.

3.2.1 Assumptions and requirements

The following assumptions are made for creating synthetic signals:

- Over the whole flume length, which is 37.5 m, every 2.5 m a data point is chosen, in order to get more details about what happens along the entire flume length. Additionally, the WG locations as used during the experiments are added to these data points. This results in the following data points, with X the distance in m of the data point from the beginning of the flume:

X = [	0.00	2.50	5.00	6.00	6.40	7.50	10.00	12.50	14.15	15.00	...
	15.15	15.55	17.50	20.00	20.25	22.50	24.50	25.00	27.50	28.85	...
	30.00	32.50	32.85	33.85	34.10	34.25	35.00	37.50	]		

  For each data point a wave signal as well as a velocity signal is created.
- The bottom slope of the 'foreland' (see section 4.2.1) is not taken into account so that over the whole flume length the water depth is 0.15 m.
- The 'measuring of the velocity' with the EMF's is done at a depth of 0.10 m (measured from the still water level downwards), which is 0.05 m above the bottom level of the flume. This is comparable to the measuring heights of the EMF's at the elevated bottom profile during the experiments.
- Assumed is that 0.01% noise (SNR = 1/0.0001 = 10,000) is a reasonable value in the wave flume of the Stevin III laboratory. More details about the noise level in the lab can be found in section 5.3. Besides the actual noise in the signal, also other sources of noise are present: for example due to damping or to an error in the phase velocity. Therefore it is estimated that for the total noise in the flume an amount in the order of 1% is realistic.
- The reflection in the laboratory is estimated to lie around 30% for the experimental runs (R = 0.30 as main input value).
- Only regular waves are taken into account.
- No friction is taken into account during these synthetic signals.
- Assumed is that linear wave theory is valid.

After validation and verification of the implementations, they can be used to analyse the experimental data.

3.2.2 Parameters

The variables to take into account for creating the synthetic signals are the wave conditions (H, T), the amount of reflection (R) and the amount of noise, in the form of the signal-to-noise ratio (SNR).

Wave conditions

The chosen wave conditions can be found in table 3.2. They give a wide range in wave period (intermediate to long waves) and wave height (very small to medium) and are comparable to those used during the experiments.

Table 3.2: Overview of wave conditions for synthetic signal

	T (s)									
H (m)	1	2	3	4	5	6	7	8	9	10
0.01						x				x
0.02		x				x				
0.03										
0.04										
0.05		x								x

Reflection

The reflection values used for the synthetic signals are chosen as $R = 0\%$ (to check whether the method works), 1%, 2%, 3%, 4%, 5% (for more detailed insight in this area), 10%, 15%, 20%, 25% (for general insight of the amount of estimated reflection), 40%, 60%, 80%, 100% (to make the reflection comparison completer).

Signal-to-noise ratio

The signal-to-noise ratio compares the power of a signal to the power of background noise, but can also be described as the ratio between the variances σ^2 of the signal and the noise, see eq. (3.1).

$$\text{SNR}= \frac{\sigma^2_{signal}}{\sigma^2_{noise}} \tag{3.1}$$

Another way of formulating is the use of the SNR in dB, which can be calculated as in eq. (3.2).

$$\text{SNR}_{\text{dB}} = 10\log_{10}(\text{SNR}) = 10\log_{10}\frac{\sigma^2_{signal}}{\sigma^2_{noise}} \tag{3.2}$$

In table 3.3 the values of SNR (input) and SNR_{dB} (calculated with eq. (3.2)) are given. It can be seen that a higher SNR value implies less noise. For the testing of the methods, only SNR-values for 0.001% to 1% noise are used as these are expected to be most realistic to be found in the flume. The calculation for the actual noise value in the flume during experiments can be found in section 5.3.

Table 3.3: Signal-to-noise ratio

Noise (%)	SNR	SNR_{dB}
0.001	100,000	50.00
0.01	10,000	40.00
0.1	1000	30.00
0.5	200	23.01
1	100	20.00
2	50	16.99
5	20	13.01
10	10	10.00
20	5	6.99
50	2	3.01
100	1	0.00

3.3 Validation: synthetic signal runs

The implementations are tested with various synthetic signals. At first, a synthetic signal without noise ('clean signal') is run, to see if the implementation works. Then, the values for SNR and R are varied.

It is found that the wave condition is not of significant influence on the outcome of K_r, especially the wave height. Therefore it is chosen to use only one wave condition for all synthetic signal runs (H01T60). The 'measuring height' for the velocity signal is 0.10 m below the still water level (0.05 m above the elevated bottom profile), but a height of 0.05 m below the still water level gives no significant differences. In this section, friction is not taken into account. Adding an extra term into the synthetic signal that describes friction would make it possible to do so.

In all of the following analyses all three options of the script for irregular waves (I2, I3, I4) give an error, so no K_r-value can be determined. This could be caused by having too regular waves to perform calculations with an irregular waves script or by an error in the script.

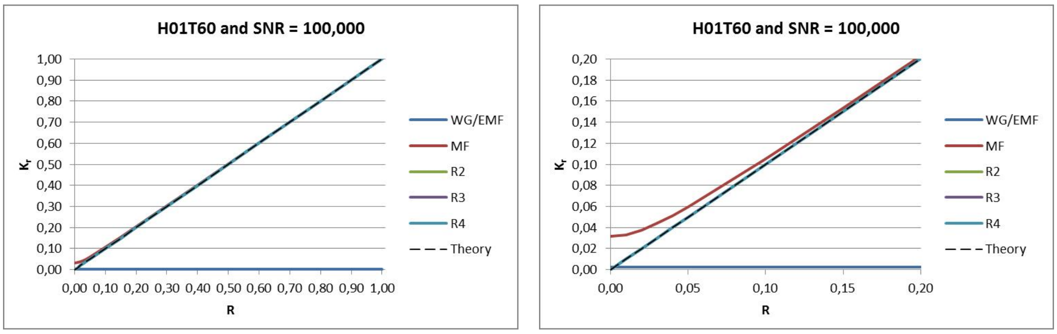
3.3.1 Comparisons

1. No noise, no reflection
At first, a synthetic signal without noise ('clean signal') is run for all six before mentioned wave conditions, to see if the implementations work. The input reflection is set to $R = 0\%$, which results in an unreflected, regular wave with a given H and T. If the implementation returns these values (K_r), it works. As there is no noise, also no signal-to-noise ratio is needed, so SNR is infinitive (in practice: skipped).

For the WG/EMF-implementation the amount of (output) reflection (K_r) is negligible (in the order of 0.1%). For the MF-implementation the reflection is higher, but still negligible (in the order of 1%). R2 is in the order or 5E-6, R3 and R4 both in the order of 3E-5. Concluding, the implementations for WG/EMF, MF and the three inmplementations for regular waves (R2, R3, R4) work well for a clean signal. No abnormalities are found in them, and they can be used in further testing.

2. Varying input reflection R for several values of signal-to-noise ratio SNR
For several values of SNR the output reflection K_r is plotted against the input reflection R. It is expected that the amount of output reflection equals the amount of input reflection: $K_r = R$. For the signal-to-noise values SNR = infinite (no noise), SNR = 100,000 (which means a noise level of 0.001%), SNR = 10,000 (0.01% noise), SNR = 1000 (0.1% noise) and SNR = 100 (1% noise) this analysis is made. For SNR = 100,000 the results are given in figure 3.1. It can be seen that the implementations for R2, R3 and R4 follow the theoretical line of $K_r = R$ very well. For low values of R, the MF-implementation overestimates K_r but from approximately R = 0.15 the theoretical line is followed much closer. The results for the WG/EMF-implementation lie very low (K_r is a constant, very low value) and are therefore not reliable for this amount of noise.

For the other SNR-values there is no significant difference found: for all signal-to-noise levels R2, R3 and R4 follow the theory very well, MF gives higher K_r-values for low values of R and WG/EMF gives a constant low K_r-value. The only difference between the cases is that this constant value becomes higher for a lower SNR-value (thus more noise).



(a) Full reflection range **(b)**Zoomed in to 20% reflection

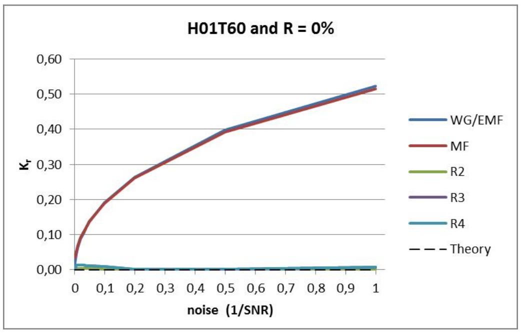
Figure 3.1: K_r-values as function of R for SNR = 100,000

3. Varying signal-to-noise ratio SNR for several values of input reflection R
When SNR as a function of R is varied for wave condition H01T60, it can be seen that the implementations of both WG/EMF and MF give unreliable results, and R2, R3 and R4 approach the theoretical value much better. The influence of the noise is given in figure 3.2a for R = 0.00, in figure 3.2b for R = 0.20, in figure 3.2c for R = 0.30 and in figure 3.2d for R = 0.40. The theoretical values should lie on a constant line at the value of the analysed R. Figure 3.2 also shows that for MF, the K_r-values for 0% noise is accurate, but is no longer correct when adding noise.

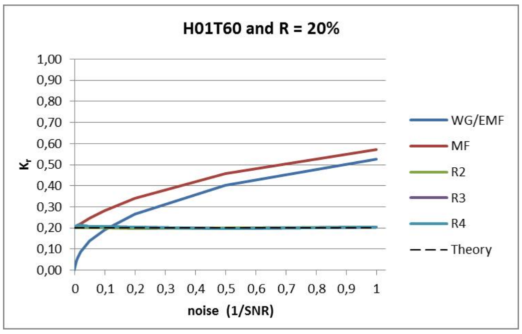
3.3.2 Remarks and preliminary conclusions

For the analysis of the calculated K_r-values with synthetic signals, there are some point to discuss.

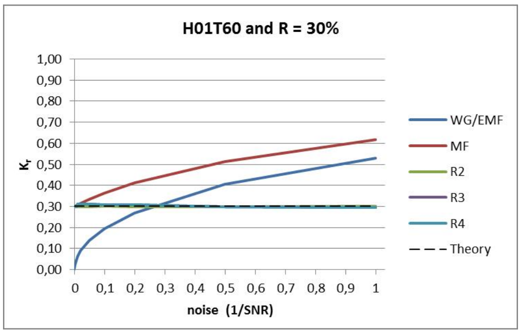
Sometimes an implementation gives a deviating result, which is often very obvious to see (for example: a K_r-value of 2). This is caused by the random noise that is added to the clean signal. It can be solved by recreating the signal (preferably at least twice for certainty) and analysing it to see if the error no longer occurs. It is expected that for the experiment data (chapter 5) this is no problem, but it is important to be aware of it.



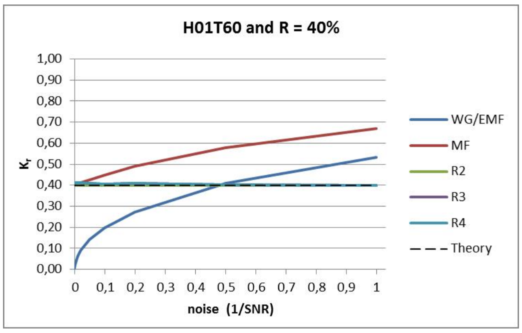
(a) K_r as function of SNR, for $R = 0$



(b) K_r as function of SNR, for $R = 0.20$



(c) K_r as function of SNR, for $R = 0.30$



(d) K_r as function of SNR, for $R = 0.40$

Figure 3.2: K_r-values as function of SNR, for each reflection implementation and $R = 0$, 0.20, 0.30 and 0.40

In figures 3.1 and 3.2 it can be seen that R2, R3 and R4 return K_r-values that compare well to the given input of R, relatively and absolutely. The results for R3 and R4 are very similar and overlap in the comparing figures. Therefore R4 is not taken into account in further analysis; more equipment and a longer distance are needed to get the same results as with R3.

Both R2 and R3 work well. R2 gives better results than R3, but this might be due to the very narrow spectrum that is used in this analysis: the analysed signal is a synthetic one, which is much more regular than the experimental signals with the same wave conditions. In the flume also the influence of the foreland has to be taken into account, which can cause wave deformations. Assumed is that these deviations with respect to the synthetic signals can be taken care of better with R3, which uses an additional wave signal for its analysis.

The MF-implementation tends to overestimate the reflection value ($K_r > R$). For WG/EMF the outcome depends on both R and SNR, but it is unclear in what way; this implementation is considered too unreliable. Both MF and WG/EMF will therefore not be taken into account in further analyses.

The implementation for irregular waves doesn't work for the used synthetic signals, and is therefore not used in the analysis of the experimental data.

4 Experiment setup

The research question described in chapter 1 is studied by conducting experiments in the wave flume of the Stevin III laboratory (TU Delft) and analysing their results. In this chapter the setup for the experiments is described, and in chapter 5 the experimental results are given. The goals of these experiments are to find an optimal wave absorber lay-out for the given available flume length, and to compare the various reflection implementations with experimental data.

The experiments conducted for this research can be divided into two parts. From the first part, conclusions are drawn which are very helpful for setting up the second part; it forms the basis for the measurement plan of the experiments used for the research on reflection. The experiment setup and approach for the first part of the experiments can be found in appendix C. In this chapter only the setup and approach of the second part are described, as this is the part which is used for the research on reflection.

4.1 Starting points

About the first series of experiments (described in appendix C) the following conclusions and points of adjustment are made:

Non-uniformly breaking waves and upcoming water
To model the foreland and relatively shallow area where the 'mangroves' will be placed in subsequent research, a built-in bottom profile is constructed in the flume. During the first experiments it is found that the sides of the bottom profile are not closed off properly, which results in water coming up along the sides as the waves move along the flume length. Especially for the longer wave periods, in between two wave crests, this is clearly noticeable. Also, waves started breaking at the sides of the crests, while the middle of each crest broke some time later. This breaking pattern was thought to be caused by this upcoming water. Indeed the non-uniformity of the breaking waves decreased after closing off the sides of the bottom profile: the crests were more stable, although not all of the effect was eliminated.

3D-effects due to the shape of the wave absorber
In these first experiments two types of wave absorber fronts were modelled: slopes and berms. It was seen during the experiment runs that wave crests could be a little 'wobbly': shifting of the crest perpendicular to the travelling direction. It is assumed that this (and perhaps other) 3D-effect appears when the wave absorber front is not straight enough relative to the cross-section of the flume. Therefore, in the following experiments extra care is taken to construct the front of the wave absorber.

Number of experiment runs per lay-out
For each lay-out a number of experiment runs was performed, varying between two (for

checking a changed parameter) and ten (for one lay-out which was intended as a reference case). This amount of runs was found to be too low to make a proper comparison and subsequent conclusions possible. Especially taking the other points into account: adjusting the bottom profile (closing off the sides) appeared to have a much larger impact than expected on beforehand. Therefore, in the second series of experiments great care is taken to design the approach in such a way that only one parameter is changed at a time, and that there are enough runs per lay-out that can be compared to those of other lay-outs.

Water level
In the first series of experiments a water level of 0.10 m was used. For some wave conditions it could be difficult to measure the desired input at this level, and therefore the water level is increased to 0.15 m at the elevated part of the bottom profile (see figure 4.1). This results in more stable and easier to measure waves.

4.2 Experiment setup

4.2.1 Flume and profile

The dimensions of the wave flume to model a mangrove forest physically for this research are approximately 40 m long, 0.80 m wide and it can be filled to around 1.50 m. At one end of the flume a wave paddle can create waves; at the other end of the flume a deeper outflow section is present. For these experiments, the outflow section and the flume are separated with a (closed) wooden plate, which reduces water exchange to a minimum.

To model the foreshore, which is a very gentle slope, an elevated bottom profile is created, which is 0.50 m higher than the original bottom. The transition between both bed levels consists of a slope of 1:10 from the original bed level, towards a slope of 1:20, to the elevated bottom. This profile can be seen in figure 4.1 in which the wave paddle is at the left (not shown); generated waves travel through the flume to the right. The outflow section is not shown here but is positioned at the right side of the figure. The experiments for this research are only performed on an 'empty' bottom profile. No 'mangroves' (which can be modelled by wooden sticks) are placed, which enables to measure the reflection without obstacles and extra effects, such as deviant flows induced by the sticks.

4.2.2 Wave conditions

The focus of these experiments lies on regular waves (Re), in particular longer waves, in a water depth of 0.15 m on the elevated bottom profile (d_{15}), which is 0.65 m at the beginning of the flume (d_{65}). For these conditions, the combinations of the chosen wave heights (H) and wave periods (T) are given in table 4.1 and given as codes in table 4.2. These values for wave height and wave period are as specified for the wave paddle, which generates the waves in a water depth of 0.65 m. By shoaling the waves deform, and the resulting (scaled) wave conditions are representative for the Vietnamese coast. Not all wave conditions are run for each wave absorber lay-out (see section 4.2.5). In table E.1 is given which conditions are run for each lay-out.

Table 4.1: Wave conditions (used wave heights per wave period)

	T (s)									
H (m)	1.2	1.4	1.6	2.0	2.5	3.0	4.0	6.0	8.0	10.0
0.01								x	x	x
0.02			x	x		x	x	x		
0.05	x	x	x	x	x					

Table 4.2: Wave conditions (codes)

$H = 0.05$ m	$H = 0.01$ m	$H = 0.01$ m
ReD65H05T12	ReD65H02T16	ReD65H01T60
ReD65H05T14	ReD65H02T20	ReD65H01T80
ReD65H05T16	ReD65H02T30	ReD65H01T100
ReD65H05T20	ReD65H02T40	
ReD65H05T25	ReD65H02T60	

4.2.3 Equipment positions

The wave gauges (WG) and electromagnetic flow meters (EMF's) are placed at the locations given in table 4.3. In figure 4.1 the equipment positions are plotted (note that the horizontal and vertical scale are not the same). The calculation of the equipment positions can be found in appendix B.

Table 4.3: Locations of WG's and EMF's, distances in m from the wave paddle

# WG	# EMF	Location WG (m)	Location EMF (m)
1	1	5.00	5.00
2		6.00	
3		6.40	
4	2	14.15	14.15
5		15.15	
6		15.55	
7	3	20.25	20.25
8	4	24.25	24.25
9	5	28.25	28.85
10	6	32.85	32.85
11		33.85	
12		34.10	
13	7	34.25	34.25

4.2.4 Calibration

The wave gauges need to be calibrated before data can be analysed. For the method of calibration, see appendix D.

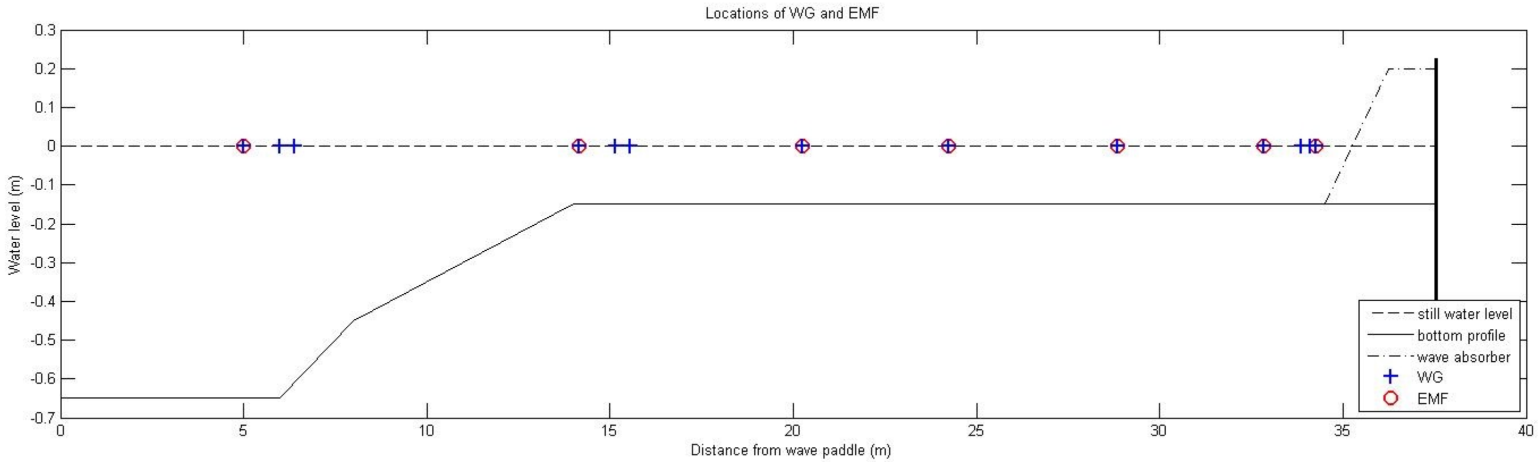


Figure 4.1: Locations of the wave gauges and EMF's along the flume

4.2.5 Wave absorber lay-outs

The wave absorber (WA) lay-outs vary in slope steepness, length and front. For the slope, steepnesses of 1:3, 1:5, 1:10 and 1:15 are used; the choice of these slopes is explained in section 2.1. For most of the lay-outs the length at still water level (SWL) is chosen to be 1.50 m, so that this length is not a varying parameter. The changes at the front of the wave absorber consist of cutting the slope off at certain heights above the bottom. For all lay-outs the water depth for the runs is 0.15 m (0.65 m at the beginning of the flume). In table 4.4 the details for all lay-outs are given, and in figures 4.2 to 4.9 a side view of all lay-outs are shown (all measurements are given in m; note that the horizontal and vertical lengths are not at the same scale). The given figures are schematic; for most lay-outs the horizontal length of the top of the wave absorber is slightly lower than the given 0.20 m, but still higher than 0.15 m. The front of the wave absorber is for all lay-outs 0.20 m or might be slightly higher; the breaking waves and the run up however never reach above approximately 0.20 m. Great care is taken to make the slope as straight as possible, without undulations but also without flattening the surface too much, as both have influence on the wave reflection. For all given lay-outs the back of the flume (above the built-in bottom) is closed off.

Table 4.4: Wave absorber lay-outs

Name	Lay-out	Slope	Toe height (m)	Length at SWL (m)	Total length (m)	Figure
Reference	A					4.2
WA 1:3 (short)	B	1:3		1.50	1.95	4.3
WA 1:5	C	1:5		1.50	2.25	4.4
WA 1:10	D	1:10		1.50	3.00	4.5
WA 1:3 (long)	E	1:3		2.55	3.00	4.6
WA 1:10, toe 5cm	F	1:10	0.05	1.50	2.50	4.7
WA 1:10, toe 7.5cm	G	1:10	0.075	1.50	2.25	4.8
WA 1:15, toe 5cm	H	1:15	0.05	1.50	3.00	4.9

4.2.6 Experimental runs

In section 4.2.5 the wave absorber lay-outs are presented in order of decreasing slope steepness and extra details. In practice, this order is not the most convenient way to construct the wave absorbers; therefore a different sequence is used during the experiments, which is described in appendix E.

4.3 Expectations

In advance of the experiments, the following is expected:

- On a vertical wall the reflection is highest. When the wall is perfectly vertical, and no friction along the bottom or leakage along the wall are present, from theory it can be expected that there is 100% reflection. Also a standing wave pattern can be expected. Of course, in the experiments friction has significant influence, so the waves shall be damped out during traveling from measuring point to wall and back to the same measuring point, so the reflection lies lower.

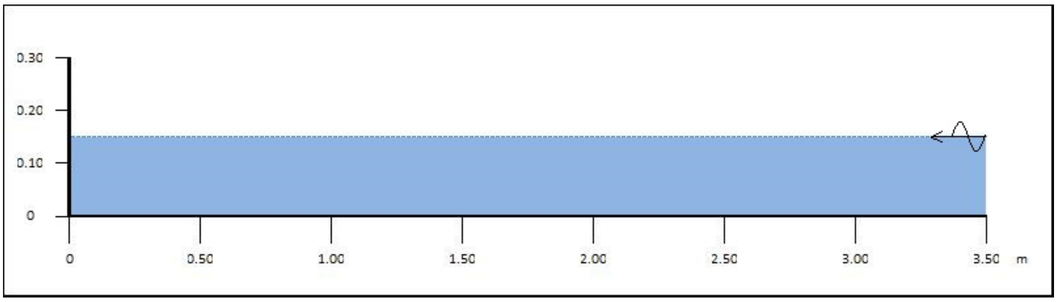


Figure 4.2: Lay-out A: Empty flume

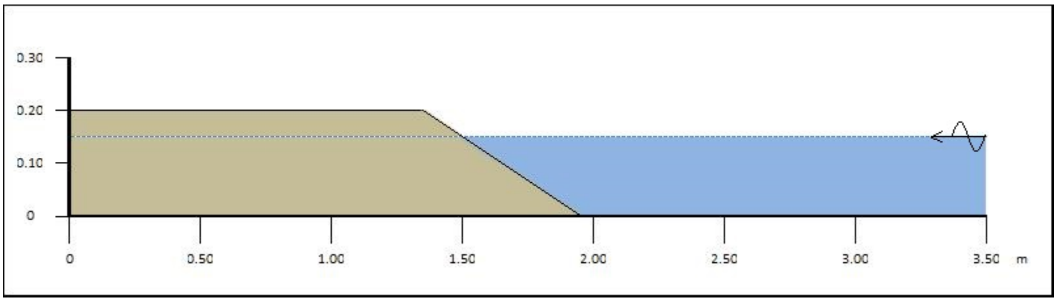


Figure 4.3: Lay-out B: Wave absorber with a 1:3 slope and length at SWL of 1.50 m

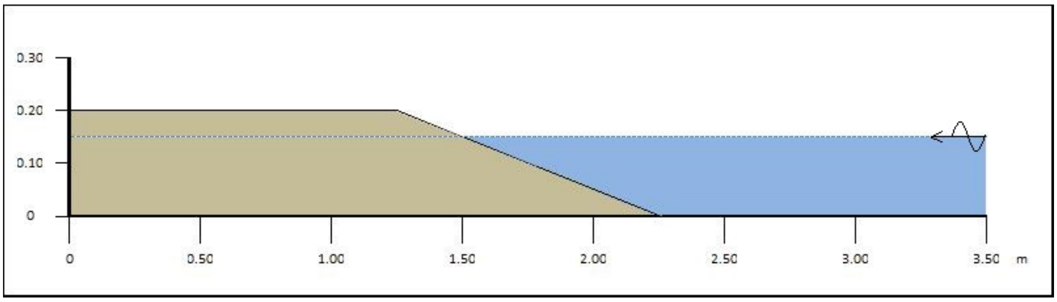


Figure 4.4: Lay-out C: Wave absorber with a 1:5 slope and length at SWL of 1.50 m

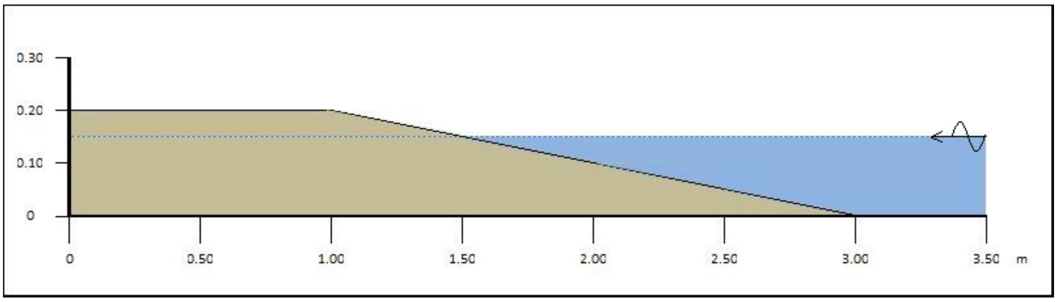


Figure 4.5: Lay-out D: Wave absorber with a 1:10 slope and length at SWL of 1.50 m

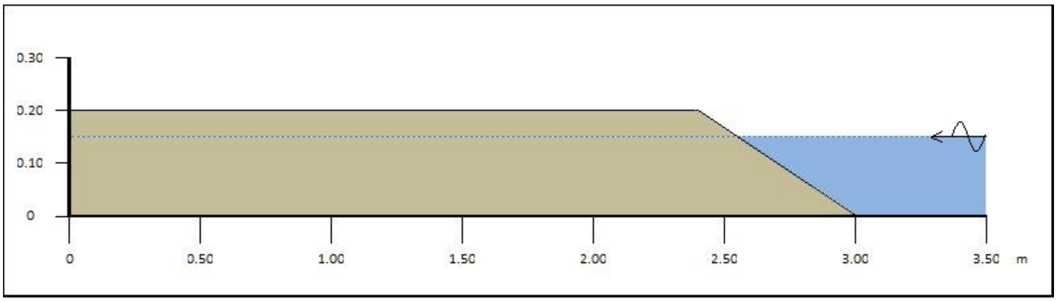


Figure 4.6: Lay-out E: Wave absorber with a 1:3 slope and bottom length of 3.00 m

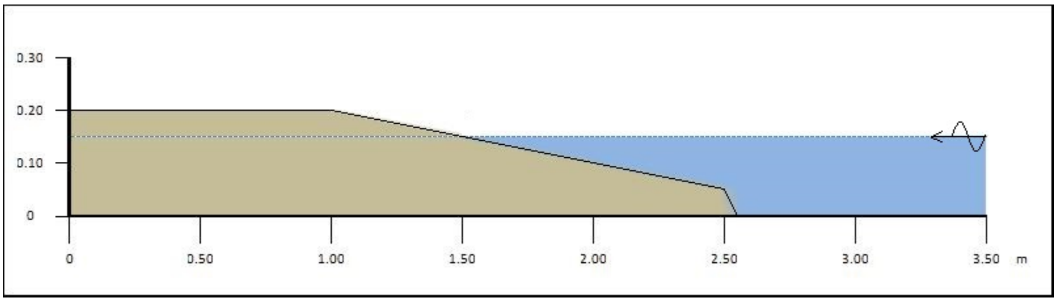


Figure 4.7: Lay-out F: Wave absorber with a 1:10 slope and length at SWL of 1.50 m, with a toe shortened at 0.05 m height

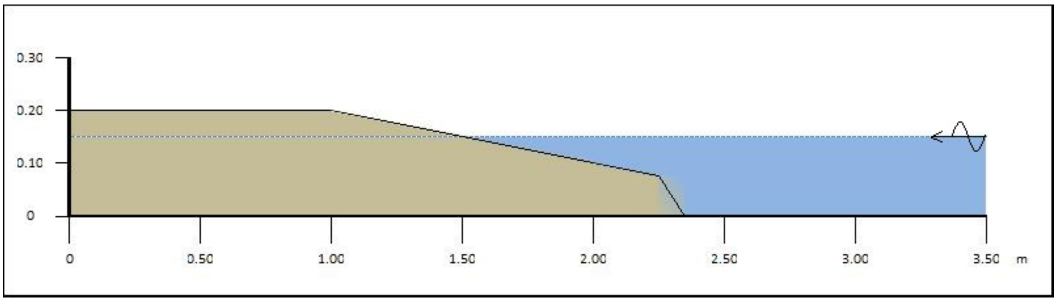


Figure 4.8: Lay-out G: Wave absorber with a 1:10 slope and length at SWL of 1.50 m, with a toe shortened at 0.075 m height

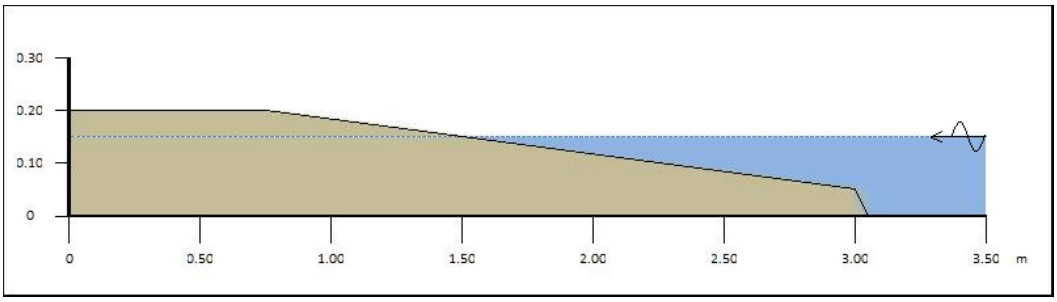


Figure 4.9: Lay-out H: Wave absorber with a 1:15 slope and length at SWL of 1.50 m, with a toe shortened at 0.05 m height

- A more gentle slope will reduce the reflection more than a steeper slope. On a gentle slope waves have more time and distance to break, and thus to lose their energy.
- A longer wave absorber is expected to result in less reflection than a shorter wave absorber with the same slope. For the longer wave absorber waves lose more energy than for shorter lengths.
- Cutting off part of the wave absorber toe results in more reflection, as for most of the chosen wave conditions the 0.15 m depth can be seen as shallow or intermediate water and they will therefore 'feel' this adaptation.

5 Experimental results

After calibrating the equipment used in the flume (WG's and EMF's) and running the experiments, the data is analysed using Matlab. As was found in chapter 3, the implementations of Zelt and Skjelbreia for regular waves with two and with three wave gauges (R2 and R3) seem most reliable. During the analysis of the experiment results for this chapter, it was found that the implementation of R3 gives a more complete dataset of results (see section 5.1) and is therefore chosen to use.

The experiments are carried out in two parts, as mentioned in chapter 4. After running and analysing the first part of the experiments, several adaptions in setup and runs are made, based on the conclusions that are drawn from these first experiments. More details can be found in appendix C. The runs carried out in the second part of the experiments are used for the analysis and calculations to find an optimal wave absorber lay-out for the given available length, as described in the following sections and chapters.

5.1 Remarks on experimental runs

Before discussing the results of the second series of experimental runs, a few general remarks are made:

- In the cases that a wave condition has multiple values (when the wave condition is run several times for a certain wave absorber lay-out), the average value is taken.
- In some cases, especially for certain wave conditions, both R2 and R3 return the K_r-value to a value higher than 1. For these runs the calculated wave length T is lower than the input value of T. The cause for these deviating values might be unstable waves, dispersion or a wave length that does not fit well within the used wave gauge distances. These deviating values are not usable and are therefore left out, resulting in a few gaps in the data. For the wave conditions H05T25 (which is run for three lay-outs) and H02T40 (run for eight lay-outs) all runs give unusable K_r-values. For the wave conditions close to these two mentioned conditions, the results also seem less stable: for H05T20 almost half of the values can't be used; for H02T30 no values for R3 are usable and for H02T60 almost no values for R2 are usable.
- As can be seen in appendix E, the wave absorber lay-out with a 1:10 slope (without shortened toe, see figure 4.5) is run twice. Not all runs can be compared because they are not run for both cases, but those that can give similar results. It is important to know this: on the first version of this lay-out (case 5 in appendix E) all wave conditions are run, and the results can be compared to all other cases. On the second version (case 8) less wave conditions are run; this version is newly constructed and used as a basis to construct lay-outs F (figure 4.7) and G (figure 4.8).

5.2 Results

5.2.1 Influence of length at SWL

Two wave absorber lay-outs have a slope of 1:3, but differ in length at SWL: for one lay-out the total length of the wave absorber is 3.00 m, which gives a length at SWL of 2.55 m (lay-out E, see figure 4.6 and case 4 in appendix E), and for the other lay-out the length at SWL is 1.50 m (lay-out B, see figure 4.3 and case 6 in appendix E). By comparing the reflection results for these lay-outs, it can be seen whether the length at SWL has influence on K_r. In figure 5.1 the results are compared for the R3-implementation.

Due to the unusability of some data points, not all wave conditions have values to compare, even though all wave conditions are run for both lay-outs. For most wave conditions that can be compared, it seems that there is not a large difference in values; the short lay-out is slightly better in reducing wave energy than the elongated version, which makes the short lay-out a better option to choose, as it saves space.

The lack of difference could be explained by stating that there is indeed no difference between the lay-outs, if shorter waves are damped over a distance shorter than 1.50 m (the length at SWL for the shortest absorber) and longer waves don't damp significantly more over a distance longer than 2.55 m (the length at SWL for the longest absorber). Therefore it doesn't matter which of these two lay-outs to use. It is also a possibility that the evanescent modes influence the outcome.[1] The waves are more likely to fall in the 'active' range for the long wave absorber lay-out, and not any more for the short lay-out.

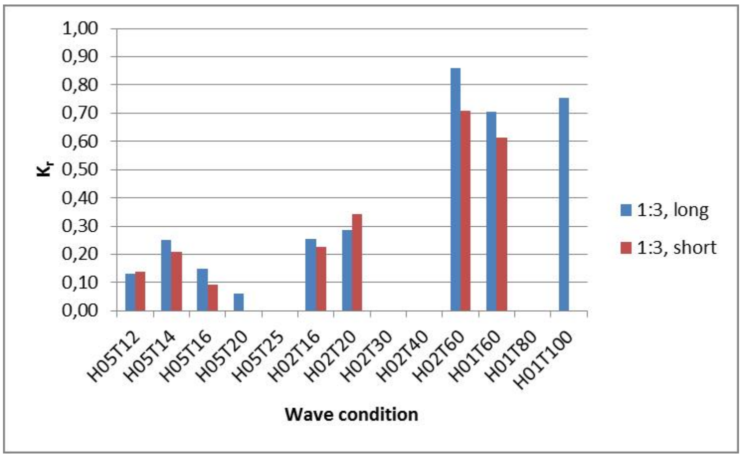


Figure 5.1: Comparison of the results for runs 4 and 6 (both with a 1:3 slope wave absorber, but different in length), for implementation R3. K_r on the vertical axis

5.2.2 Influence of shortening the wave absorber (creating a toe)

For the runs of lay-outs D (figure 4.5, case 8 in appendix E), F (figure 4.7, case 9) and G (figure 4.8, case 10) the slope of the wave absorber is 1:10 and the toe decreases, to see the influence of a shortened wave absorber. The results of these three runs are compared to

[1] Evanescent waves can occur alongside reflection. The energy of evanescent waves decays exponentially with distance. For the scope of this research it is not relevant to go into more detail on this subject.

those of lay-out H (figure 4.9, case 11), which has a more gentle slope (1:15) but also has a shortened toe. In figure 5.2 the results of the experiment runs are given for implementation R3. It can clearly be seen that for all runs with a 1:10 slope wave absorber the lay-out which is complete (lay-out D) gives the least amount of reflection, and with decreasing toe length the K_r-value increases. Comparing the 1:10 slopes with the 1:15 slope, the more gentle slope is more effective in reducing K_r for the longer wave periods with a lower wave height, despite the length reduction. For wave conditions with a lower wave period and higher wave height, the benefit in K_r-reduction is less, but it is also difficult to draw conclusions due to the lack of data.

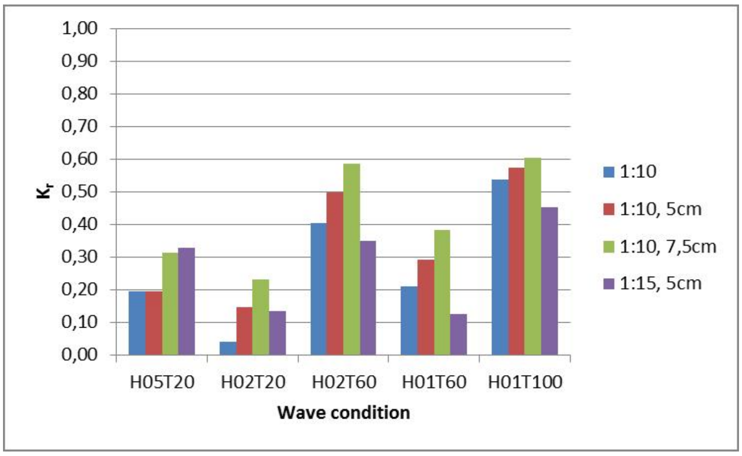


Figure 5.2: Comparison of the results for runs 8 to 10 (all with a 1:10 slope wave absorber, but different in toe) and run 11 (1:15 slope wave absorber), for implementation R3. K_r on the vertical axis

5.2.3 Influence of slope

In this comparison the influence of the slope is discussed. Compared are lay-out B (1:3 slope, see figure 4.3 and case 6 in appendix E), lay-out C (1:5 slope, see figure 4.4 and case 3), layout D (1:10 slope, see figure 4.5 and cases 5 and 8) and lay-out H (1:15 slope with toe, see figure 4.9 and case 11). All wave absorbers have a length at SWL of 1.50 m and all, except case 11, are 'complete' (the slope continues until the bottom). In figure 5.3 the results can be seen for the R3-implementation.

The runs are placed in order of slope steepness to make comparison more convenient: from steepest to most gentle. Both 1:10 slopes are shown in figure 5.3. In general, the steepest slope (1:3) results in the most reflection. Also the 1:5 slope results in less reflection than the 1:3 slope, for the cases in which it is possible to compare them. The wave conditions with relatively large wave height and small wave period don't seem to benefit much from an even more gentle slope (1:10 for case 5). For the wave conditions with lower wave height and longer wave period there is no usable data available to compare steeper slopes, so the comparison is as mentioned in the previous comparison: between 1:10 and 1:15 slopes only. The two data points that are available show that the steeper 1:3 slope results in significantly more reflection than the 1:10 and 1:15 slopes, so it is expected that for these wave conditions a 1:15 slope (including the toe) is most effective in reducing the reflection.

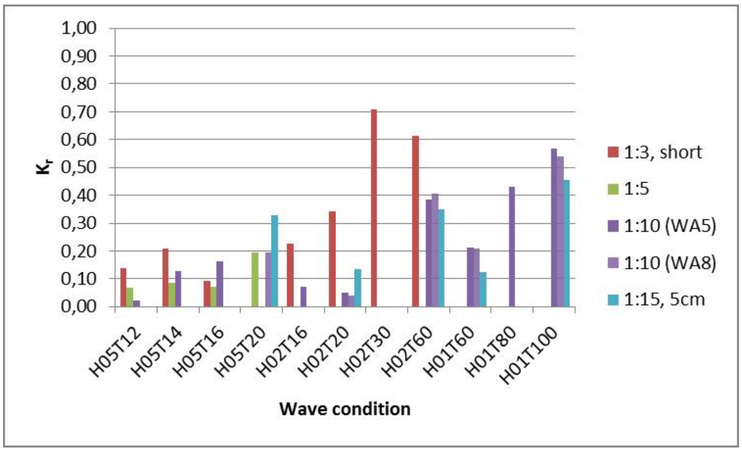


Figure 5.3: Comparison of the results for runs 6 (1:3 slope), 3 (1:5 slope), 5 and 8 (1:10 slope) and 11 (1:15 slope), for implementation R3. K_r on the vertical axis

5.2.4 Effectiveness

Comparing lay-outs D (figure 4.5) and E (figure 4.6) a conclusion about the efficiency of the lay-outs can be drawn, taking into account the results of the comparisons between wave absorber length and slope. Both lay-outs have a total length of 3.00 m. Lay-out E (1:3 slope, long) gives similar results to lay-out B (1:3 slope, short), which gives higher K_r-values than lay-out D (1:10 slope). For two lay-outs of equal length, it is therefore concluded that for the studied wave conditions a more gentle slope is more effective than a larger wave absorber length.

5.3 Noise level in the flume

To calculate the actual amount of noise present in the flume, eq. (5.1) can be used. Herein, the variance of the signal (σ^2_{signal}) can be written as in eq. (5.2), with a the amplitude of the wave ($a = 1/2H$).

$$\text{SNR}= \frac{\sigma^2_{signal}}{\sigma^2_{noise}} = \frac{\frac{1}{8}H^2}{var(stillwater)} \tag{5.1}$$

$$\sigma^2_{signal} = \frac{1}{2}a^2 = \frac{1}{8}H^2 \tag{5.2}$$

For the variance of the noise (σ^2_{noise}) the value is taken from the considered data. From eq. (5.1) it can be seen that the wave height H influences the signal-to-noise ratio: a larger wave height results in a higher SNR and thus a lower noise value. In table 5.1 the order of magnitude for both SNR and the noise are given for the in the experiments used wave heights, as an average of four lay-outs of the experiment results. For one lay-out with many experiment runs, the distribution of the results per wave height can be seen well (figure 5.4)

Table 5.1: Signal-to-noise ratio and noise level for used wave heights, calculated from experiment results

H (m)	SNR	Noise
0.01	12,000	O(0.0001)
0.02	30,000	O(0.00005)
0.05	300,000	O(0.00001)

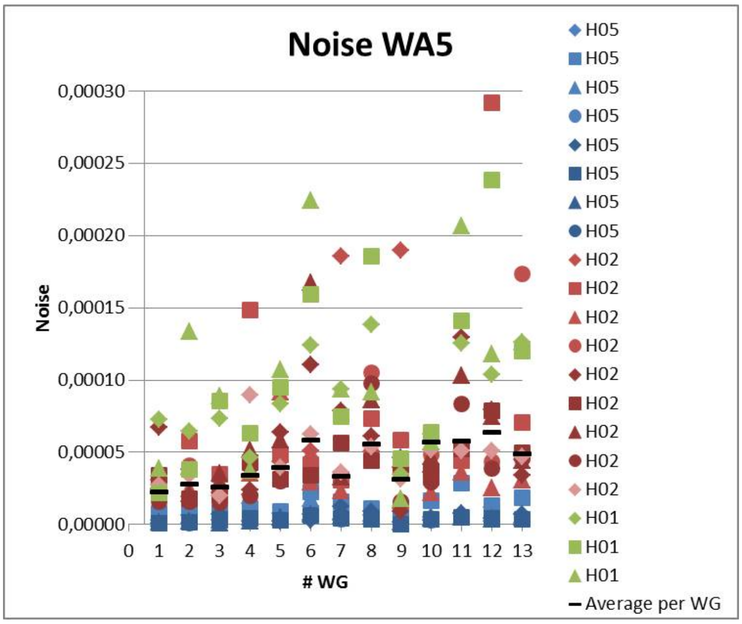


Figure 5.4: Distribution of results and average value per WG, for one wave absorber lay-out (all experiment runs)

5.4 Conclusions

In general it can be said that for a lower wave height H and longer wave period T, the differences between the lay-outs can be distinguished better and it is easier to draw conclusions from them than for higher wave heights and shorter wave periods.

It was expected that a more gentle slope results in a higher reduction of reflection. This is indeed the case for the wave conditions with a lower wave height and longer wave period. The wave absorber length which is possible in the short discance available in the flume doesn't seem to influence this, which makes it probable that long waves get reduced by slope steepness rather than wave absorber length. For the wave conditions with a lower wave period and higher wave height, the expectation of more reflection reduction for more gentle slopes is less evident.

The expectation that a longer wave absorber reduces the reflection more than a shorter wave absorber with the same slope can't be met; there is not much difference in the results for these experiment runs.

It was also expected that cutting off part of the wave absorber tail results in more reflection, which is indeed the case. High wave height/small wave length-wave conditions seem to be influenced by this shortening more than low wave height/large wave length-conditions.

Analysis

6

Two dimensionless parameters are evaluated: the Iribarren parameter ξ, which gives an indication for the type of wave breaking, and the Ursell number U, which is a measure for the non-linearity of waves. For each experiment run, the Ursell number and Iribarren number are calculated, and the reflection value K_r of the corresponding run is plotted against ξ and U.

6.1 Ursell number

The Ursell number U, as described by Ursell, (1953), can be calculated as in eq. (6.1), in which H is the wave height near the wave absorber, and is calculated at the same location as K_r. L is the wave length near the wave absorber and h is the water depth. The Ursell number gives an indication of the non-linearity of waves; for a value of U « 100, linear wave theory can be used for long waves. For larger values a non-linear theory needs to be applied.

$$U = \frac{HL^2}{h^3} \tag{6.1}$$

For each experimental wave condition, U and K_r are calculated; per wave absorber lay-out (as given in section 4.2.5) the results are given in figure 6.1. A trend seems present: for steeper wave absorber slopes the reflection for a given value of U lies higher. It can also be seen that Ursell values larger than 100 are found which indicates non-linearity, but this is not discussed in more detail in this study.

6.2 Iribarren parameter

The Iribarren parameter ξ (or breaking- or surf similarity parameter), as described by Battjes, (1974), shows the relation between the slope and the wave steepness of the waves that break on that slope. It is a dimensionless number and is expressed as in eq. (6.2).

$$\xi = \frac{\tan(\alpha)}{\sqrt{H/L_0}} \tag{6.2}$$

For the slope ($\tan(\alpha)$), the wave absorber slope is chosen, as the bottom slope is horizontal and doesn't induce breaking. For the wave steepness ($\sqrt{(H/L_0)}$) the deep water wave length L_0 is calculated from the wave period T; the wave height at the point of calculation H is calculated from the used implementation. It is the incoming wave height that is calculated to use to calculate the reflection according to that implementation ($H_{15} = H_{in} = 2\ a_{in}$).

For breaking waves on a slope (inshore), the classification per ξ-value can be distinguished as in table 6.1 (Battjes, 1974).

Table 6.1: Wave classification according to Battjes, (1974)

Classification	Value
Surging or collapsing	ξ >2.0
Plunging	0.4 <ξ <2.0
Spilling	ξ <0.4

For each experiment wave condition, ξ and K_r are calculated. There seems to be no trend present per wave absorber lay-out, so all results together are given in figure 6.2. Also plotted are the theory lines according to Battjes, (1974) for smooth, impermeable slopes ($K_r = 0.1\ \xi^2$) and according to Zanuttigh and Van der Meer, (2006) for rock permeable slopes ($K_r = \tanh(0.12\xi^{0.87})$). As a whole, the data points lie well below the theory of Battjes, (1974): the wave absorbers, consisting of stones, absorb more wave energy than a smooth, impermeable slope, which results in less reflection. The theory of Zanuttigh and Van der Meer, (2006) seems more fitting, although it is designed for breakwater armour.

6.3 Combining Ursell and Iribarren

As both Ursell and Iribarren are dimensionless, combining them can give new insights in a relation between the input parameters of both equations and the output value K_r. In figure 6.1 it can be seen that a trend could be present between the outcomes and the slope, which is investigated in more detail. It is found that combining the Ursell number with the slope-part of the Iribarren number gives good results. As eq. (6.1) can also be written as a combination of the dimensionless depth (H/h) and the steepness of the waves near the wave absorber (L/h), see eq. (6.3), it can easily be combined with the slope to get eq. (6.4) to calculate a new factor F. This factor consists of the three mentioned aspects, each to a power (in eq. (6.4) given as A, B and C) which needs to be determined.

$$U = \frac{HL^2}{h^3} = \frac{H}{h}\left(\frac{L}{h}\right)^2 \tag{6.3}$$

$$\text{F}= \left[\frac{H}{h}\right]^A \left[\frac{L}{h}\right]^B \left[\tan\alpha\right]^C \tag{6.4}$$

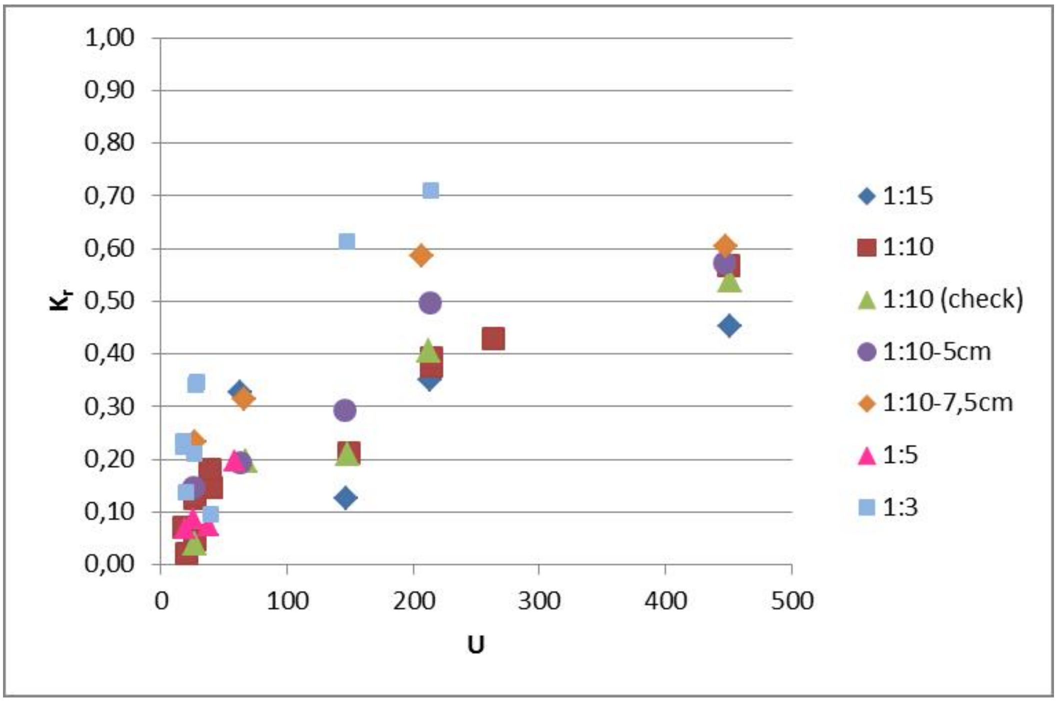


Figure 6.1: Reflection and Ursell number for all wave absorber lay-outs

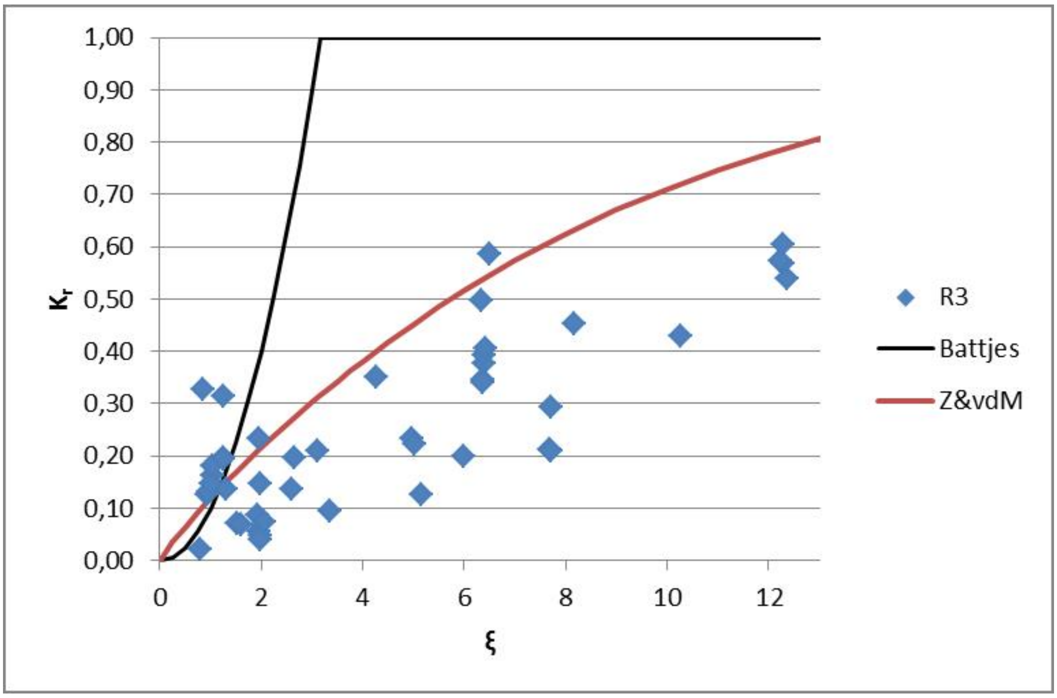


Figure 6.2: Reflection and Iribarren number for all wave absorber lay-outs, compared to theorical lines of Battjes, (1974) and Zanuttigh and Van der Meer, (2006)

In figure 6.3 for all data points K_r is plotted against this factor F (compare to figure 6.1); values of A = 1, B = 2 and C = $\frac{2}{3}$ are used, which give a well fitting theoretical line for the relation between H, L, h, $\tan\alpha$ and K_r. The equation for this trend line is given in eq. (6.5).

$$K_r = 0.028\mathrm{F}^{2/3} \qquad (6.5)$$

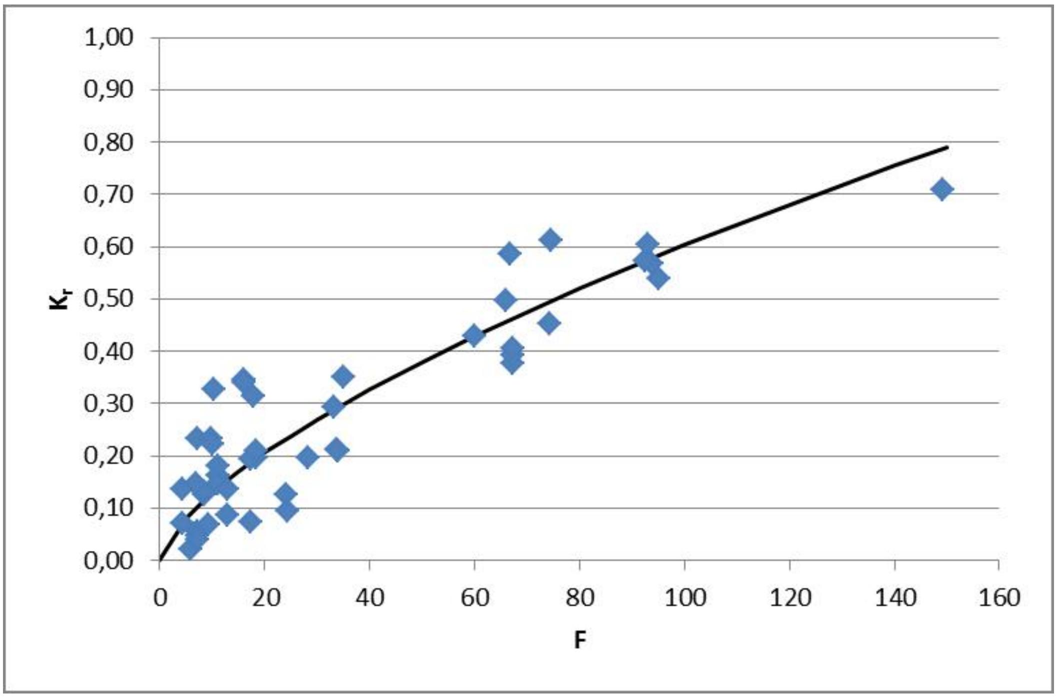


Figure 6.3: Reflection as function of factor F (Ursell number combined with slope), for all wave absorber lay-outs, compared to trend line (eq. (6.4))

7 Numerical modelling: SWASH

To give a more complete analysis of the experiments, the experiment set-up and wave conditions can be modelled in SWASH. It is attempted to get the same result from the SWASH-model as obtained from the experiments.

SWASH (Simulating WAves till SHore) is a numerical model which can be used to simulate various hydraulic phenomena in coastal waters. Not only linear waves can be modelled: SWASH is suitable for unsteady, non-hydrostatic, free-surface, rotational flow and transport phenomena, so that all wave conditions used in this research should be possible to model (in chapter 6 it was found that for many wave conditions linear wave theory is not applicable). It is suitable to model waves, tides, buoyancy and wind forces as driving forces. The wave transformations can be modelled from deep water to coast or other shallower areas, such as ports, and can describe complex changes to quickly varied flows as well as density driven flows in hydraulic areas as coastal seas, estuaries, lakes and rivers.

7.1 Validation of experimental results

7.1.1 Model set-up

For the set-up used in the SWASH-model the situation of the experiments is approximated as closely as possible. The experiment set-up can be found in section 4.2.

The dimensions of the flume in SWASH are equal to those of the real flume: a length of 37.5 m, divided into 3750 horizontal gridpoints (so each gridcell is 0.01 m long) and modelled with one vertical layer. The bottom profile also contains the same foreland as in the physical model (with gridcells of 0.10 m length), as given in figure 4.1. The width of the flume is not taken into account.

For the wave absorber lay-outs (as given in section 4.2.5) the shape, porosity and stone size are of importance. For the porosity a value of 0.40 is chosen and a stone size of 0.03 m is used, which are expected to be comparable to respectively the porosity and stone size of the real wave absorbers. It is also possible to model a 'sponge layer' in SWASH, which can be placed behind the flume instead of a wave absorber. When long enough, the sponge layer absorbs all wave energy and no reflection is present (a length of minimally three to five times the wave length is needed to achieve this), simulating a never ending flume. With a shorter sponge layer length the remaining wave energy is reflected against the end of the sponge layer. One set-up is modelled with a sponge layer of 50 m, which fits the longest wave length (for T = 10.0 m the wave length at 0.15 m water depth is L_{15} = 12.12 m) approximately four times.

In most model runs, friction is taken into account: a Manning's friction coeffiecient of 0.019 is used (the default value in SWASH) as a starting point. In the experiments the water level is relatively low, so the default value of SWASH for the Manning friction is probably too low compared to the real value in the flume. As a small change in the friction coefficient can have a large impact on the result (see section 7.3) this parameter can be used to fine-tune the model results if needed.

The locations for which a wave signal as well as a velocity signal is calculated are the same as those for the synthetic signals (see section 3.2.1): every 2.50 m plus the locations used in the experiments. The modelled wave conditions are H01T100, H01T60 and H02T20. The used implementations are R2 and R3, unless otherwise stated.

7.1.2 Results

It turns out that numerically reproducing the experimental results is not possible. The reflection values calculated from the SWASH-model runs don't match those of the experimental results; it is uncertain why. The correspondence between the physical and numerical results depends on the wave conditions: it is found that higher waves give better corresponding results than lower waves. One wave condition is modelled for varying parameters (number of horizontal grid points, number of vertical layers) but this does not give a solution to the problem. Assumed is that the bathymetry of the foreshore makes it very difficult or even impossible to reproduce the experiment set-up and wave conditions numerically. It is concluded that it is not possible to reproduce the physical modelling results by SWASH, without changing so many parameters per individual model run that it is not generally applicable any more. In appendix F the results are described in more detail.

7.2 Comparison of wave absorbers without experiment bathymetry

As it is not possible to reproduce the experiment results, probably due to the foreland in the bottom profile, a more basic set-up is modelled in SWASH. This does not make it possible to compare the K_r-values of the SWASH-model with those from the experiments, but comparisons between the wave absorbers themselves are possible.

7.2.1 Model set-up

The new set-up to compare the wave absorbers amongst each other is almost equal to that as described in section 7.1.1, with the only difference that the foreland is not modelled: instead, the water level is 0.15 m over the whole flume length.

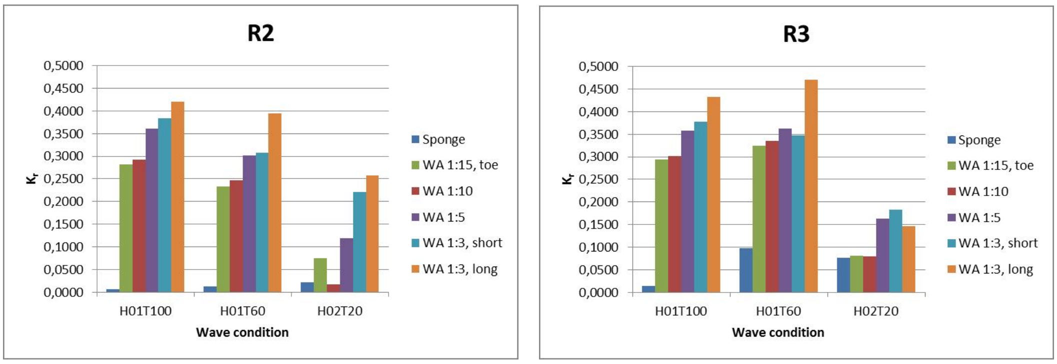
In this comparison values are kept as pre-set by the model. In the experiments the water depth is relatively low, so the default value of SWASH for the Manning friction is probably too low compared to the real value in the flume.

The modelled wave conditions are H01T100, H01T60 and H02T20 for all wave absorber lay-outs and the sponge layer. Also modelled are H05T16 and H02T60, which don't give usable results (compare to the experiment results in section 5.1). It is expected that the wave gauge spacing causes mentioned wave conditions to be unusable; these wave lengths might not fit in the chosen sections between gauges.

7.2.2 Results

In chapter 3 it was found that the implementations of the method of Zelt and Skjelbreia, (1992) for two and for three wave gauges (R2 and R3 respectively) give the best results. In chapter 5 not all wave conditions turned out to be usable, and that for R2 less results could be used than for R3. In this SWASH analysis (modelling the experiment set-up without foreland bathymetry) the same is found: for some of the mentioned wave conditions that are unusable, R3 gives more often a usable value than R2.

In figure 7.1 the K_r-values for the wave conditions H01T100, H01T60 and H02T20 are compared, given per wave condition for a 50 m long sponge layer and various wave absorber lay-outs. They are modelled with SWASH and calculated with implementations R2 and R3.



(a) K_r-values for implementation R2 (b) K_r-values for implementation R3

Figure 7.1: K_r-values per wave condition for a 50 m long sponge layer and various wave absorber lay-outs, for implementations R2 and R3, modelled with SWASH

For these wave conditions, overall the same conclusions as in chapter 5 can be drawn:

- Comparing the wave absorber lay-outs with a 1:3 slope and different lengths (lay-outs B (figure 4.3) and E (figure 4.6)), the shorter wave absorber gives lower K_r-values for most wave conditions. This effect could be caused by the longer distance between absorber and nearest equipment: waves are damped out more than for the longer wave absorber.
- The influence of the slope is clear in these model run results: a more gentle slope returns lower K_r-values. The differences between reflection values are not as large as found for the experiments, but nonetheless clearly present.
- For longer, lower waves the results are more distinguishable than for shorter, higher waves.
- The comparison of applying a toe is not studied. It is expected that the same conclusions as in the experiments can be drawn.

Surprisingly, in this analysis, the results for the WG/EMF-implementation are well comparable to those of the R2-implementation, even though in the synthetic signal analysis (chapter 3) and the experiment results analysis (chapter 5) this is not found. The implementations of MF and R3 are also here not very well comparable, at least not to the same extend as WG/EMF and R2 are.

7.3 Scale effects

Although scale effects are not extensively studied in this research, it is interesting to have a qualitative look at them. With SWASH a quick comparison can be made between two situations, taking scale effects into account.

7.3.1 Scaling methods

There are two options to model scale changes: by changing the flume dimensions and modelling time in the SWASH-model with Froude scaling, or by changing the friction coefficient. For Froude scaling, the dimensionless Froude number Fr (eq. (7.1)) should be equal when modelling in different scales. If for example the length scale is multiplied by 20, the time scale has to be multiplied by $\sqrt{20}$ to get the same Froude value. Situations with a different scale and equal Froude values can be compared.

$$\text{Fr}= \frac{u}{\sqrt{gh}} \tag{7.1}$$

For a simpler approach the friction coefficient can be adjusted instead of scaling the length and time scales: for a larger scale the friction is relatively low compared to a smaller scale model. Instead of using a model with larger dimensions the friction is reduced. For this research the Manning friction coefficient is used in the SWASH-model. A low value indicates little friction, thus for a 'larger scale' model the friction needs to be reduced when keeping the dimensions the same.

The Manning friction coefficient n depends on the material and the water level of the modelled and real situations. According to Webb et al., (2010) the Manning friction coefficient can be scaled with the linear dimension L in the model and real situation as in eq. (7.2), in which n_r is the ratio between the Manning friction coefficients for the real and modelled situation (see eq. (7.3); the same applies to L_r).

$$n_r = L_r^{1/6} \tag{7.2}$$

$$n_r = \frac{n_{real}}{n_{model}} \tag{7.3}$$

In this research scaling is only studied by changing the value of the Manning friction coefficient. From eqs. (7.2) and (7.3) it is derived that for a situation with, for example, ten times larger dimensions, the friction coefficient of the (experiment scale) model needs to be multiplied by 1.47.

The question to be answered is how the bottom friction influences the amount of reflection. The reflection is calculated from the wave amplitude a (which is half the wave height H), so in this section the decrease in wave height is compared for different modelled situations.

Note that the default value of the SWASH-model is expected to be relatively low to model the experiment situation: the water in the flume is very shallow, and also the wall friction is expected to be significant, but is not taken into account in the friction coefficient in SWASH. With increasing water depth in the experiment and keeping n constant, the friction influences the waves relatively less. The situation in the field is entirely different: no wall friction is present but instead the friction is expected to be much higher due to the presence of vegetation and uneven subsurfaces.

7.3.2 Modelling

For simplicity only the set-up with a sponge layer is run, and the decreasing wave height is compared to that of the comparable run of section 7.2. All parameters are kept the same as in this run, except the friction coefficient. The wave conditions used are H01T100 and H01T60.

The value of the Manning friction coefficient is calculated for a 'field situation' with twenty times larger length scale dimensions ($L = 3.00$ m), which is representative for (part of) the Mekong Delta in Vietnam (Phan Khanh et al., 2015). With eq. (7.2) the corresponding Manning friction value is 0.0313 $\mathrm{s/m^{1/3}}$, as for the runs in section 7.2 a friction value of 0.0190 $\mathrm{s/m^{1/3}}$ is used. For more insight also a friction coefficient for a hundred times larger length scale ($L = 15.00$ m), a four thousand times larger length scale ($L = 600.00$ m) and a third of the original length scale ($L = 0.05$ m) are modelled. The corresponding n-values are 0.0409, 0.0757 and 0.0158 $\mathrm{s/m^{1/3}}$ respectively. In table 7.1 all values can be found.

Table 7.1: Friction coefficient for various length scales

L (m)	0.05	0.15	3.00	15.00	600.00
n ($\mathrm{s/m^{1/3}}$)	0.0158	0.0190	0.0313	0.0409	0.0757

In figure 7.2 and table 7.2 the decrease in wave height for H01T100 and H01T60 over a distance equal to the (relatively short, total) flume length of 37.5 m can be seen, for the values of the Manning friction coefficient as given in table 7.1. Figure 7.2 shows that a small change in the value of n can have a large influence on the wave damping. A larger friction coefficient results in a faster wave height decay than smaller coefficients. Per n-value, the two wave conditions give almost equal results for the wave height decrease over the distance, and for the largest amount of friction it can be seen best that the wave height for H01T60 decreases slightly faster than that for H01T100.

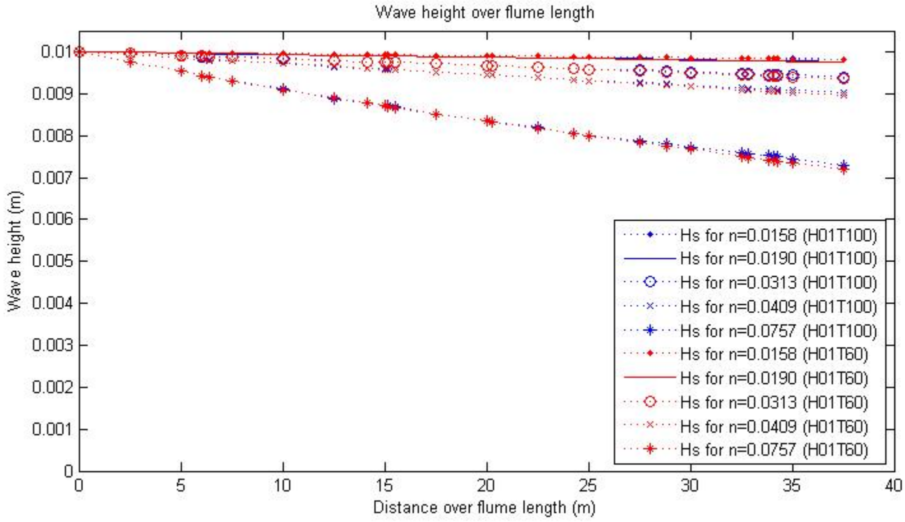


Figure 7.2: Decrease in wave height for two wave conditions over 37.5 m distance for various friction coefficient values

Table 7.2: Decrease in wave height for various friction coefficient values, compared to $H_{initial}$ = 0.01 m

Wave condition	L (m)	n (s/m$^{1/3}$)	$H_{37.5\mathrm{m}}$	%
H01T100	0.05	0.0158	0.00983	-1.7
	0.15	0.0190	0.00976	-2.4
	3.00	0.0313	0.00939	-6.1
	15.00	0.0409	0.00901	-9.9
	600.00	0.0757	0.00729	-27.1
H01T60	0.05	0.0158	0.00982	-1.8
	0.15	0.0190	0.00974	-2.6
	3.00	0.0313	0.00935	-6.5
	15.00	0.0409	0.00895	-10.5
	600.00	0.0757	0.00719	-28.1

8 Discussion

Combining all gathered knowledge, the following points are discussed.

Comparable reflection analysis implementations
Analysing the synthetic signals in chapter 3, the implementations for WG/EMF and MF are found to be not reliable in this research. Regarding the number of measurement signals, the WG/EMF implementation is expected to be comparable to the R2-implementation (both using two input signals, and therefore explicitly to solve), and the MF-implementation is expected to be comparable to the R3-implementation (both using three input signals). In chapter 3 it was found that the results differ significantly. Especially for the comparison between MF and R3 this is surprising, as the methods on which the implementations are based should be the same, according to Zelt and Skjelbreia, (1992). The R2 and R3 implementations gave good results in the analysis with a synthetic signal, and it is therefore assumed that the implementations for WG/EMF and for MF are wrong.

Interesting to mention is that for the SWASH analysis (chapter 7) with a water level of 0.15 m, some wave conditions give much better comparable results for WG/EMF and R2, and also for MF and R3. For very long, low waves the K_r-values of the WG/EMF-implementation are not significantly deviating from the values for R2, and the same holds for MF and R3. When decreasing the wave height, the differences increase. Also for the experimental results WG/EMF and R2 are more comparable to each other than expected from the synthetic signal analysis, as well as MF and R3, although here the differences are larger.

Wave conditions
In this research only regular waves are modelled, which are chosen to have a relatively small wave height and large wave period to prevent breaking. For waves that are higher and/or shorter (linear wave theory applicable), it is expected that the crests are more stable, and energy dissipation by dispersion is lower. However, for these waves the water level needs to be increased to prevent breaking at the end of the foreland. Modelling irregular waves is expected to result in some breaking after the foreland, but also in less dispersion. Both wave breaking and dispersion lead to energy loss before the waves can reach the wave absorber; to study the effectiveness of the absorber it is important to keep breaking and dispersion low.

The modelled waves have a large Ursell number (» 100) which makes linear wave theory not applicable on them, although this is assumed on beforehand and also used in the analysis of the results (chapter 6). Using a non-linear wave theory makes analysis much more complicated and is therefore not used.

Foreland
The foreland slope used in the flume for the experiments represents a 'real' mangrove coast slope with a steepness in the order of 1:1000. To compress the horizontal length scale, the

choice is made to use a 1:10 slope and 1:20 slope combination (see also figure 4.1). This choice gave some problems during the physical modelling: the wave height needed to be decreased and the water level to be increased to prevent wave breaking (which was not desired), which results in a relatively shorter 'mangrove area'. In the numerical modelling (chapter 7) the foreland resulted in modelling problems: it was not possible to reproduce the experiment results. It might therefore be possible that the chosen experiment foreland slope is too steep, and results could improve with a more gentle slope. If doing so, it needs to be taken into account that the foreland will take much more horizontal flume length, which results in a shorter available length for a mangrove section.

Reproduction of experiment results by SWASH

The reproduction of the results obtained by the experiments and analysis of the measuring data by SWASH was not possible (chapter 7). There are various options what could have caused this. Besides the problems with the foreland, on which the modelled waves reflect, it is also possible that the modelled wave conditions give problems, even though SWASH is applicable to linear and non-linear waves. The small wave heights in combination with large wave periods result in relatively high Ursell numbers, which are a measure for non-linearity (see chapter 6); it is possible that these wave conditions are not suitable to be modelled in SWASH, or that an extensive fine-tuning of various parameters in the SWASH model is needed.

Modelling the experiment set-up and conditions for a bathymetry with a water level of 0.15 m over the whole flume gives results which are not quantitatively comparable any more to the experiment results, but which can be compared amongst each other. It is assumed that the chosen foreland dimensions make it impossible to create a model set-up in SWASH for which all modelled wave conditions give comparable results to those of the physical modelling. In the flume it could already be seen that for many wave conditions wave crests were unstable and the wave height needed to be decreased. For waves with a longer period a dispersive tail could be seen; this also decreases the wave energy as it is divided over the smaller waves.

Equipment placement

As the locations of the wave gauges and EMF's are fixed in the experiments, they are as well in the numerical modelling, to make a good comparison possible. Also the wave absorber length at SWL is kept constant for most lay-outs, which makes the distance between the absorber and the nearest equipment a constant value for most runs. This is convenient for comparison: it is expected that additional effects, such as evanescent modes, damp out in an equal amount, and wave heights and reflection values can be compared. However, one wave absorber lay-out has a deviant length at SWL: lay-out E (figure 4.6) is placed much closer to the measuring equipment. It was found that this lay-out also gives the highest reflection value of all tested lay-outs. Possibly because of the presence of evanescent modes: an effect which increases the water level, but which is damped out after a distance of a few times the water depth. With the very shallow water depth of 0.15 m the length on which this effect is damped out is also very short and could fall within the additional absorber length of lay-out E with respect to the other lay-outs, resulting in a higher K_r-value for lay-out E.

Conclusions and recommendations

9

9.1 Conclusions

In this section the conclusions that can be drawn from this research are given. First of all, the research question is answered; separated in the two parts mentioned in section 1.3.1. Secondly all other conclusions from this research are stated.

9.1.1 Research question

The main research question is formulated as follows:

> *When modelling a mangrove coast in a wave flume (with a bottom profile that is shortened and steepened compared to a field situation), how can the reflection be minimised by the lay-out of a wave absorber and how can the reflection of long, regular waves be measured best?*

The conclusions of the two components of this question are answered separately. First of all,

> *How can the reflection be minimised, by the shape of the wave absorber in a flume?*

It can be concluded about the slope of the wave absorber that the expectation that a more gentle slope results in less reflection, is correct: a slope as gentle as possible gives the best results in reflection reduction. For the examined wave absorber lay-outs it was found that shortening the toe of the slope results in more reflection, but still the 1:15 slope with shortened toe at 0.05 m gives a lower reflection value than the 1:10 slope without shortened toe.

> *With what method can the reflection of long waves in a flume best be estimated, for both long and short regular waves?*

From the results of the analysis with the synthetic signal (chapter 3) it was found that the 2 WG and 3 WG implementations of the theory of Zelt and Skjelbreia, (1992) for regular waves (R2 and R3 respectively) work well. It depends on the desired amount of equipment, available length and sensitivity of noise which implementation is preferred: R2 uses less wave gauges and needs less flume length, whereas the R3-implementation uses the third wave gauge (and associated extra flume length) for less sensitivity to noise. In this research, it was found that for the experimental results more results of R3 than of R2 could be used (in other words: had a reliable outcome), which also increases the preference for R3.

9.1.2 Other conclusions

Reflection analysis implementations
Based on the analysis with a synthetic signal (section 3.2) it can be concluded that the implementation using a combination of WG/EMF is unreliable to use for reflection analysis. Also the MF-implementation is unreliable, when adding noise. Both can not be used for reflection analysis of a synthetic signal, but seem to give better results for real datasets. The implementation for irregular waves doesn't work and is also rejected to use. The implementations R3 and R4 give exact equal results in this research. As R3 needs less equipment and distance, it is preferred over R4 to use. As described in section 9.1.1 both R2 and R3 work well, and the choice for use depends on the user's preferences in application.

Physical modelling and wave absorber lay-out
For modelling in the wave flume (section 4.1), the following can be concluded:

- It is important to close off the sides of a built-in bottom profile. Even with a very small space between the bottom and the sides of the flume, water exchange is possible. This can result in non-uniformly breaking waves, which influences the results. This is especially the case for longer waves. The water exchange also results in lower reflection values.
- The final way of construction of the wave absorber lay-outs is important: if the shape of the wave absorber front is not twodimensional, it affects the reflected waves and can result in distorted waves. This can also influence the accuracy of the measurements.
- To make a good comparison possible between different wave absorber lay-outs, it is important that on each lay-out enough experiment runs are performed. Also changes between lay-outs need to be kept to a minimum to study the influence of them on the reflection (or other parameters to be examined). One change per lay-out at a time is recommended, also if it seems only a minor change.
- As the examined waves are relatively low (the maximum wave height is 0.05 m), measuring them is easier with a higher waterdepth. Increasing the depth from 0.10 m to 0.15 m results in more stable and easier to measure waves.

About the wave absorber lay-out (section 4.2.5 and section 5.2) the following can be concluded:

- In general it can be said that for a lower wave height H and longer wave period T, the differences between the lay-outs can be distinguished better and it is easier to draw conclusions from them than for higher wave heights and shorter wave periods.
- A more gentle slope results in a higher reduction of reflection for the wave conditions with a lower wave height and longer wave period. The wave absorber length which is possible in the short space available in the flume doesn't seem to influence this, which makes it probable that long waves get reduced by slope steepness rather than wave absorber length. For the wave conditions with a lower wave period and higher

wave height, the expectation of more reflection reduction for more gentle slopes is less evident.

- A longer wave absorber does not necessarily reduce the reflection more than a shorter wave absorber with the same slope. For the modelled lay-outs there is not much difference in the results for these experimental runs.
- Cutting off part of the wave absorber toe results in more reflection. Wave conditions for which the wave height is large and/or the wave length is small seem to be influenced by this shortening more than low wave height/large wave length-conditions.

Generally, modelling waves which are relatively long and low for low water levels can be difficult.

SWASH analysis
It has not succeeded to obtain the experiment results by modelling the experiment conditions in SWASH. It is expected that this is caused by the chosen foreland dimensions, which caused waves with (relatively) large wave heights to break at the end of the foreshore, which was not desired. To prevent this, lower wave heights were chosen, which resulted in energy loss in the form of a dispersive tail.

Modelling the wave conditions used during the experiments showed that the correspondence between both depends on the examined wave condition. It is found that higher waves give better corresponding results than lower waves.

9.2 Recommendations for further research

Comparable reflection analysis methods and implementations
Looking at the method of solving, it is expected that the implementations for MF and R3 should give comparable results. Both implementations use three wave gauges and FFT to come to an answer. However, the results are significantly different. It is recommended to have a more detailed look into both scripts, to see if it can be explained why this happens.

Additionally, also the WG/EMF implementation and R2 could be expected to give comparable results: both use two signals, either of two wave gauges or of a wave gauge in combination with an EMF. This results in not being able to separate the noise out of the signal. Also here it is recommended to take a closer look at the scripts to see whether the differences can be explained.

New method or implementation
In the same line, it might be possible to create a new method using two wave gauges and an EMF, thus using three signals over a shorter length. This gives the advantages of less sensitivity to noise, which is not possible for WG/EMF or R2, and also keeping the needed distance in the flume shorter than what is necessary for the more detailed implementation of R3. Also, looking at the WG spacing, it could maybe save the extra needed wave gauge when running both intermediate (or short) and long waves, as the distance between two wave gauges shouldn't be too small or large: the EMF provides extra information which could be needed if the distance between the two gauges is too small.

Implementations for irregular waves
There also is a matlab script available that calculates the reflection for irregular waves, using two or more WG's. This script is not used in this research, as it was too unreliable to use: it gave multiple errors and looking at the cause of them was too labour intensive, especially because there were other implementations that worked very well. It is recommended to have a look at this script in more detail, as it is used often in other master theses.

Wave absorber lay-out
It is interesting to have a more detailed look at the efficiency of the wave absorber. Can a ratio between reflection reduction and the needed length (or for example the wave absorber volume) be derived? Also the influence of shortening the toe can be studied in more detail: to have a closer look at how much cutting off the toe of the wave absorber influences the amount of reflection. It is found that a 1:15 shortened slope reduces the reflection more than a 1:10 'complete' slope, but can it be predicted where the transition lies? Is there a relation between the reduction of the wave absorber length and the increase of the reflection?

Also other wave absorber lay-outs are possible, for instance a smaller or larger stone size, constructing the front of the wave absorber with a berm (which can be compared with a very gentle slope and a toe), involving the outflow section in the wave absorber design, designing with a longer available space, etcetera.

Analytical solution for permeable constructions
In chapter 6 the dimensionless Iribarren parameter is compared to theoretical values. These theories are based on smooth, impermeable slopes (Battjes, 1974) or permeable rock used as breakwater armour, which is expected to have a less permeable core underneath (Zanuttigh and Van der Meer, 2006), whereas the wave absorbers that are studied are permeable. It could be looked at if a good analytical solution can be found for reflection on permeable wave absorbers (or similar constructions) build with rock.

Bathymetry
The bathymetry used in this research was chosen on beforehand[1] as a combination of a 1:10 and a 1:20 slope, to compress the needed horizontal length for a natural mangrove coast (with a slope steepness in the order of 1:1000 or even more gentle). As it is expected that these chosen dimensions have a significant influence on the modelled wave conditions, it is recommended to do a more detailed study to optimalisation of the foreshore. Questions to answer could be: What is the influence of the bathymetry on the reflection? Does a more gentle slope give better results, and is it possible to model the experiments in SWASH for that slope? Is there an optimal slope for a given available space in a wave flume?

Measuring equipment
The influence of equipment placement can be studied in more detail in follow-up research. Due to limited availability of measuring equipment choices needed to be made regarding the placement of the wave gauges and EMF's: wave gauges were placed at set locations, but the lay-out of the wave absorber could vary, and so did the distance (measured at SWL) between the absorber and the equipment nearest to it. It can be studied whether certain wave conditions result in comparable reflection results when varying the distances between the wave gauges, or that they give significantly deviant results. Also the influence of the distance between the wave absorber and the equipment placed furthest can be looked at

[1]PhD research by L. Phan Khanh on long wave penetration in mangroves

in more detail: for example, are evanescent modes or other aspects of influence on the results?

Wave conditions
Generally, modelling waves which are relatively long and low can be difficult. It is recommended to choose conditions with a lower Ursell number (although that is still no guarantee for effortless comparisons) by increasing the water level, increasing the wave height and/or decreasing the wave length. In this research many wave conditions have a high Ursell number, for which linear wave theory is not applicable. In follow-up research it can be studied whether using a non-linear wave theory gives better results.

Numerical analysis of experimental results
It would be interesting if the results obtained from the physical modelling in the flume can be simulated by SWASH (or another numerical model). As it is unknown why for some wave conditions the results don't match in the modelled cases and for other conditions the results match better, it is recommended to study in more detail why this happens.

Sensitivity analysis with SWASH
For the rock used to construct the wave absorbers, a porosity of 0.40 and a stone size of 0.03 m are chosen, which are expected to be comparable to respectively the porosity and stone size of the real wave absorbers. As the experimental results could not be reproduced in SWASH, also no fine-tuning of these parameters is done, and therefore the influence of changing the porosity or stone size is not studied. In further research these parameters could be studied more extensively, both numerically by changing the values in SWASH, and physically, by using other (rock) material in experiments.

Adding mangroves
This research is conducted with an 'empty' flume: no mangroves were added in either the physical or the numerical modelling. This made placing of the equipment in the flume for the experiments very easy: they could be placed wherever desired. When adding mangroves, more attention has to be paid to the placing. The 'mangroves' can influence the signal by local effects, such as currents around the sticks.

General
From the aspects mentioned in section 1.1 only the reflection is investigated in this research. The set-up, influence of the foreland bathymetry and scale effects could be taken into account in follow-up research.

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Appendices

Reflection methods

A

In this appendix, more details are given about the reflection methods used to base the reflection analysis implementations on.

A.1 Guza et al. (WG+EMF)

The method of Guza et al., (1984) uses a wave gauge (WG) and an electromagnetic flow meter (EMF) at one certain location. With the combination of the wave height and the horizontal water velocity the wave signal can explicitly be separated into an incoming (eq. (A.1)) and a reflected (eq. (A.2)) wave signal.

$$\eta_{in}(t) = \frac{1}{2}(\eta + u\sqrt{\frac{h}{g}}) \tag{A.1}$$

$$\eta_{re}(t) = \frac{1}{2}(\eta - u\sqrt{\frac{h}{g}}) \tag{A.2}$$

In eqs. (A.1) and (A.2), η_{in} is the incoming wave signal, η_{re} is the reflected wave signal, η is the measured wave signal at the chosen wave gauge, u is the horizontal water velocity at the chosen EMF, h is the water level and g is the acceleration of gravity.

Assuming linear wave theory, the horizontal velocity profile is influenced by the bottom friction and the measured velocity depends on the measuring height. Therefore the velocity response function K_u, as described by Buckley et al., (2015), is introduced in eq. (A.3).

$$K_u = \frac{cosh(k \cdot h_u)}{cosh(k \cdot (h_0 + \bar{\eta}))} \tag{A.3}$$

In eq. (A.3), h_u is the the measuring height (the distance between the bed and the height at which the velocity is measured), h_0 is the still water depth, k is the wave number and $\bar{\eta}$ is the wave signal averaged over time (wave setup or setdown). Adding this factor to eq. (A.1) and eq. (A.2) leads to eq. (A.4) and eq. (A.5) respectively, in which f is the frequency ($1/T$).

$$\eta_{in}(t) = \frac{1}{2}(\eta + u \cdot \frac{2\pi f}{gkK_u}) \tag{A.4}$$

$$\eta_{re}(t) = \frac{1}{2}(\eta - u \cdot \frac{2\pi f}{gkK_u}) \tag{A.5}$$

A.2 Zelt and Skjelbreia (2^+ WG)

The theory of Zelt and Skjelbreia, (1992) assumes linear wave theory and a one-dimensional wave field. This wave field is decomposed into component waves, which travel in opposite direction (incoming and reflected waves). The basic equation for the water level elevation at a certain location (the pth wave gauge out of a total of N) is given in eq. (A.6). The signal of the wave field can be approximated as in eq. (A.7), which is a Fourier sum of the incoming (I) and reflected (R) waves.

$$\eta_p(t) = \sum_{j=-N/2}^{N/2} A_{j,p} e^{i\omega_j t} \tag{A.6}$$

$$\eta(x_p, t) = \sum_{j=-N/2}^{N/2} \{a_{I_j} e^{ik_j x_p} + a_{R_j} e^{-ik_j x_p}\} e^{i\omega_j t} \tag{A.7}$$

Combining eqs. (A.6) and (A.7) gives eq. (A.8), which can be solved for each Fourier component j to estimate the values of a_{I_j} and a_{R_j}. These are the amplitudes of the incoming (a_I) and reflected (a_R) waves and are needed to calculate the reflection. For this research it goes into too much detail how to solve these equations to estimate a_{I_j} and a_{R_j}.

$$A_{j,p} = a_{I_j} e^{ik_j x_p} + a_{R_j} e^{-ik_j x_p} \tag{A.8}$$

When two wave gauges are used, eq. (A.8) can be solved exactly and is equal to the theory of Goda and Suzuki, (1976). Using more than two wave gauges requires another solving method, for example a least squares approach with uniform weighting, as is done by Mansard and Funke, (1980), who use three wave gauges. Zelt and Skjelbreia, (1992) use a weighted least squares approach, which can be used for any number of wave gauge signals.

B Calculation of equipment positions

To measure wave signals, use is made of thirteen wave gauges (WG), which measure the wave height, and seven electromagnetic flow meters (EMF), which measure the horizontal flow velocity. For the positioning of the equipment, the WG positions are of importance; there are multiple needed (at least two, depending on the method) to determine the reflection. The EMF's, of which seven are used, should be placed at the same location as the WG's, with one as near to the wave absorber as possible.

B.1 Wave gauge spacing

The most interesting locations to calculate the reflection are as close to the wave absorber as possible (here the reflection is strongest), at the beginning of the flume (to calibrate the equipment) and just after the foreland, between the location where the waves break and the location where the mangroves are placed (for follow-up research).

B.1.1 Back: near the wave absorber

Based on Wenneker and Hofland, (2014) the locations of the WG's are determined for the location near the wave absorber, at the back of the flume. To do this, the wave lengths of the modelled wave conditions are needed, of which L_{max} and L_{min} are multiplied by ε and E respectively. These values give a lower and upper boundary in between the distance between WG1 and WG2 (indicated by x_{12}) must lie, see eq. (B.1).

$$\varepsilon L_{max} < x_{12} < E L_{min} \tag{B.1}$$

In table B.1 the values for ε and E are given, for various reflection determining methods (see chapter 3). In this table W is the number of wave gauges. The abbreviations for the methods to determine the reflection (the setting names) are GS for Goda and Suzuki, (1976) (using two WG's), MF for Mansard and Funke, (1980) (using three WG's), and ZS for Zelt and Skjelbreia, (1992) (using four and fifty WG's).

In table B.2 the wave lengths for 0.15 m depth (L_{15}) of the chosen wave periods (T) are given.

Table B.1: Values $\varepsilon\ x_{12}/L_{max}$ and $E\ x_{12}/L_{min}$ for various gauge array settings (W-value and relative gauge spacings) (Wenneker and Hofland, 2014)

Setting name	W	x_{23}/x_{12}	x_{23}/x_{12}	ε	E	L_{max}/L_{min}
GS(2)	2	–	–	0.05	0.45	9
MF(3a)	3	0.50	–	0.04	0.95	24
MF(3b)	3	0.15	–	0.05	2.96	59
ZS(4)	4	0.22	0.15	0.05	13.5	270
ZS(50)	50	1	1	0.002	0.498	249

Table B.2: Wave length and wave number for different wave periods for d = 0.15 m

T	L_0	L_{15}	k_{15}
1.2	2.25	1.35	4.64
1.4	3.06	1.61	3.90
1.6	4.00	1.86	3.37
2.0	6.25	2.37	2.66
4.0	24.98	4.82	1.30
10.0	156.13	12.12	0.52

To determine the WG locations, for each method the lower and upper boundary are calculated, with eq. (B.1) and all wave lengths (L_{min} = 1.35 m for T = 1.2 s and L_{max} = 12.12 m for T = 10.0 s). This results in the values as given in table B.3.

Table B.3: Lower and upper WG distance boundaries, calculated with eq. (B.1), for all waves

	GS(2)	MF(3a)	MF(3b)	ZS(4)	ZS(50)
Lower boundary	0.6059	0.4847	0.6059	0.6059	0.0242
Upper boundary	0.6091	1.2858	4.0064	18.2725	0.6741

It can be seen that for the method with two WG's (GS), the upper and lower boundary only differ 0.032 m, which is too detailed to be useful in the flume. Therefore the wave lengths are separated into long(er) and short(er) waves. For all wave periods, the corresponding L_{15} and k_{15} values are plotted in figure B.1. In figure B.1 the most left bullet represents T = 10.0 s and the most right bullet T = 1.2 s. The shallow water limit is 20*h = 3.00 m (wavelengths longer than 3.00 m are considered as long and for those waves the water is shallow), the deep water limit is 2*h = 0.30 m (waves shorter than 0.30 m are considered as short, for those waves the water is deep). For the water depth of 0.15 m the two longest waves are long waves, and the remaining four waves are intermediate waves. The wave periods are separated into long waves (T = 4.0 s and T = 10.0 s) and intermediate waves (T = 1.2 s up to T = 2.0 s).

The calculation of the lower and upper boundaries needs to be repeated, because the longest or shortest wave length changes by separating the wave lengths. This gives for the intermediate waves the values as given in table B.4, and for long waves as given in table B.5.

First of all, there are not enough WG's to use the ZS(50) method, so this method will not be considered. Also, only one method for three WG's is used, so a value in between those of MS(3a) and MS(3b) is also accepted.

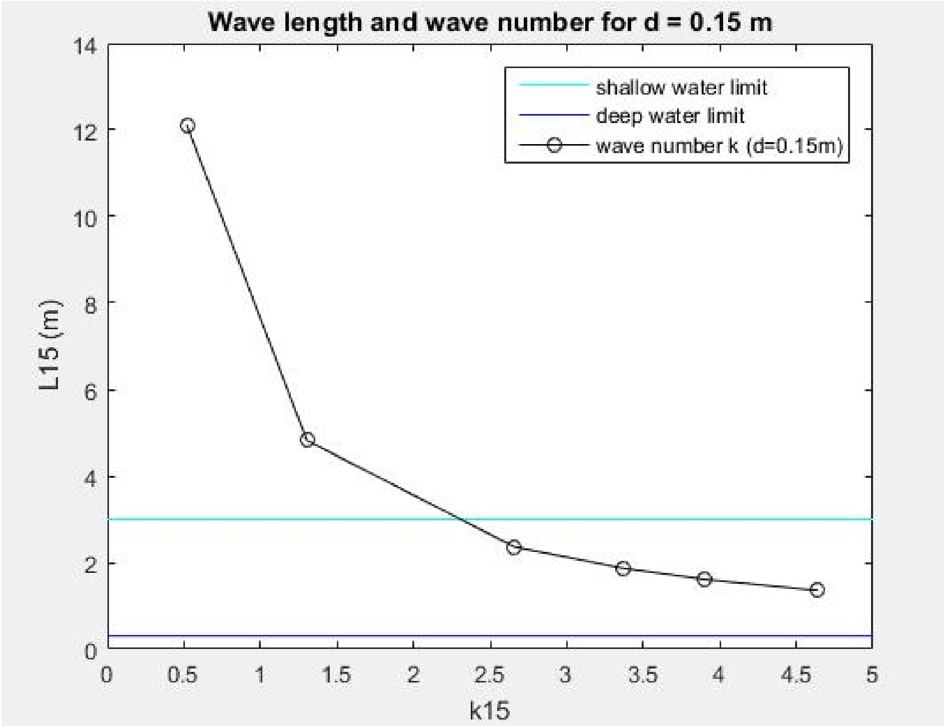

Figure B.1: Wave length and wave number for different wave periods for $d = 0.15$ m

Table B.4: WG distance boundaries for intermediate waves, calculated with eq. (B.1), in m

	GS(2)	MF(3a)	MF(3b)	ZS(4)	ZS(50)
Lower boundary	0.12	0.09	0.12	0.12	0.004
Upper boundary	0.61	1.29	4.01	18.27	0.67

Table B.5: WG distance boundaries for long waves, calculated with eq. (B.1), in m

	GS(2)	MF(3a)	MF(3b)	ZS(4)	ZS(50)
Lower boundary	0.61	0.48	0.61	0.61	0.02
Upper boundary	2.17	4.58	14.27	65.09	2.40

The most efficient use of the WG's is when four WG's can be used for each range of wave lengths: the same distances as used for ZS(4) can be used for MF(3a/b) as well as GS(2). The WG position furthest away will also be used to place an EMF. See figure B.2, in which the black line represents the length over the flume, with incoming waves from the left. A dark grey line represents a WG (chosen location for the corresponding method), a light grey line represents a possible WG location (not used in the corresponding method) and a dark red line represents an EMF. The distances x_{xx} represent the values that need to be calculated.

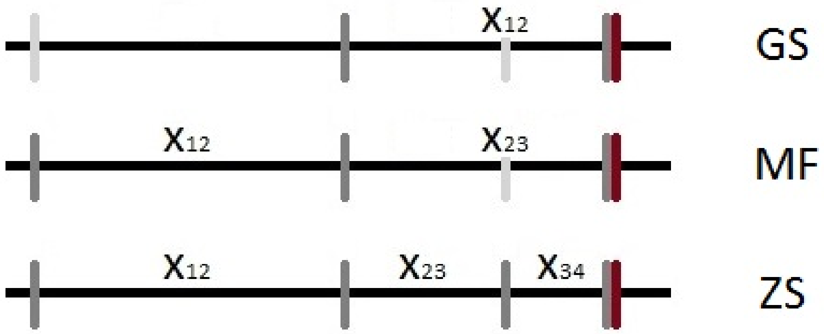

Figure B.2: Wave gauge spacing for intermediate and shallow water (dark grey indicates a WG, light grey indicates no WG, red indicates an EMF at shown positions)

As there are two ranges of wave lengths (long and intermediate waves) which both will use a maximum of four WG's, the most optimal use of the equipment is to choose the distances such that five WG's are needed, see figure B.3 with indications for the ZS method.

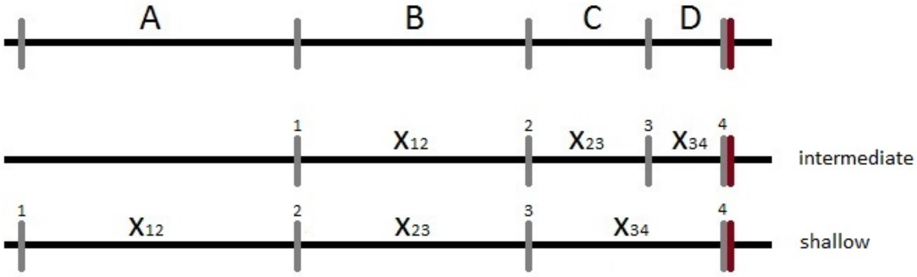

Figure B.3: Wave gauge spacing for intermediate and shallow water (dark grey indicates a WG, red indicates an EMF at shown positions)

For the intermediate range wave lengths, the distances B, C and D are used. For the long waves, the distances A, B and C+D are used. In the following a step-by-step-calculation is done to find the indicated distances.

First a value has to be chosen from which the other distances can be calculated. This is done for the shortest WG spacing: D. The distance should be easily measurable in the laboratory, not too short so that a small positioning inaccuracy will not have too much influence, and also taking into account the size of the measuring equipment. It is chosen that D = x_{34} = 0.15 m. Using the limit values from tables B.4 and B.5, and the ratios between different distances and values of ε and E from table B.1, the other distances can be chosen, first for the intermediate range distances (B, C, D), which are checked for the long wave distances (adding A). This gives:

A = 4.00 m
B = 1.00 m
C = 0.25 m
D = 0.15 m

For C the distance is changed from 0.22 m (which follows from calculation) to 0.25 m, which also satisfies. For A the distance can lie between 2.47 m and 4.55 m. A shorter length for A (for example 3.00 m) makes the ratio A/C too large compared to the recommended ratio from table B.1; a larger length (for example 4.50 m) makes the ratio A/D too small. Therefore the value of 4.00 m is chosen, which approaches both ratios well.

B.1.2 Other locations for wave gauges

From the thirteen WG's, five are used at the back of the flume, so the remaining eight are distributed as follows: three are needed at the front of the flume, to use for the calibration. Another three are used at the start of the flat, elevated bottom profile, so after the sloping 'foreland', to determine the reflection at that location. For further research involving the mangroves this is an important location. This leaves two WG's, which are evenly distributed over the middle of the flat part, so that there is some insight in the wave behaviour here.

The two groups of three WG's (plus an EMF) can be used to calculate the reflection with the WG/EMF method of Guza et al., (1984), the two WG method of Goda and Suzuki, (1976) and the three WG method of Mansard and Funke, (1980) for intermediate waves, and also for the method of Goda and Suzuki, (1976) for long waves. It is proposed to use the same spacing for both groups as is used near the wave absorber, so that the locations can be compared best.

For each group of WG's one 'reference location' is chosen, which is used in previous experiments, and is marked along the flume. It can be difficult to determine the exact locations of the equipment, as the flume is very long, so using a marked location makes positioning the equipment more convenient. The distances from the wave paddle are chosen as given in table B.6.

Table B.6: Wave gauge locations (distance from beginning of flume, in m)

WG1	WG2	WG3	**WG4**	WG5	WG6	WG7
5.00	6.00	6.40	**14.15**	15.15	15.55	
WG8	WG9	WG10	WG11	WG12	**WG13**	
	28.85	32.85	33.85	34.10	**34.25**	

WG's 1, 4 and 13 are the reference locations (bold). For the two remaining WG's there is 28.85 – 15.55 = 13.30 m left. Divided into three gives approximately 4.45 m. There are two reference locations, at 20.25 m and at 24.25 m; this is close enough to the otherwise calculated locations for WG7 and WG8. The complete overview of WG locations is given in table B.7.

Table B.7: All wave gauge locations (distance from beginning of flume, in m)

WG1	WG2	WG3	WG4	WG5	WG6	WG7
5.00	6.00	6.40	14.15	15.15	15.55	20.25
WG8	WG9	WG10	WG11	WG12	WG13	
24.25	28.85	32.85	33.85	34.10	34.25	

B.2 Placing of EMF's

The seven EMF's need to be placed at the same location as a WG. It is chosen to place EMF's at WG1, WG4 and WG13 (these are important locations to determine reflections: at the beginning of each group of three WG's and at the back of the flume with the last WG). Along the elevated bottom profile the remaining four EMF's are distributed more or less evenly over the WG's: at WG7, WG8, WG9 and WG10, so that each in-between distance is approximately 4.00 m. The complete overview of equipment locations is as given in table B.8.

Table B.8: All wave gauge and EMF locations (distance from beginning of flume, in m)

WG1	WG2	WG3	WG4	WG5	WG6	WG7
5.00	6.00	6.40	14.15	15.15	15.55	20.25
EMF1			EMF2			EMF3
WG8	WG9	WG10	WG11	WG12	WG13	
24.25	28.85	32.85	33.85	34.10	34.25	
EMF4	EMF5	EMF6			EMF7	

Experiments part 1

C

In this section the experiment set-up for the first series of experiments is described. Although the final reflection results are not used in the general reflection analysis as performed in the main report, other conclusions are drawn from these experiments and used in the subsequent experiments.

C.1 Experiment set-up

C.1.1 Flume and profile

Between the first series of experiments (described in this appendix) and the second series (see chapter 4), there are some changes in the set-up of the flume and profile lay-out:

- In these first series of experiments the plate at the back of the flume, which separates the flume (behind the wave absorber) from the outflow section in the back, contains holes to maximise the water exchange. It is assumed that the outflow section provides 'additional length' to the wave absorber, and helps to reduce the wave energy. During these first experiments there was no significant difference found in reflection reduction; to simplify the experiment set-up in the sequencing experiments the back is closed off behind the wave absorber.
- The water level at the elevated part of the flume was chosen to be 0.10 m in the first experiments. This is adjusted to 0.15 m depth during subsequent experiments.
- In the second series, one WG is added (thirteen instead of twelve), as well as four EMF's (seven instead of three). Therefore the equipment positions differ; compare section 4.2.3 and appendix C.1.3.
- In the first experiments two stone sizes are compared, in the final experiments only one stone size is used.

C.1.2 Wave conditions

On beforehand the wave conditions are chosen, which are run in the flume for different wave absorber lay-outs. The wave periods for the first experiments are chosen based on Mallayachari and Sundar, (1994), who plot the parameter kb against the reflection coefficient K_r. The factor kb consists of the wave number k and the width of the porous media (which is the wave absorber) at still water level, b. The reflection coefficient K_r is the ratio between the reflected wave height to the incident wave height and lies between 0 and 1, as the reflected waves will not be higher than the incident waves. In figure C.1 an example can be seen; values of kb are given between 0 and 8.0, as for higher values K_r remains more or less constant.

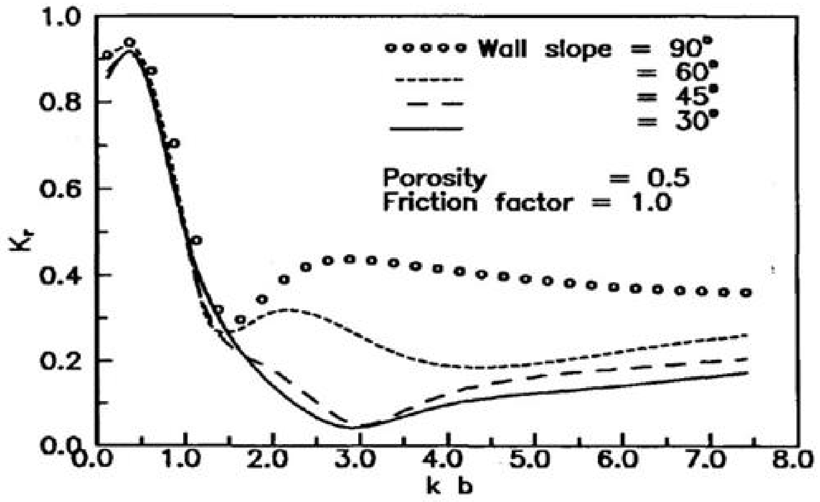

Fig. 9. Effect of wall slope on reflection coefficient.

Figure C.1: Effect of wall slope in reflection coefficient (Mallayachari and Sundar, 1994)

To get to values for the wave period T , first values of k are needed, which can easily be calculated using kb and b. For kb, values are chosen ranging between 1.0 and 6.0, in steps of 1.0, so that there is a more or less even spreading. To see more detail at the left part of the graph of figure C.1, also smaller values than 1.0 are chosen. Because $k \sim 1/L$, the low kb-values represent long waves and the higher kb-values represent short waves.

The length of the wave absorber at still water level (b) is 2.0 m in the first design (see appendix C.1.5). With the found values for k, the deep water wave length L_0 (eq. (C.1)) can be calculated as a first estimate, and can be used to calculate the corresponding wave period T (eq. (C.2)). The value of T is rounded to a convenient value T_{chosen}, which is used for the experiments. The steps can be seen in table C.1.

$$L_0 = \frac{2\pi}{k} \tag{C.1}$$

$$T = \sqrt{\frac{L_0 2\pi}{g}} \tag{C.2}$$

For the wave height the values as shown in table C.2 are used.

C.1.3 Equipment positions

For all executed experiments use is made of twelve wave gauges (WG's), which measure the wave heights (in figure C.2 shown in red), and three EMF's (electromagnetic flow meters), which measure the velocity (shown in green). In table C.3 the locations of the wave gauges and EMS's are given, measured from the wave paddle (distances in meters).

Table C.1: Determination of T with starting point kb

kb	b (m)	k	L_0 (m)	T (s)	T_{chosen} (s)
0.10	2.0	0.05	125.66	8.97	10.0
0.25	2.0	0.13	50.27	5.67	6.0
0.50	2.0	0.25	25.13	4.01	4.0
1.0	2.0	0.5	12.57	2.84	3.0
2.0	2.0	1.0	6.28	2.01	2.0
3.0	2.0	1.5	4.19	1.64	1.6
4.0	2.0	2.0	3.14	1.42	1.4
5.0	2.0	2.5	2.51	1.27	1.3
6.0	2.0	3.0	2.09	1.16	1.2

Table C.2: Used wave heights for the various used wave periods

	T (s)					
H (m)	1.2	1.4	1.6	2.0	4.0	10.0
0.02					x	x
0.03					x	x
0.04			x			
0.05	x	x	x	x		

Table C.3: Locations of measuring equipment

# WG	Location WG (m)	Location EMF (m)
1	5.00	
2	5.65	
3	5.86	
4	12.00	
5	17.00	
6	17.20	
7	17.35	17.35
8	18.25	18.25
9	22.25	
10	26.25	
11	30.25	
12	34.25	34.25

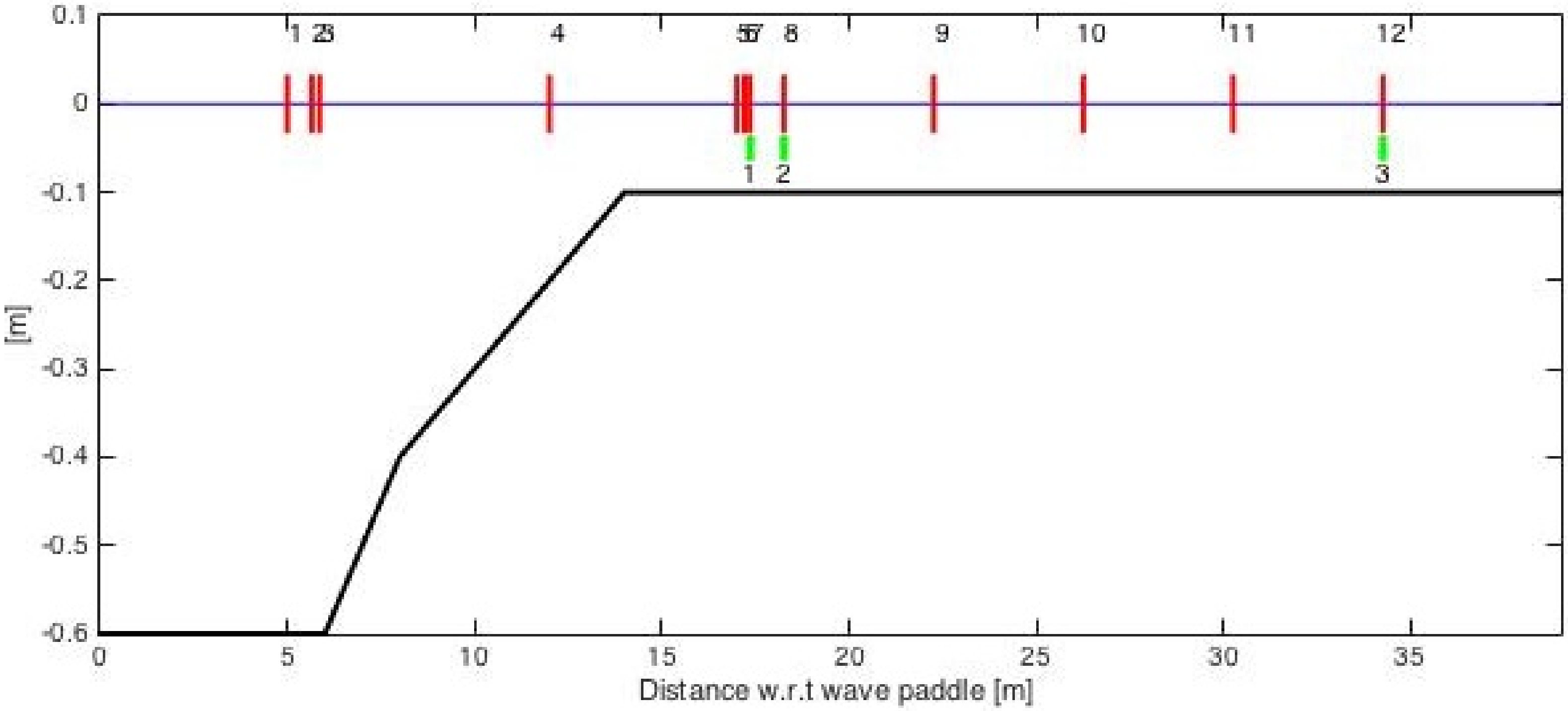

Figure C.2: Locations of the wave gauges and EMF's along the flume for the first series of experiments

C.1.4 Calibration

For the method of calibration, see appendix D. The calibration values are not given for this part of the experiments.

C.1.5 Wave absorber lay-outs

At the back end of the flume, just before the wooden plate which separates the flume and outflow section, a wave absorber is constructed. To construct this wave absorber, rock is used; it absorbs some of the wave energy and thus reduces the reflection of the incoming waves. Exchange between the flume and the outflow section is possible if the wooden plate contains several holes. This helps reducing the reflection, which works best with as many holes as possible (without losing strength to hold the stones of the wave absorber).

The shape of the wave absorber is assumed to have significant influence on the amount of reflection measured in the flume. Therefore various parameters are investigated on their influence on the reflection. These parameters are:

- The length of the wave absorber at the still water level (L_{SWL}). The tested options are lengths of 1.0 m and of 2.0 m.
- The possibility of reflection at the end of the wave absorber: is there a difference if the end of the wave absorber is closed off, and if water exchange between flume and outflow section is possible?
- The front of the wave absorber: what shape is more effective? The tested versions are a 1:5 slope and a berm around still water level.
- The stone size: the used stone sizes are 25-40 mm and (approximately) 40-70 mm.

As boundary condition the edges of the built-in bottom profile of the flume need to be sealed as good as possible. Otherwise the gaps between the profile and the sides of the flume cause flows along the sides of the flume, by water moving vertically along the bottom edges of the build in-bottom.

The model runs are performed on the following wave absorber lay-outs; in table C.4 the lay-outs are given for easy comparison:

1. Reference
As a reference for all experiments is needed, the first lay-out is chosen to have all mentioned parameters as expected to be most effective. This reference wave absorber has a length of 2.0 m at still water level (which is 0.60 m at the beginning of the flume and 0.10 m at the wave absorber end of the flume), a berm at the front side, and is built with stones of 25-40 mm in size. The back of the flume is closed off with a plate containing multiple holes.

2. Slope
The first aspect for change is the front of the wave absorber: in this lay-out the berm is replaced by a 1:5 slope. All other aspects are similar as in lay-out 1.

3. Closed off back
For this lay-out, the plate behind the wave absorber (containing holes) is replaced by a

closed plate, so that the end of the flume is closed off. In all other lay-outs the end of the flume has a plate with multiple holes in it right behind the wave absorber. The rest of this lay-out is equal to that of the reference configuration. By this change the influence of the basin of the outflow section behind the wave absorber can be investigated.

4. Closed off sides
During the experiments of lay-outs 1, 2 and 3 it was seen that wave crests started breaking at the sides of the flume; the middle of each crest broke some time later. Also, an upward flow was seen at the sides of the flume: water came up from under the build-in bottom. It is expected that the upcoming water caused the non-uniformly breaking waves. Therefore the gaps along the bottom plate are closed off. To see what the influence of this measure is on the reflection coefficient, this lay-out is added to the experiment.

5. Shorter
To see the influence of the length of the wave absorber, its length at still water level is decreased from 2.0 m to 1.0 m. This lay-out also contains a berm, so that it is comparable to the reference lay-out: only the length differs.

6. Larger stones
It could be interesting to see whether the stone size has a large influence on the absorption of waves or not. Therefore the stones (25-40 mm) are removed and replaced by larger stones (40-70 mm, although there were a lot of chips present, as it was the last remainder of what was left in the bag). Also more holes are drilled in the plate behind the wave absorber (which might influence the amount of reflection). The length of this wave absorber lay-out is 1.0 m.

Earlier (probably before or during the runs of lay-out 5) some holes are drilled in the bottom itself, at the end of the wave absorber, to let out the water during filling. It is expected that this doesn't have a significant influence on the results, as it considers vertical water movement.

Table C.4: Lay-outs experiments part I

Lay-out	Description	Length at SWL (m)	Front	Stone size (mm)	Back	Sides
1	Reference	2.00	Berm	25-40	Open	Open
2	Slope	2.00	**Slope**	25-40	Open	Open
3	Closed off back	2.00	Berm	25-40	**Closed**	Open
4	Closed off sides	2.00	Berm	25-40	Open	**Closed**
5	Shorter	**1.00**	Berm	25-40	Open	**Closed**
6	Larger stones	**1.00**	Berm	**40-70***	Open	**Closed**

C.2 Expectations

It is expected that reflection can be minimised by increasing the length of the wave absorber, which can be done by lengthening the actual wave absorber or by maximising the total area of holes in the back plate, resulting in the outflow basin to become part of the wave absorbing structure. Also a larger stone size is expected to decrease the reflection. The front of the wave absorber is expected to be most effective in decreasing reflection when formed as a berm, as compared to a 1:5 sloped front.

C.3 Experimental runs

For the experimental runs, each wave condition is given a certain code. These codes consist of the following parts:

- Regular (Re) or irregular (Ir) waves;
- Water depth (D) at the start of the flume, in cm: for example a water depth of 0.60 m near the wave paddle results in D60;
- (Significant) wave height (H) of the chosen waves in cm; for example for the waves of 0.05 m, this gives H05;
- (Significant) wave period (T) of the chosen waves in tenths of seconds, with an exception for the wave period of 10 s, which is in seconds; for example the waves with $T = 1.6$ s are labelled T16.

For regular waves, 100 waves are simulated. For irregular waves 1000 (significant) waves are simulated. In table C.5 the runs for each configuration in the first part of the experiment are given. For all wave conditions in this part of the research the water depth is 0.60 m.

Table C.5: Experiment runs (part I)

	Runs	Configurations					
Short regular waves	ReD60H05T12	1	2				
	ReD60H05T14	1	2				
	ReD60H05T16	1	2		4	5	6
	ReD60H05T20	1	2				
	ReD60H04T16	1	2				
Long regular waves	ReD60H02T40	1		3		5	6
	ReD60H03T40	1		3			
	ReD60H02T10	1		3	4	5	6
	ReD60H03T10	1		3			

C.4 Results

C.4.1 Observations

During these first series of experiment runs, the following points are worth noting:

Non-uniformly breaking waves and upcoming water
For lay-outs 1, 2 and 3 it was seen that water came up from the sides of the build-in bottom. Especially for the longer wave periods, in between two waves, this was clearly noticeable. Also, wave crests started breaking at the sides, while the middle of each crest broke some time later. This breaking pattern was thought to be caused by this upcoming water. Therefore the sides of the bottom were closed off better. During the runs hereafter, indeed the non-uniformity of the breaking waves was decreased. The crests were more stable, although not all of the effect was eliminated.

3D-effects
It might be possible that 3D-effects, for example a shift of the wave crests in the perpendicular direction, are less present with a wave absorber with berm than for sloped wave absorbers (although the slope angle might also be of influence).

Other factors
There are also various other factors to be pointed out that could influence the value of K_r:

- Disturbances during the experiment run, for example by turning on or off another (heavy) device in the Stevin III laboratory;
- Inaccuracies in the measuring equipment;
- Inaccuracies in the equipment between measuring and recording the data. This could happen when two measuring devices are connected to different converting devices which are calibrated differently;
- Selection of the interval of which the reflection value is calculated in Matlab. This could result in a difference of 25% in the K_r-value.

C.4.2 Comparisons

The data is analysed in Matlab with the WG/EMF implementation, to obtain the reflection values for all runs. It has to be kept in mind that for the experiment runs of lay-out 4 and later, the bottom profile sides will be kept closed off.

Theory of Mallayachari and Sundar, (1994)
Unfortunately, it is not possible to fit the results in the graphs of Mallayachari and Sundar, (1994). The trend line as found in their research could not be reproduced with the results of these experiments when plotting K_r against kb: all calculated K_r-values are more or less between 0.20 and 0.40 and the peak for low kb-values towards $K_r = 1$ is not present. Reasons for this could be that Mallayachari and Sundar perform their experiments in deep water, whereas the experiments for this research are executed in intermediate to shallow water (depending on the wave period). Another explanation is that the WG/EMF-implementation is not suitable to use for the analysis of the experiment data (see section 3.3.1).

Open or closed bottom profile sides
The water that is coming up from the sides, causing waves starting to break earlier at the sides of the flume, might cause damping of the waves and thus a lower reflection rate. For the two wave conditions that are compared, the effect of closing off the sides of the built-in bottom is significant: closing off the sides results in approximately 20% higher K_r-values. The difference was not expected to be so large; therefore only two wave conditions were run. This makes it much more difficult to compare the following lay-outs (5 and 6) to the reference lay-out (1).

Slope or berm
For short waves the effectiveness of the front of the wave absorber is evaluated: is a slope or a berm more effective? Lay-out 1 has a berm with a slight slope at still water level, and lay-out 2 has a 1:5 sloped front. It is found that for most examined wave conditions the 1:5 slope is more effective (has a lower K_r-value) than a berm, which is different from the expectations.

Effect of closed back
Comparing the experiment runs for lay-outs 1 and 3, it is found that if there is no exchange possible between the water in the wave absorber and the basin: there is more reflection.

Wave absorber length
The results for lay-outs 1 (2.0 m long) and 5 (1.0 m long) are compared and as expected, a longer wave absorber is more effective in keeping the reflection low. For short waves the length of the wave absorber might not be of great influence: after a certain length (which is larger than the wave length) the waves are damped, so a longer wave absorber can't damp more short waves, as they already are.

Stone size
Before replacing the stones (with a larger stone size) for lay-out 6, more holes were drilled in the back plate. This makes the back more open, which has influence on the reflection in the flume, as found before. There are therefore two differences between lay-outs 5 and 6: the stone size and the additional holes in the back plate. It can be noticed that for the short wave condition that is run, the smaller stones are more effective in absorbing waves, but for the long wave conditions there is no clear conclusion to be drawn. It must be kept in mind that the additional holes in the back plate might have some influence, and the reflection values for lay-out 6 could be slightly higher. Compared to the 'reference case' of lay-out 1, both lay-outs 5 and 6 give outcomes that are well comparable to 1, even though 1 scores better because of the 'open' bed sides. Overall, there is too little information to draw a definite conclusion about whether stone size has influence.

Wave height
For the same value of kb (and thus the same wave period T), the reflection coefficient is higher when the generated wave height is lower. Only for the longest wave period ($T =$ 10.0 s) the result for the higher wave is slightly higher.

C.5 Conclusions

Due to changing too many parameters per experiment lay-out (or running too little lay-outs), it is very difficult to draw good conclusions from the performed experiments. It can be said that closing off the sides of the bottom profile is much more important than expected, and it is therefore recommended to pay close attention to the connection between profile and flume sides. Furthermore, due to the small water level waves can become unstable. Decreasing the wave height made the waves more stable, but made measuring the desired input more difficult. Increasing the depth could reduce this problem. The analysis of these results to find a good wave absorber lay-out is a first indication; in further research (the second series of experiments) this can be investigated more accurately.

Calibration

D

The WG's need to be calibrated before data can be analysed. The calibration values depend on the WG itself and on the cable that connects the WG with the measuring box, so each combination of WG and cable gives a different calibration value. Also the settings on the measuring box influence the calibration value: it can be set on a certain voltage.

To calibrate the WG's, the water level with respect to the length of the WG that is submerged into the water needs to be measured. For this, two methods can be used: either the WG is moved up or down, or the water level is increased or decreased. As use is made of thirteen WG's and all WG's can be 'read' simultaneously, the second method is used.

The WG's are kept at a certain height, and will not be moved during the calibration. Also the voltage is kept at the chosen value (in this case 50 V for WG's 1 to 6 and 20 V for WG's 7 to 13), only the water level is changed during calibration. One (or more) measurement is taken at 'low' water level, which is around 0.15 m (0.65 m at the beginning of the flume) and one (or more) measurement is taken at 'high' water level, which is around 0.21 m (0.71 m) to 0.23 m (0.73 m) height. For both water levels it is important that there are no waves or ripples, and that the water level is read as accurately as possible, so that the calibration values are also as accurate as possible.

Using Matlab the average voltage for each WG is calculated for both the high and the low water level, after which the water level difference is divided by the difference in average voltages. This gives the calibration value for each WG.

Of course, due to minor fluctuations in water level, reading or equipment inaccuracies, the calibration values need to be checked on accuracy. This is done by performing multiple calibrations. In total, three calibrations were performed during experiment runs 2 to 7 and two calibrations were performed during experiment runs 8 to 11; the used calibration values can be seen in tables D.1 and D.2 respectively.

Table D.1: Calibration experiment runs 2 to 7

WG1	WG2	WG3	WG4	WG5	WG6	WG7
0.0232	0.0224	0.0245	0.0264	0.0226	0.0223	0.0103
WG8	WG9	WG10	WG11	WG12	WG13	
0.0101	0.0095	0.0091	0.0088	0.0087	0.0093	

Table D.2: Calibration experiment runs 8 to 11

WG1	WG2	WG3	WG4	WG5	WG6	WG7
0.0226	0.0226	0.0246	0.0263	0.0216	0.0207	0.0531
WG8	WG9	WG10	WG11	WG12	WG13	
0.0099	0.0094	0.0088	0.0079	0.0083	0.0090	

E Experimental runs

To give more insight in the experiment process, more details are given. The order of performing the experiments is different from the lay-out order given in section 4.2.5. The experiments are performed in the following order; for each set up the wave conditions that are run are given in table E.1.

1. The wave absorber is constructed as in lay-out C, with the end of the flume not closed off, but containing holes to provide water exchange between the flume and the outflow basin behind the flume. The equipment set up is different in these series.[1]
2. Using the same wave absorber lay-out (lay-out C) as in 1., but changing the equipment positions as given in table 4.3.
3. Closing off the back of the flume; all other parameters as in 2.
4. The wave absorber is constructed as in lay-out E: with a 1:3 slope and a bottom length of 3.00 m.
5. The wave absorber is constructed with a 1:10 slope (lay-out D).
6. The wave absorber is shortened to lay-out B: with a 1:3 slope and a length at SWL equal to that of 5.
7. The wave absorber is removed (lay-out A) to make a 'reference' for all wave absorbers to study the amount of reflection when no wave absorber is present.
8. The 1:10 slope is reconstructed (lay-out D) and tested to see if the results are comparable to those of 5. For this case and the following cases (8. to 11.) EMF1 is not connected.
9. Part of the wave absorber toe is cut off to create lay-out F.
10. An extra part of the wave absorber toe is cut off to create lay-out G.
11. The slope is adapted to 1:15 and the wave absorber is lengthened to create lay-out H.

[1] Equipment set-up of L. Phan Khanh, to make any comparison with her research easier.

Table E.1: Wave conditions run for each experiment set-up

	Runs	Experimental runs 1	2	3	4	5	6	7	8	9	10	11
Regular waves ($H = 0.05$ m)	ReD15H05T12	x	x	x	x	x	x	x				
	ReD15H05T14	x	x	x	x	x	x					
	ReD15H05T16	x	x	x	x	x	x	x				
	ReD15H05T20	x	x	x	x	x	x	x	x	x	x	x
	ReD15H05T25				x	x	x					
Regular waves ($H = 0.02$ m)	ReD15H02T16				x	x	x	x				
	ReD15H02T20				x	x	x	x	x	x	x	x
	ReD15H02T30				x	x	x					
	ReD15H02T40	x	x	x	x	x	x		x	x	x	x
	ReD15H02T60				x	x	x	x	x	x	x	x
Regular waves ($H = 0.01$ m)	ReD15H01T60				x	x	x	x	x	x	x	x
	ReD15H01T80				x	x	x	x				
	ReD15H01T100	x	x	x	x	x	x	x	x	x	x	x
Irregular waves	IrD15H05T16	x	x	x	x	x	x	x	x	x	x	x

Numerical runs

F

The experiment set-up and wave conditions are modelled in SWASH. It is attempted to get the same results from the SWASH-model as obtained from the experiments. In this appendix the SWASH results are given. The model set-up can be found in chapter 7.

F.1 Results

F.1.1 Reflection values

First of all, the synthetic signal is reproduced. In the SWASH-model, the water depth d is set to 0.15 m over the whole flume length of 37.5 m. No friction is added and instead of a wave absorber, a sponge layer of 50 m length is used. The results can be found in table F.1. The K_r-values are expected to be be very low, because of the sponge layer. It can be seen that for all modelled wave conditions R2 gives relatively low reflection values, which lie around 1%, but those of R3 are significantly higher, with an exception for H01T100. It is uncertain what causes this large deviation, especially compared to H01T60, as the only difference between these two SWASH-runs is the wave period.

The wave absorber that is found to be most effective in the experiments, with a 1:15 slope and a toe that is shortened at 0.05 m height (lay-out B, figure 4.9), is modelled in SWASH. Besides the wave absorber also friction and the foreland bathymetry are added. In table F.1 it can be seen that SWASH underestimates the reflection values for H01T100 and H02T20, but overestimates the values for H01T60. Finetuning the SWASH-results by changing the friction coefficient gives no explanation for these differences in outcome; it is not possible to find a friction coefficient for which all wave conditions give comparable reflection results between numerical and physical modelling.

For the 1:10 slope wave absorber it is tried to find better matching results. For all mentioned wave conditions the results are given in table F.1. On one wave condition different adaptions in SWASH are tried; H02T20 is chosen as it has a relatively low Ursell number (lower than 100, which indicates that linear wave theory is applicable) and is run three times during the experiments (giving results that don't differ much from each other). It is found that increasing the number of horizontal grid cells, vertical layers or both does not give better results. When using a 30 m long sponge layer with this wave condition, increasing the friction coefficient by 1.5 times halves the reflection values.

Table F.1: Comparison of K_r-values between experiments and SWASH, for different wave conditions and implementations R2 and R3

Wave absorber lay-out	Implementation	H01T100			H01T60			H02T20		
		K_r		Difference	K_r		Difference	K_r		Difference
		experiment	SWASH		experiment	SWASH		experiment	SWASH	
Sponge (50 m)	R2		0,006			0,013			0,022	
	R3		0,013			0,097			0,077	
1:15 slope with toe	R2	0,462	0,281	- 39%	0,105	0,234	+122%	0,104	0,075	- 28%
	R3	0,454	0,294	- 35%	0,126	0,324	+157%	0,136	0,080	- 41%
1:10 slope	R2	0,585	0,293	- 50%	0,273	0,247	- 9%	0,026	0,018	- 34%
	R3	0,568	0,301	- 47%	0,211	0,335	+59%	0,055	0,080	+45%

F.1.2 Wave signal and wave height

Looking at the wave signals, for H02T20 both signals agree well, so the wave height and wave period seem to match. However, after the foreland the wave height of SWASH gets higher compared to the experiment wave height, and the SWASH-signal also seems to have a larger phase speed than that of the experiment signal. For aditionally modelled wave condition H02T60 the wave periods match, but the shape of the wave signal differs. This looks like a difference in dispersion, which can be investigated by increasing the number of layers or by decreasing the grid size. As mentioned before, both options give no solution to this problem. Another point to notice for H02T60 is that the SWASH-signal lags behind the experiment signal after passing the foreland, and starts to show a dispersive tail (additional small waves on the main wave), which also indicates dispersion issues. The experiment signal also shows this behaviour, but after a longer distance.

The wave height of the incoming part of the experiment signal should be comparable to the total signal created by SWASH when modelled with a sponge layer: in both situations reflection is not taken into account. For H02T20 the significant wave height of SWASH is much higher than that calculated from the experiment data. The wave heights before the foreland match very well, but after the foreland not anymore. For H02T60 the wave heights after the foreland are better comparable than those of H02T20, but over the first meters (at 0.65 m water depth) the SWASH-values lie below the experiment values. The dispersion doesn't seem to match between the two cases for H02T60.

F.2 Conclusion

It is uncertain why the reflection values calculated from the SWASH data don't match the experimental results. The correspondence between both depends on the wave conditions. It is found that higher waves give better corresponding results than lower waves. For the wave condition H02T20 and the 1:10 slope wave absorber lay-out the solution doesn't lie in decreasing the number of horizontal grid points or vertical layers.

It is concluded that it is not possible to reproduce the physical modelling results by SWASH, without changing so many parameters per individual model run that it is not generally applicable any more.