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Understanding the influence of beach morphology on the alongshore variance in wave run-up on an intermediate reflective beach, considering bars and cusps

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by

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Cover image: beach cusps at Napatree point, Rhode Island (downloaded from https://commons.wikimedia.org/wiki/File:Beach_cusps_at_Napatree_Point_(52404).jpg)

Abstract

The topic which is considered in this thesis is: understanding the influence of beach morphology on the alongshore variance in wave run-up on an intermediate reflective beach, considering bars and cusps. The focus of this thesis is laid inside the swash zone, in which the water motion is present of waves that run up and run down on a beach. Energy from wave run-up could deliver erosion to the beach. It is relevant to know what the magnitude is of run-up during extreme events, in order to protect the beach. Several studies are done to wave run-up. There are relations which specify run-up, however, the alongshore variability is not studied in detail and less knowledge is available about this topic. At Anmok beach in South-Korea an intermediate reflective beach is present containing beach cusps and crescentic sandbars. A rhythmic bar and beach state contains the most complex morphology, furthermore the morphology changes a lot within intermediate beaches (Wright and Short [1]). The characteristics of this beach are used to perform an analysis to the influence of cusp and bar morphology on alongshore variation in wave run-up.

Run-up is composed of setup and swash. Setup is the super elevation of the mean water level, swash is ''a time-varying location of the intersection between the ocean and the beach'' according to Stockdon, Holman [2]. Swash can be decomposed into two parts, incident band swash and infragravity band swash. Swash and setup depend on beach slope, deep-water wave height and the deep water period[2].

To analyse the alongshore variability multiple bathymetries have been generated on which 500 waves are modelled for 60 different wave condition. First of all a reference case is modelled with a uniform bathymetry. Secondly beach cusps are used as input with different length scales and at last a beach cusp with crescentic sandbar is used. The length scales of the cusps are 452, 300 and 100 metres. The bathymetries are idealized bathymetries with the characteristics of Anmok beach. The run-up and components are calculated and an analysis is done to the magnitude of run-up and the standard deviation along the beach.

The magnitude of run-up is lower for a cusp system compared with the reference situation and even lower for the cusp bar system. Furthermore there are no large differences in magnitude of run-up between different cusp lengths. A larger alongshore variance is observed when a cusp (bar) system is present. A cusp system of 452 metres contains larger run-up at the horn compared with the embayment, this holds for large and small wave heights. The difference is 18% and 8.4% respectively. However, when a cusp bar system is present less alongshore variability is visible and an opposite behaviour is visible for small wave heights. In this case the same pattern can be seen for large wave heights. A difference of 3.68% is seen when the horn is compared with the embayment. However, for small wave heights the run-up is 10.5% smaller at a horn compared with an embayment.

A cusp length of 100 metres shows different behaviour compared with a cusp length of 452 metres. Run-up is larger at an embayment compared to the horn. This holds for large wave heights. The alongshore variance is in this case larger compared to larger cusp lengths. A cusp of 452 metres and 300 metres leads to similar results, whereas a 100 metres cusp shows deviations. It could be edge waves which could have an influence on a cusp with a length of 100 metres.

Acknowledgements

This thesis report is the final requirement of the master Hydraulic Engineering at Delft University of Technology. This research is carried out at Deltares in Delft, this is an independent institute for applied research in the field of water and subsurface.

When I started my master at the university I spoke with my fellow student about Deltares. We discussed topics about hydraulic engineering and about how nice it would be to work on a thesis report at Deltares. Back then it were only thoughts. Now I am at the end of my graduation work, which I started at the end of February at Deltares. I am glad that I had the opportunity to fulfil my thesis at this company.

However, this had not been possible without my thesis committee. Specials thanks go to my daily supervisor Robert McCall who assisted me throughout this period. There were moments in this period where I was kept stuck on certain topics. Luckily, discussions with Robert eventually led to new insights. He kept me on the right path to follow, which brought me to my final report. Furthermore, I want to thank Ad Reniers and Bas Hofland. They gave me new insights and enough input at each progress meeting. I want to thank them for the feedback on my work. I experienced a good cooperation with my thesis committee during this year.

Beside the thesis committee I want to thank the students at Deltares. During the coffee breaks and lunch I asked many of the students certain questions which brought me further with my Matlab struggles. Moreover, it was nice to join all the conversations and also the 'Student drinks'.

I want to thank Timon and Marijn for the good time we had in our study period in Delft. They shared their thoughts and vision about my thesis during dinners. My family and especially my parents supported me during my study period, which I want to thank them for. Finally I want to thank Maaike for her personal and positive support during my study period in Delft.

B.H.W.J. van Luit
Delft, November 2017

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Nomenclature

β	Slope of bathymetry	[deg]
β_f	Foreshore slope	[deg]
β_{mean}	Mean slope	[deg]
d	Depth	[m]
dy	Alongshore grid resolution	[m]
η	Setup, super elevation of the water level	[m]
$\overline{\eta}_{max}$	Alongshore maximum setup	[m]
$\overline{\eta}$	Alongshore averaged setup	[m]
$\eta_{c,max}$	Maximum cusp height	[m]
f_p	Peak frequency	[Hz]
f_s	Frequency spread	[Hz]
g	Gravitational constant	[m/s^2]
gamma-jsp	Frequency spread	[-]
H	Wave height	[m]
$H_{\infty,s}$	Offshore deep water wave height	[m]
H/L	Wave steepness	[-]
H_{m0}	Significant wave height	[m]
H_{m0}	Significant wave height	[m]
∞ cusp	Uniform bathymetry	-
k	Wave number	[m^{-1}]
K	Constant	[-]
K_1	Constant of proportionality	[-]
K_2	Constant	[-]
L_0	Deep water wave length	[m]
L_e	Longshore wave length edge waves	[m]
Ma	Main angle of incidence	[deg]
n	Mode number	[-]
P_{br}	Probability of breaking waves	[-]
R	Vertical wave run-up	[m]
$\overline{R}$	Normalized run-up	[-]
$R_{2\%}$	Two percent exceedance value of run-up	[m]
$R_{2\%,max}$	Alongshore maximum R2%	[m]
$\overline{R}_{2\%}$	Alongshore averaged R2%	[m]
$R_{n\%}$	Nth percent run-up	[m]
R_s	Significant run-up height	[m]
R_s^{ig}	Infragravity run up	[m]
$\overline{R}_s^{ig}$	Normalized infragravity run-up	[-]
R_s^{ss}	Incident run-up	[m]

s	Directional spread	[-]
S	Swash, time varying location of the intersection between ocean and beach	[m]
$S_{\max}$	Alongshore maximum total swash	[m]
$\overline{S}$	Alongshore averaged total swash	[m]
S_{IG}	Infragravity band swash	[m]
$S_{IG,\max}$	Alongshore maximum infragravity band swash	[m]
$\overline{S}_{IG}$	Alongshore averaged infragravity band swash	[m]
σi	Radian frequency incident waves 2pi/T	[Hz]
σIg	Variance infragravity frequencies	[m^2]
σInc	Variance incident frequencies	[m^2]
σθ,0	Deep water directional spread	[deg]
S_{inc}	Incident band swash	[m]
$S_{\text{inc,max}}$	Alongshore maximum incident band swash	[m]
$\overline{S}_{inc}$	Alongshore averaged incident band swash	[m]
std	Standard deviation	[m]
SWL	still water level	[m]
T	Wave period	[s]
T0	Deep water wave period	[s]
Te	Wave period of edge waves	[s]
Tm-1,0	Spectral wave period	[s]
Tp	Peak period	[s]
X24hr	Value for 24 hours model computation	[m]
Xi	Value for timeslot i	[m]
Xi	Value for a subset of data i of one timeslot	[m]
y-jsp	Gamma-jsp, frequency spread	[-]
ξ	Iribarren number	[-]
θ	Main angle of incidence	[deg]

1 Introduction

This document is a report for the MSc thesis: Understanding the influence of beach morphology on the alongshore variance in wave run-up on an intermediate reflective beach, considering bars and cusps. The MSc thesis is the last part of the MSc study Hydraulic Engineering performed at Delft University of Technology (TU Delft).The MSc thesis is carried out at Deltares, an independent institute for applied research in the field of water and subsurface. It is part of the project CoMIDAS – East Coast Case.

This MSc thesis will focus on the hydrodynamics inside the surfzone, but particularly focussing on the swash zone. The latter which is included in the surf zone consist of the motions of the water due to waves, which run up and eventually run down on the beach slope which is known as swash.

The energy which is delivered by wave run-up in the swash zone could create erosion to dunes or the beach. From an engineering point of view it is important to know what the magnitude is for wave run-up at extreme conditions in order to protect the beach and adjacent properties.

Wave run-up has been studied over the last decades to get insight in relations and to predict wave run-up. Relations are specified for wave run-up. However, the longshore variability in wave run-up is not studied in detail and less knowledge is available about this topic. This MSc thesis will focus on the run-up, swash motions and particular to the alongshore variability in wave run-up on an intermediate reflective beach. The research questions for this MSc thesis are related to the longshore variability in wave run-up.

This MSc thesis specifically focuses on a particular location, the East Coast of South Korea. The beach of interest is Anmok beach in Gangneung. In Figure 1-1 to Figure 1-3 the location is shown. The images are taken from Google Earth.

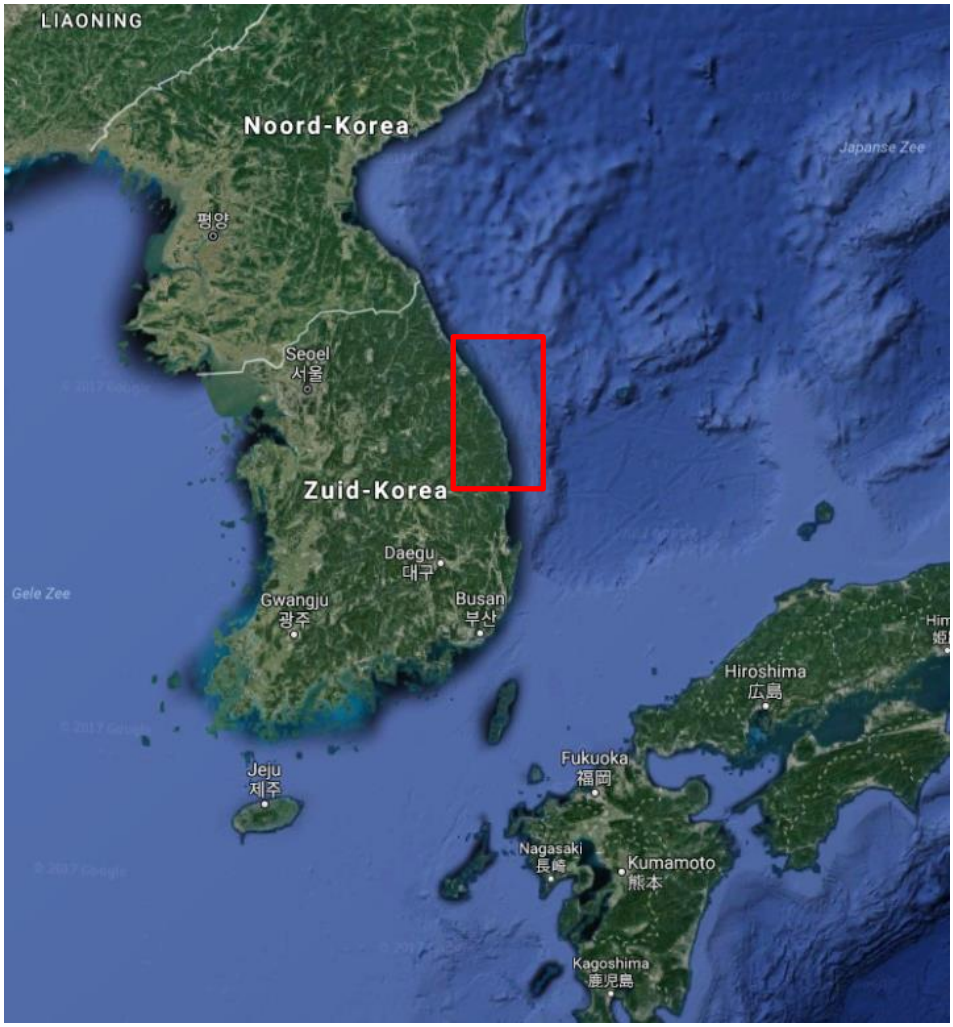

Figure 1-1: South Korea, location highlighted with a red rectangle

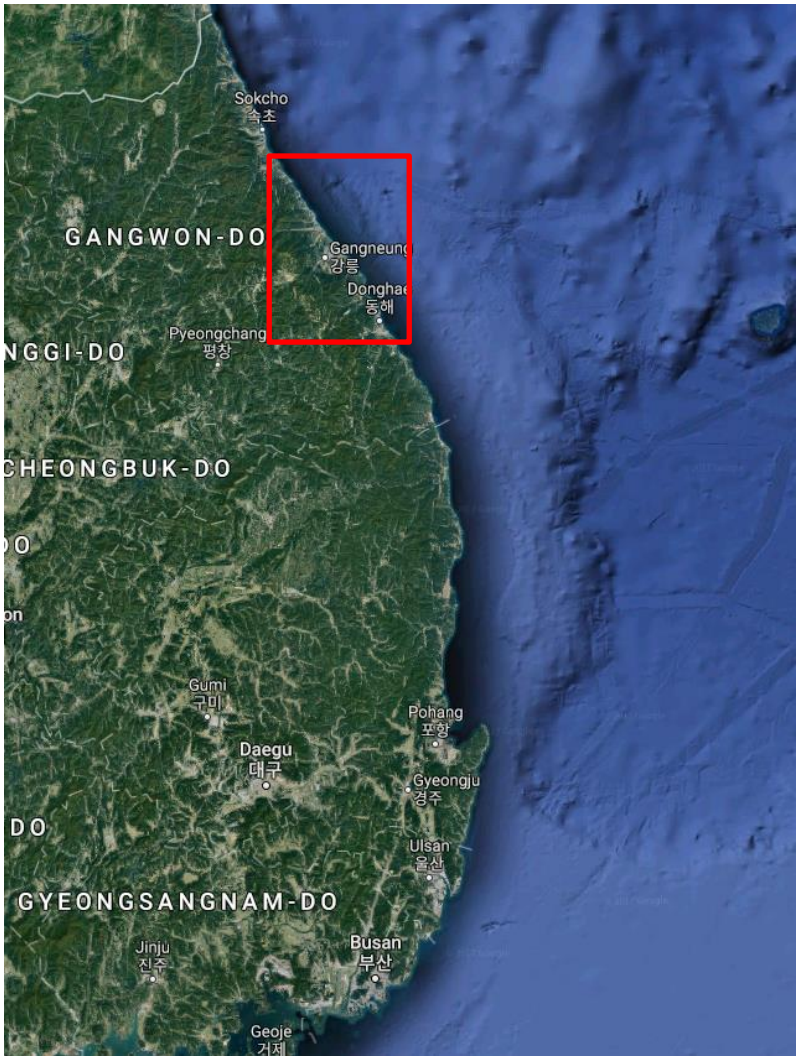

Figure 1-2: East coast of South Korea, with Gangneung the location of Anmok Beach, location highlighted with a red rectangle

Figure 1-3: Anmok Beach in Gangneung

Anmok Beach consists of a complex system due to both natural conditions and human interventions. Crescentic sandbars are an example of a natural condition and the port which bring along a breakwater is an example of human interventions. Anmok beach is classified as an intermediate beach, as described in section 2.1.3, it consist of a rhythmic bar and beach state. In the past years a regression of the coast is observed during storm conditions. This is an unwanted situation and research is needed to explore the erosional processes along the coast.

To get insight in erosional processes studies have to be done to the hydrodynamics. Hydrodynamics and morphodynamic processes are strongly related to each other. However, this thesis will focus on hydrodynamics only. The processes inside the swash zone are not understood in detail and insight is needed in the wave run-up on the beach. This holds especially for the longshore variations in wave run-up on beaches with rhythmic bar and beach cusps.

Most of the studies are related to wave run-up and wave climate. There are relations for wave run-up as described in the literature study in section 2.3. Alongshore variations in wave run-up do occur in combination with beach cusps, however, little is known about the alongshore variability of run-up. The interaction between beach morphology, consisting of cusps and bar, and the wave run-up in storm condition is not known.

An intermediate beach state can vary a lot in morphology as described in section 2.1.3 'intermediate beach'. This means that cusps and bar morphology changes and this could have an influence on alongshore variation in wave run-up. A change in cusps height can be considered as a change in the foreshore beach slope. The incident band swash height can be related to a change in beach slope as described in section 2.3.1 'alongshore variability'. However, the correlation with the foreshore slope for infragravity band swash is smaller compared to the incident band swash height. Stronger correlations between beach slope and swash are found for large cusps compared to small cusps, considering the wavelength of the cusps. Beside the cusps also bars could have an influence on run-up and it is recommended to include this in future studies as described in section 2.3.1 'alongshore variability', this will also be studied in this MSc thesis. The question arises if there are other parameters which influences the alongshore variance in swash height and if they do show a clear pattern in the alongshore variability of run-up.

Based on two fields it is desired to get more insight in the longshore variability in wave run-up, these are the engineering and the scientific field. From an engineering point of view it is relevant to know the magnitude and the longshore variability of run-up considering the impact on dunes and coastal structures. If this is known beforehand a safe design can be made to protect the hinterland against for example the impact of the water along the coast during extreme storm events or hot spots of erosion due to wave run-up. From a scientific point of view it is desired to get more knowledge in longshore variations in wave run-up considering crescentic bars and cusps on a beach, it could give more insight in the infragravity waves that could play a role. The prediction of run-up could be better if relations are found between the run up and varying dimensions of the bars and cusps.

1.1 Problem formulation and research questions

In this section a problem formulation is written and based on this formulation different research question are made. An expectation is given for the results of the research questions.

1.1.1 Problem formulation

The East South Korean coast is retreating during storm situations. Wave run-up is a process which is involved in erosion of the coast. Different studies have previously been performed to get insight in run-up, but little is known about the alongshore variability in wave run-up with alongshore varying bathymetries. Alongshore variability in wave run-up does influence the prediction of wave run-up. If more knowledge is gained about which parameters influence the wave run-up with respect to the alongshore variability, then the predictions of wave run-up are more accurate.

This lack of knowledge is especially the case when the beach morphology consists of rhythmic bars and beach cusps. There are no relations found between the dimensions of the bars/cusps and the prediction of wave run-up. Beside the dimensions of the bar and cusps in the beach morphology, it is also not known in detail if there are strong correlations between different parameters and the alongshore variability in wave run-up.

If knowledge is gained in the relation between beach morphology, considering beach cusps and offshore bar, and the wave run-up then it could provide scientific relations. With these scientific relations a better prediction can be made for wave run-up. If a more accurate prediction is made of wave run-up, it could enhance designs from an engineering point of view.

In this MSc thesis the research is based on the question if beach morphology, to be specific bars and offshore cusps, do affect the alongshore averaged wave run-up. Next to this, a research will be done to different parameters to investigate whether these are related to the alongshore variance in wave run-up.

1.1.2 Research questions

Main research question:

- Do cusps and bar morphology significantly affect alongshore variation in wave run-up on intermediate, rhythmic bar and beach state, beaches?

Sub research questions:

1. What is a useful definition of significant alongshore variance in wave run-up?
2. How does the magnitude and the alongshore variance in wave run-up vary relative to cusp characteristics and are there any dependencies visible?
3. How does the magnitude and the alongshore variance in wave run-up vary on bar characteristics in combination with cusp characteristics and is this different from that found for question 2?

1.1.3 Expected outcomes

An expectation is given for the answer on each of the above formulated sub questions, these are described below.

1. If a beach is considered with a uniform bathymetry and normal incidence waves are present with a certain directional spread, than it will cause alongshore varying run-up. A remark is made that this holds for a short period of time. If a long period is considered, the differences in wave run-up will disappear and there will be a uniform run-up present along the coast. Thus, the variance should decrease to eventually zero and one value remains for the wave run-up. So it is expected that for a certain amount of time there will be differences in wave run-up.

2. When beach cusps are considered the slope of the beach face is changing in alongshore direction. It is repeatedly changing from a less steep slope to a steeper slope and vice versa. It is expected that more short wave energy will be dissipated on a flatter slope, located in the bays of a cusp. Therefore the contribution of the infragravity band swash to the run-up will be relatively higher in an embayment compared to a horn [3]. This is also described in section 2.3.1.1. It could also be expected that the downwash of the swash motion is concentrated in the embayment, which could influence the magnitude of the run-up. This creates an alongshore variance in wave run-up.

3. In this case a combination of beach cusps and an offshore bar is modelled. This is likely to result in relatively higher contribution of the infragravity band swash to the run-up compared to incident band swash to the wave run-up due to the offshore bar. In an embayment this could lead to a stronger effect of the infragravity band swash on run-up because there is locally a milder slope present.

Concluding from the three hypotheses above the expectation for the main question is that cusps and bar morphology will affect the alongshore averaged wave run-up.

1.2 Outline report

This MSc thesis starts with a short literature overview in chapter two. The topics which are covered: beach states, morphodynamics in cusp formation, wave run-up and longshore variability of run-up including the environmental parameters which influence run-up. Based on the research question a methodology is written in chapter three. This explains the approach how the research questions will be answered. After this section the results of the analysis per research questions are treated. Chapter four considers the results of the uniform bathymetry. Chapter five consists of the results of the cusp system and chapter six contain results of the cusp bar system. Next to this the alongshore variation is described with respect to the hydrodynamic forcing which is given in chapter seven. In this chapter the results are given of the uniform bathymetry, the cusp and cusp bar system. Physical results are explained in chapter eight and a discussion is given in chapter nine. The conclusion is given in chapter ten, answering the main research question of this MSc thesis. Finally recommendations are added in chapter eleven. At the end of the report the references are added together with the appendices.

2 Relevant Literature

In this section a brief review is given from the existing literature which is related to the main topic of this thesis. First an introduction will be given to the different beach states, proceeding to beach cusps and how they are initiated. After that the definition of run-up will be given and the relation according to wave run-up is described. Last the alongshore variability in wave run-up is described.

2.1 Beach states

There are six different natural beach states according to Wright and Short [1]. The hydrodynamic processes, sediment transport and morphology differ expansively as a function of beach state. This depends on which state is represented on the surf zone and beach. There are three main states; the dissipative state, the intermediate state and the reflective state. The intermediate state is subdivided into four separate states. Which state is represented depends on local environmental conditions, sediment and preceding wave conditions. Differences in beach states are clearly seen in the morphology, but can also be seen in fluid motions.

2.1.1 Dissipative beach

The dissipative beach is characterised by flat and shallow beaches, it can be compared with the typical 'winter' profile from a beach which varies seasonally. On dissipative beaches significant irregularities are not common and this also holds for longshore rhythms. Incident waves break in the surf zone and after that, in the swash the infragravity oscillations becomes dominant. This is typical for dissipative beaches. Guza and Thornton also found that surf beat or the infragravity waves dominate the run-up on the beach [4].

2.1.2 Reflective beach

The dissipative beach is an extreme beach state, a reflective beach is the opposite extreme beach state and does not contain any dissipative aspects. A reflective beach is characterized by a steep beach profile, and a step in grain size. After this step the slope decreases. Rhythmic beach cusps are often present in the surf zone and a straight crested berm is found when low energy wave conditions are present. The reflective beach can be compared with the typical 'summer' profile. In contrast to the dissipative beach where waves are breaking, waves on reflective beaches will reach the beach face without breaking and surge up onto the beach. Most of the energy of the waves is present in the incident wave frequency range. Sub harmonic waves are also found; these are waves with a period which is doubled compared to the incident wave period. The infragravity motions could be present however, they are very weak.

2.1.3 Intermediate beach

In contrast to the dissipative and the reflective beaches, the intermediate beach contains both dissipative and reflective aspects. Next to this it contains the most complex morphology. The morphology can vary a lot within the intermediate beach state.

The rhythmic bar and beach state is one of the four intermediate states, this beach type is highlighted because it is of main interest for this MSc thesis. The waves will break over the bar and after that they stop to decay and reform in the trough. There is a relatively high run-up present. A characteristic of this beach state is the rhythmic longshore undulations of the beach and the crescentic bar. To make clear how this looks like, a top view and cross shore transect is given in Figure 2-1 taken from Wright and Short [1].

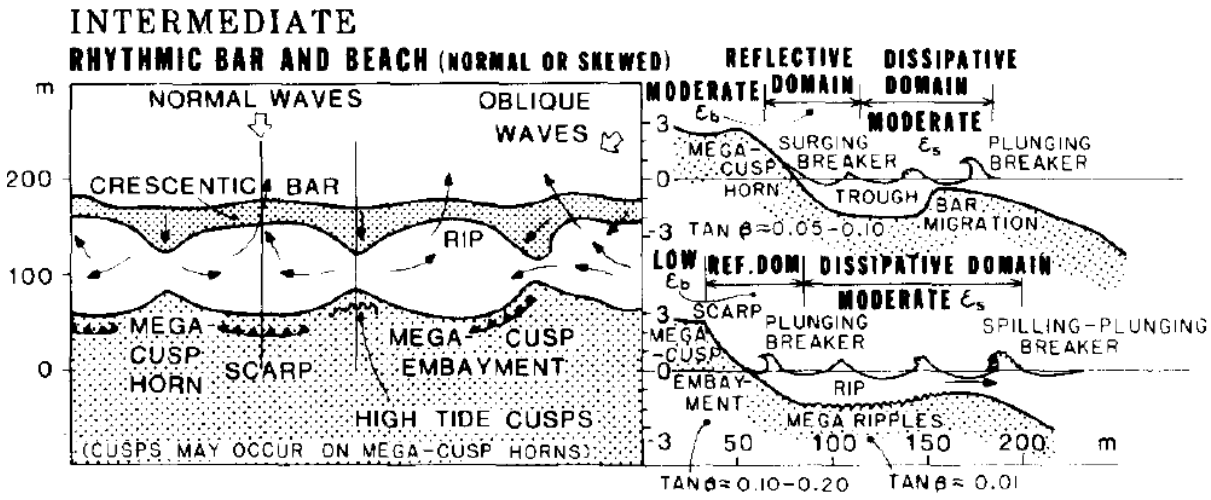

Figure 2-1: intermediate rhythmic bar and beach state, taken from Wright and Short [1], on the left a top view and on the right two cross shore transects.

The distance between the horn and the crescentic bar is in the order of 100 to 300 meter. In the proximity of the embayment a rip current is present, this current is considered to be weak to moderate.

In this beach state the incident waves/short waves are dominant in the surf zone, however, there are subharmonic and infragravity motions at some locations. The infragravity motions occur near the rip current and the subharmonic waves increases in amplitude near the beach. The infragravity motions could be a result of edge waves.

2.2 Beach cusps

In this section cuspate and crescentic beaches will be described. The origin of beach cusps will be provided as background material.

According to Sallenger [5] beach cusps are formed on shorelines which shows a crescentic character. This is concave in seaward direction. The quasi-uniform longshore wavelength varies between less than one to 60 meters. According to Inman and Guza [6] it can vary from a few centimetres to kilometres.

Inman and Guza describe two types of beach cusps [6]. These are the surf zone cusps and the swash cusps. Surfzone cusps originate from currents due to the nearshore circulation cell. The shape of the beach is in the order of the surfzone width. Wave action will put sediment into motion and carries this onshore, where it will be deposited. This happens in an onshore flow between the rip currents. The rip current is a seaward flow and erodes a channel. The current is generated from alongshore variation in wave forcing inside the surfzone. In this case beach cusps are formed with a longshore wavelength which equals the nearshore circulation. This wavelength varies between couples of meters for a lake while it can be hundreds of metres on shoreline of oceans. These are also called ‘giant’ cusps. Surfzone beach cusps are also described by Sallenger [5], a beach cusp will involve erosion and accretion processes which eventually result in net accretion of the foreshore.

The second type of cusps, ‘swash’ cusps, are originating from the swash and backwash on the beachface. The wavelength of these cusps varies between centimetres to 75 metres[6]. Incident

waves produce a large amount of swash on the beachface, especially in the case of steep reflective beaches. This is the reason why swash cusps are most common on this type of beach.

A variation in run-up of waves is caused by the superposition of swash from incoming waves with the sub-harmonic edge waves. This induces a periodic erosional perturbation. This in turn can grow to fully developed beach cusps.

Swash cusps are best observed during neap tide conditions[6]. The flow pattern and rip current is clearly seen together with the cusp horns/apex and the cusp embayment/valley in Figure 2-2.

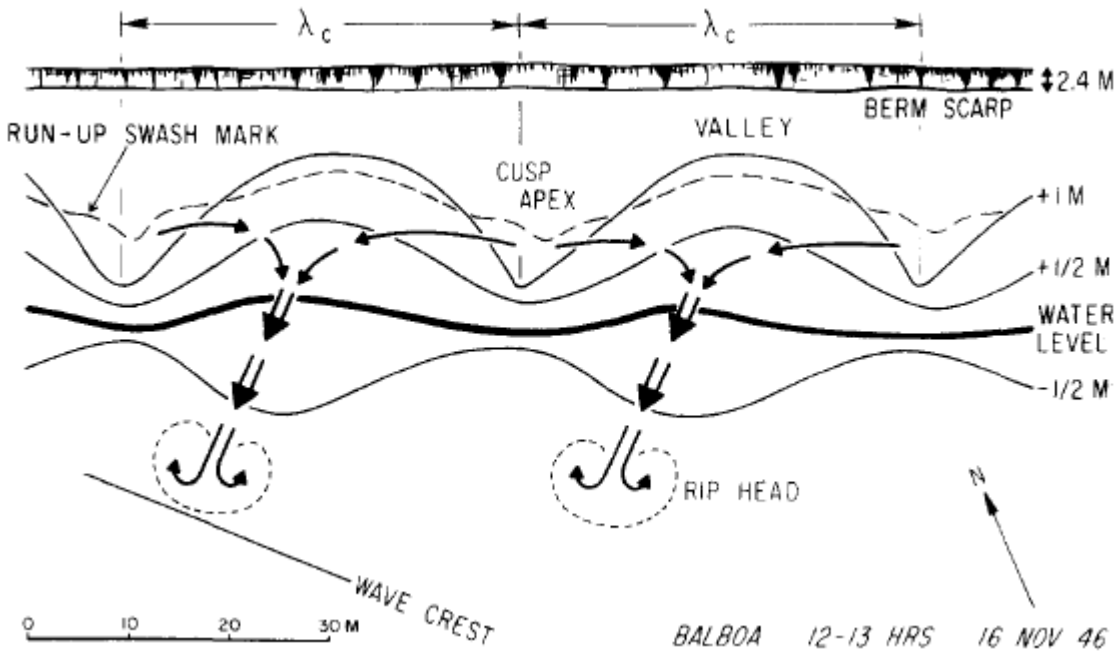

Figure 2-2: backwash cusp Balboa beach California, the arrows indicate the backward flow pattern [6]

Swash runs up creating an upwash at the horns or apex where it will divide into two flow patterns, each flow pattern to either side of the horn. A longshore flow pattern occurs flowing into the embayment/valley where it meets the opposite longshore current from the adjacent apex. These two longshore currents converge with each other and at this place there is an intense vorticity present, resulting in a rip current towards the sea. The width of this rip current can be considered small and thus intense combined with a high sediment load[6]. The sediment load is deposited when the cusp through meets the water level, creating a delta below water level. This can also be seen in Figure 2-2. In Figure 2-3 the backwash can be seen on the beach. The delta deposition is also described by Sallenger, which can also create a cusp [5]. The upwash is then converged to the ridge, which contributes to a migration shoreward which creates an embayment. The delta-like deposit is then built into a horn.

Figure 2-3: backwash on Balboa beach California [6]

When a falling water level is considered, the delta formation is eroded, because it will emerge above the water level and the rip current will erode this 'delta' part. Contrarily when water level is rising, a delta-ridge is created beneath the water level. This can cause wave convergence on the delta, so wave energy is diverging from the apex to the delta. However, wave energy which is focussed on the apex or horns, is maintaining the beach cusps. Therefore a varying water level will eventually lead to a negative feedback mechanism causing beach cusps to disappear according to Inman and Guza[6].

2.2.1 Origin of cusps and edge waves

Different studies mention edge waves in the formation of beach cusps, for instance Inman and Guza [6]. Edge waves are longshore periodic gravity waves. The longshore wavelength and the period of the edge waves are related to each other according to equation(2.1).

$$L_e = g/(2\pi) * T_e^2 * (2n+1) * \tan(\beta) \tag{2.1}$$

In which L_e is the longshore wavelength, T_e is the period of edge waves and n is the mode number, which can be 0, 1, 2, etc. Mode zero contains the edge wave with the largest amplitude, this is also the wave which is the most easily excited. Another name for the zero mode edge wave is the subharmonic wave. This wave contains a wave period which is twice the incident wave period.

A strong correspondence between predicted and observed wavelengths of cusps gives evidence that subharmonic edge waves determine the longshore beach cusp wavelength [6]. This length is determined by subharmonic edge waves which contribute to longshore periodic perturbations in the bed formation of an initially uniform beach.

2.2.2 Cusp height and run-up

The cusp height can be determined by the swash excursion from incident waves[6]. The height of the cusp is calculated by the height of the maximum run-up. The maximum cusp height is related to the significant run-up height R_S as can be seen in equation(2.2).

$$\eta_{c,\max} = K_1 R_S \tag{2.2}$$

In this case $\eta_{c,\max}$ is the maximum cusp height (the vertical difference between the embayment and the horn), K_1 is a constant of proportionality which is in the order of one and R_S is the significant run-up. The latter is defined as the vertical component of the significant swash excursions. The significant value is calculated with four times the standard deviation s and s^2 is the total variance of the measurements. Thus, R_s can be seen as the average of the highest one-third of the run-up excursion.

2.3 Wave run-up

If waves approach the coast, a lot of energy is dissipated by means of wave breaking in the surfzone. Part of the energy is converted into potential energy which results in run-up on the foreshore of the beach. It is important to understand the magnitude and the longshore variability of extreme run-up. When this knowledge is available a prediction can be made of the impact of extreme run-up on for instance dunes or other structures in the area.

Several studies are done to gain insights in run-up and to define relations for wave run-up. Run-up is defined as the set of discrete water level elevation maxima, which are measured on the foreshore with respect to the still water level according to H. F. Stockdon et al.[2].

The wave height H, deep-water wave length L_0, wave period T, and beach steepness β, are a parameter set which is used to describe run-up. The first three mentioned are related with the linear dispersion relationship. All the parameters together can be related to the Iribarren number, a non-dimensional surf similarity parameter given in equation(2.3).

$$\xi = \frac{\beta}{\sqrt{\frac{H}{L_0}}} \tag{2.3}$$

In which the squared root of the ratio wave height over wave length represents the steepness of the wave in deep water. On natural beaches it can be difficult to define the steepness of the beach, because usually they show a concave profile and sandbars can be present offshore on the bed.

Hunt [7] came with an empirical formulation for run up, shown in equation(2.4).

$$\frac{R}{H} = K\xi \tag{2.4}$$

In which R is the vertical wave run up, H is the wave height, ξ is the Iribarren number and K is a constant.

Guza and Bowen[8] showed that the run-up, defined as the vertical swash motion, does not exceed a certain value regardless of the incident wave height. The vertical run-up height is related to the incident wave field, as can be seen in equation(2.5)

$$\frac{R\sigma_i^2}{g\tan^2\beta} \leq 8 \tag{2.5}$$

Sigma equals the radian frequency of incident waves; this is two times pi divided by the incident wave period. This holds for monochromatic incident waves. Other experiments were done by Van Dorn[9] with the same conclusion, however, the constant 8 in equation(2.5) is replaced by 4. Thus, the swash excursion does not exceed a specific value. When the incident wave height is increased, the breaker height is increased but the swash oscillation is not increased. Further research by Huntley et al.[10] and Guza and Thornton[4] showed that naturally occurring swash spectra at incident wave frequencies are qualitatively consistent with equation(2.5). Thus, this is similar to the ideas about the monochromatic waves. So swash motions at incident wave frequencies do not increase with increasing incident wave height if the swash zone is saturated.

However, there are changes in run-up if the incident wave height is increased at surf beat periods according to Holman[11] and Guza and Thornton[4] . In this case equation(2.5) does not hold. Thus, in nature the swash oscillations increase with increasing incident wave height for waves with frequency spectra. Guza and Thornton[4] found a relation for the run-up on natural beaches, stated in equation(2.6).

$$R_s = K_2 H_{\infty,s} \tag{2.6}$$

In which R_s and $H_{\infty,s}$ is the significant run-up and the offshore deep water wave height respectively. The value K_2 is for their measurements equal to 0.7, but this is a function of breaker type, beach slope and permeability etc. This varies for different situations, but it is expected that K_2 is in the order of one

A more recent formulation for run-up is given by Stockdon et al. [2]. Run-up consists of two elements; these are the maximum set-up $\langle\eta\rangle(y)$ and swash $S(y,t_i)$. Set-up is the super-elevation of the mean water level. This is driven by a cross shore gradient in radiation stress resulting from breaking waves. Swash is defined as “a time-varying location of the intersection between the ocean and the beach” according to Stockdon et al.[2] Swash depends on the beach slope beta and the period. It can be decomposed into two parts [2]:

$$S = \sqrt{\left(S_{inc}\right)^2 + \left(S_{IG}\right)^2} \tag{2.7}$$

S_{inc} and S_{IG} are the contributions to swash excursion from incident and infragravity frequencies respectively. Swash is also a function of the beach slope, deep-water wave height and deep-water period. Different studies have been performed trying to relate the role of incident and infragravity frequencies to the swash motions. For instance Guza and Thornton [4] revealed that the infragravity swash height increases linearly if the offshore significant wave height increases as described earlier. Beside this, they found that dissipation across the surf zone results in saturated energy from the incident band. The linear dependence of the significant offshore wave height together with the infragravity swash height is confirmed by multiple other studies.

According to Stockdon et al. [2] the 2% exceedance value of run-up consists of the contribution of set-up and swash, it is given in equation(2.8).

$$R_2 = 1.1\left[\langle\eta\rangle + \frac{S}{2}\right] \tag{2.8}$$

$$\langle\eta\rangle, \mathrm{S_{inc}}, S_{IG} = f(H_0, T_0, \beta_f) \tag{2.9}$$

Based on measurements from Stockdon et al. they found the following relation between the run-up and the set-up together with the swash excursion:

$$R_2 = 1.1\left[0.35\beta_f\sqrt{H_0 L_0} + \frac{\sqrt{H_0 L_0 (0.563\beta_f^2 + 0.004)}}{2}\right] \tag{2.10}$$

This expression is applicable for run-up on all beaches, and can be used for the total range of beach conditions as described in section 2.1 'Beach states'. A remark is made for extreme dissipative conditions. If the Iribarren number is smaller than 0.3, equation(2.10) does not hold and equation(2.11) is used for the calculation of run-up.

$$R_2 = 0.043\sqrt{H_0 L_0} \tag{2.11}$$

2.3.1 Alongshore variability

In this section an overview is given of the alongshore variability in wave run-up.

Several studies relate the alongshore variation in swash motions to the beach face slope[2, 12] and at smaller scales it can be related to the influence of cusps [2, 3].

Wave run-up depends on the beach slope and the same holds for the swash height resulting from incident waves. This is not the same for infragravity swash height. According to measurements from Stockdon et al. [2] there is little or no linear dependence between the beach slope and the infragravity swash height. The dependency on beach slope does result in longshore variations in run-up and swash if the beach slope varies along the beach.

Measurements from Stockdon et al. [2] resulted in longshore variability in the total swash excursion when the morphology of the beach was extremely three-dimensional. In this case a regular cusp field, megacusp embayments or welded swash bars were present. A correlation analysis was made. The correlations between foreshore beach slope, β_f , and swash, S, are higher and more significant if for instance megacusps are considered. These have a rhythmic spatial variation in slope, which can be considered on a large spatial scale. The correlation is lower when irregular and short scale slope variations are considered. Beside this the incident frequency band shows most of the longshore variability in total swash and the infragravity frequency band show less alongshore variability in total swash. The slope beta was positively correlated with incident swash, while the correlation with the infragravity swash was less significant. In adverse to one location where infragravity swash was significantly correlated with the slope beta, this occurred within a well-developed cusp field. However, in this case a negative correlation was found meanwhile there was a positive correlation between the incident swash and the slope. This shows that infragravity swash and incident swash

are out of phase within the cusp field. This is related to longshore variable dynamics as a result of swash circulation within the cusp field instead of a cross shore flow according to Stockdon et al. [2].

Guedes et al. [13] showed that beside the beach face slope and the influence of cusps alongshore variations can be related to the tidal changes/motions at breaking waves over a bar. In particular if the bar is irregular it could lead to irregular breaking of the waves resulting in longshore patterning of incident swash and incident group structures. Due to the patterning of these two aspects it can result in alongshore variations in swash at infragravity bands.

Measurements from Guedes et al. [14] showed that the significant run up height increased with 70% between low and high tide, beside this a relation could be found between the run-up and the mean water level/set-up and the mean slope of the profile. At high tide the alongshore variability is higher when a local shoal is present in the bathymetry due to wave breaking on the shoal. Furthermore small scale variations in wave run-up could be seen at developing cusps. When a difference is made between the variance of infragravity band and incident band, the incident band shows similar patterns to the run-up. In contrast to the infragravity band, this shows no alongshore trend. Besides the changing magnitude of incident and infragravity swash bands, the shape of the spectra also changed alongshore. A regression analysis was used to get insights in the influence of environmental conditions on the alongshore and temporal variations. It showed that there is a linear correlation between the run-up and the mean beach slope. There are changes in the interception of the regression lines during high, mid and low tide. This suggests that there are other parameters which have an influence on temporal changes of the run-up. This is also shown by Guedes et al. [13]. Beside this it resulted in a trend in which wave breaking increases when run-up and the mean slope decrease. The correlation of wave breaking together with run up is better predicted if the temporal variability is included. The combining effect of beach slope and wave breaking together with run-up is examined in a multiple regression model. This leads to better results when a quadratic model is used instead of a linear model.

A scatterplot of the probability of breaking waves together with the mean slope is made and this results in a negative relation. This can be seen in Figure 2-4 taken from Guedes et al. [14].

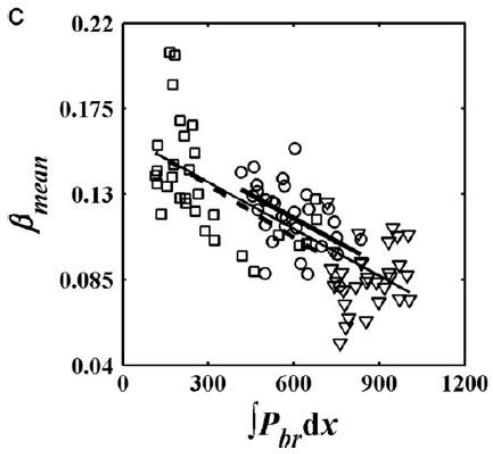

Figure 2-4: a negative correlation between the mean slope and the probability of breaking waves, triangles, circles and squares are represented by low, mid and high tide respectively. Scatterplot taken from Guedes et al. [14]

A strong negative correlation can be seen in a scatterplot showing the ratio of the variance at infragravity frequencies and incident frequencies versus the run up height ($\sigma_{IG} / \sigma_{inc}$ versus R_s). This is plotted together with the probability of wave breaking, this can be seen in Figure 2-5 taken from Guedes et al.[14].

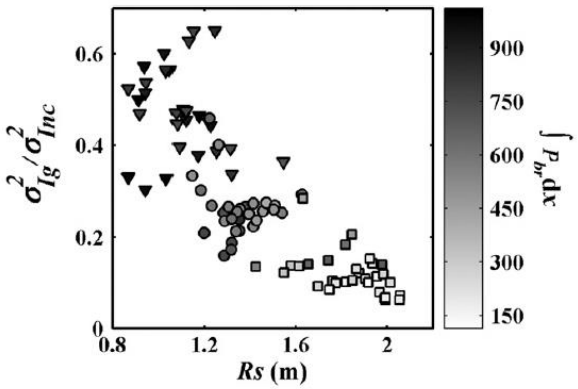

Figure 2-5: a negative correlation between the ratio of the variance in infragravity frequencies over incident frequencies and the significant run-up height, triangles, circles and squares are represented by low, mid and high tide respectively. Scatterplot taken from Guedes et al. [14]

The results are consistent as the probability increases of breaking waves which results in a decreasing contribution of incident wave energy and thus the contribution of the infragravity band is higher.

Guedes et al. [13] showed that the dominant role of changing swash motions could be due to changes in the degree of wave breaking over a bar considering tidal variations. Beside this it could be related to changes in incident swash which was dominant of the two swash factors (infragravity and incident swash). The variation in the incident swash motion was related to variation in beach slope and to variations in wave breaking. Guedes et al. [14] stated based on observations that a well-developed sandbar morphology results in alongshore variation in run up. Future studies should include the effect of alongshore variations in the beach face (the sloping section which is exposed to swash) and the sandbar. Furthermore alongshore changes in wave breaking should be taken into account to have a better prediction of alongshore variations in wave run-up.

The variation in variance at infragravity frequencies is large alongshore and it was significantly correlated with the mean slope according to Guedes et al. [14]. This is in contrast with the results from Stockdon et al. [2] described earlier. The correlation observed by Guedes et al. is not consistent, it was positively correlated during high tide and negatively during low tide. Other correlations were weak and thus it is expected that the alongshore variation of infragravity variance is determined by other parameters beside the beach face slope and the degree of breaking waves over a bar.

Alongshore changes were also found in the shape of the spectrum at infragravity frequencies. Peaks were found at frequencies lower than the sea/swell frequencies, notably when energy at infragravity frequencies was present. The changes in spectrum can be related to the existence of edge waves. Some wave energy is observed at the lowest mode, n=0 and a little energy is found in the first and second mode. The generating mechanism is not clear according to Guedes et al. [14]. The relative contribution of edge waves changed alongshore compared with the total energy density spectrum,

changes were found around a shoal in the bathymetry. The edge waves could be originated because of the shoal. The alongshore variations in variance at infragravity frequency could be related to the edge waves. However, a remark is made, infragravity frequencies is in general not dominant under reflective and intermediate conditions. According to this statement edge waves are expected not to be the dominant process of developing alongshore changes in swash motions.

2.3.1.1 Cusps and alongshore variability

Alongshore changes in swash can be seen when cusps are present on a beach. The changes occur because of the different types of energy which dominate at an embayment or a horn. In general, which is also described earlier, at the horn there is more energy found in the incident wave frequency band and less energy at the infragravity frequency band. The reverse holds for an embayment. The pattern of incident waves can be explained by the changing slope, which is steeper at a horn and less steep at an embayment. The swash excursion is reduced at a horn compared to the embayment [3].

Beach cusps enhance the channelling of the down rush which flows back to the sea [3]. This is located at the embayment of the cusps, which in turn create more local behaviour of the swash motions compared with a bathymetry without cusps. The downrush affects the following uprush in the embayment, in such a way that the uprush will be smaller.

2.3.2 Wave frequency spread and directional spread

Wave frequency spread around the peak frequency and directional spread around the mean direction can have an influence on wave run-up. Guza and Feddersen used a Boussinesq model to take into account these aspects [15]. Changes in directional spread can have an influence on the infragravity swash which is more or less equal to a change in incident wave height up to a factor of two.

The equations of Stockdon et al. [2] considering set-up and run-up are reproduced by the model. After this, the scatter in the infragravity band is studied considering the influence of frequency and directional spread. The equations mentioned are the components in equation(2.12):

$$\sqrt{H_{s,0}L_0} \text{ and } \beta\sqrt{H_{s,0}L_0} \tag{2.12}$$

In which the left component of equation(2.12) represents the infragravity band and the right component in this equation represents the set-up and the incident band.

The model showed that the normalized infragravity run-up, $R_s^{(ig)} / \sqrt{H_{s,0}L_0}$, shows a relation with frequency spread and directional spread. The normalized infragravity run-up increases if the spread in frequency increases, while it decreases if the directional spread increases. It is also shown that the normalized infragravity run-up does not depend on the slope beta. The relations between the normalized infragravity run-up and the spread are strong if the normalized run-up, $\bar{R} / \beta\sqrt{H_{s,0}L_0}$, and the normalized incident run-up, $R_s^{(ss)} / \beta\sqrt{H_{s,0}L_0}$, do not show a trend with the frequency spread and the directional spread.

A non-linear interaction occurs when two incident waves are in near resonance with an infragravity wave, this result in infragravity wave growth. In intermediate and deep water it results in a second

order bound infragravity wave. When the depth becomes finite and a small beach slope is considered together with a weak non-linearity the bound infragravity wave and near resonance infragravity wave are equal [16]. Based on this physical process a parameterization is made of the normalized infragravity run-up[15]. Equation(2.13) gives the relationship of the best fit line for the normalized infragravity run-up.

$$\frac{R_s^{(ig)}}{\sqrt{H_{s,0}L_0}} = -0.013\ln\left[\frac{f_p}{f_s}\sigma_{\theta,0}\right] + 0.058 \tag{2.13}$$

In which f_p is the peak frequency, f_s is the frequency spread and $\sigma_{\theta,0}$ is the deep water directional spread. Also with this relationship it is seen that the normalized infragravity run-up does not strongly depend on the slope beta, which is in agreement with the results of Stockdon et al. [2].

According to Guza and Feddersen [15] it is recommended to include $\left(f_p / f_s\right)\sigma_{\theta,0}$ in the parameterization of the infragravity run-up.

3 Methodology

In this part the methodology is described to answer sub question 1 – 3. The model input for the bathymetry and grid of the model are described. The method how to determine $R_{2\%}$, setup and swash are described, which holds for all the sub questions. Subsequently each method per sub question is described.

3.1 Model

To get insight in the hydrodynamics in the swash zone and the run-up several model runs should be made to answer the research questions. The model which is going to be used is XBeach. Model computations can be performed in a non-hydrostatic and a surfbeat mode. The surfbeat mode, which resolves the waves on the scale of wave groups, is not used. A 2DH model will be used to perform the calculations. A previous MSc study by K. Koudstaal [17] showed that the non-hydrostatic mode provides better results in the prediction of run-up compared to the surfbeat mode.

Hydrodynamic and morphodynamic processes are modelled by XBeach[18]. The hydrodynamic processes are:

- Short wave transformation (refraction, shoaling and breaking)
- Long wave transformation (generation, propagation and dissipation)
- Wave induced set-up, unsteady currents, overwash and inundations.

Morphodynamic processes are not taken into account for this MSc thesis, therefore the bed will be set as fixed and constant in time during all model runs.

Different modes can be considered in the XBeach model. For this thesis the non-hydrostatic mode will be used in which a non-hydrostatic pressure is included. This mode takes more computational effort and time, nevertheless it models the propagation and decay of all individual waves, so from short waves and long waves. The non-linear shallow water equations are used to solve the depth-averaged flow originating from waves and currents. The incident band run-up can be calculated, which is an advantage of the non-hydrostatic mode.

The outcomes of the model will not be compared with data from measurements, thus it will not be validated. During this MSc thesis another MSc thesis is performed by A. de Beer at Deltares, XBeach is also used in this thesis with the non-hydrostatic mode. The results of these calculations will be validated. Other research was performed earlier by McCall et al. [19] in which the model is validated for wave run-up and shows good results. This is the reason that the results of the non-hydrostatic model are to be seen as a reference situation and expected to compare well to nature.

3.1.1 Bathymetry

For the model input a bathymetry is needed. This could be a measured bathymetry of Anmok beach. However, in first instance a schematized bathymetry is used. An alongshore uniform bathymetry is created in which adjustments can be made to generate a bathymetry including beach cusps, offshore crescentic bar and a combination of both of them.

3.1.1.1 Uniform bathymetry

The alongshore uniform bathymetry is based on the characteristics of Anmok beach. Two locations are taken from the survey of 2008. In which the slope is measured. The two locations are situated at

a horn and an embayment, in this case an average slope is calculated which will be used for the uniform bathymetry.

On average the slope of the foreshore is 0.02 or 1:50. This slope does also fit the survey of 2008 best. A change in slope is observed where the crescentic bar and beach cusps are located. On average the slope of this nearshore segment is (0.079+0.109)/2=0.094 or 1:10.6.

The bottom of the profile is located at -25 meters and the water level is situated at 0.0 meter. A profile of the alongshore uniform bathymetry can be seen in Figure 3-1.

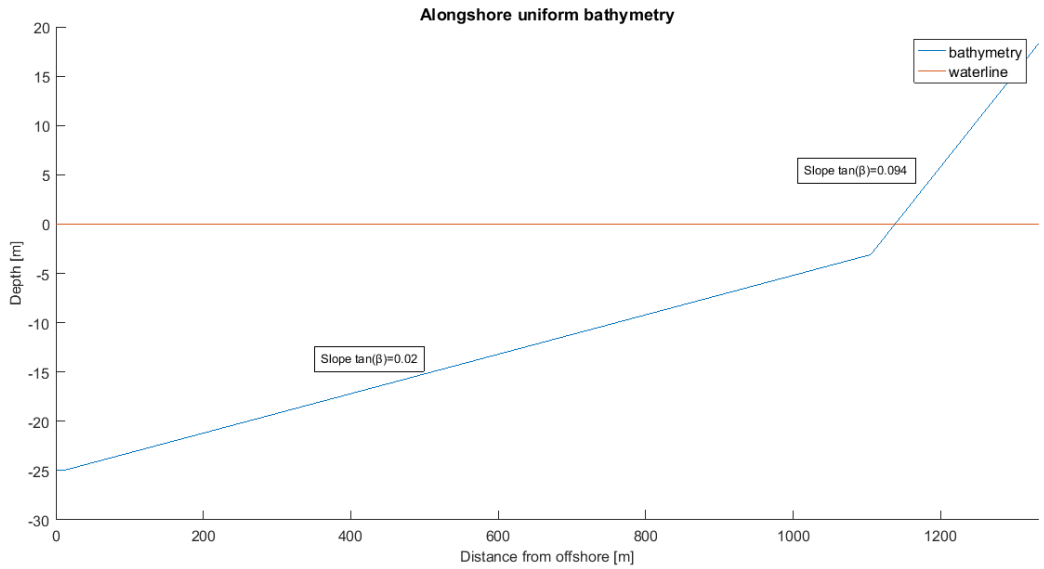

Figure 3-1: alongshore uniform profile

The model calculations are performed in 2DH. The alongshore uniform bathymetry will be 100 metres wide in alongshore direction. The 2D situation is shown in Figure 3-2.

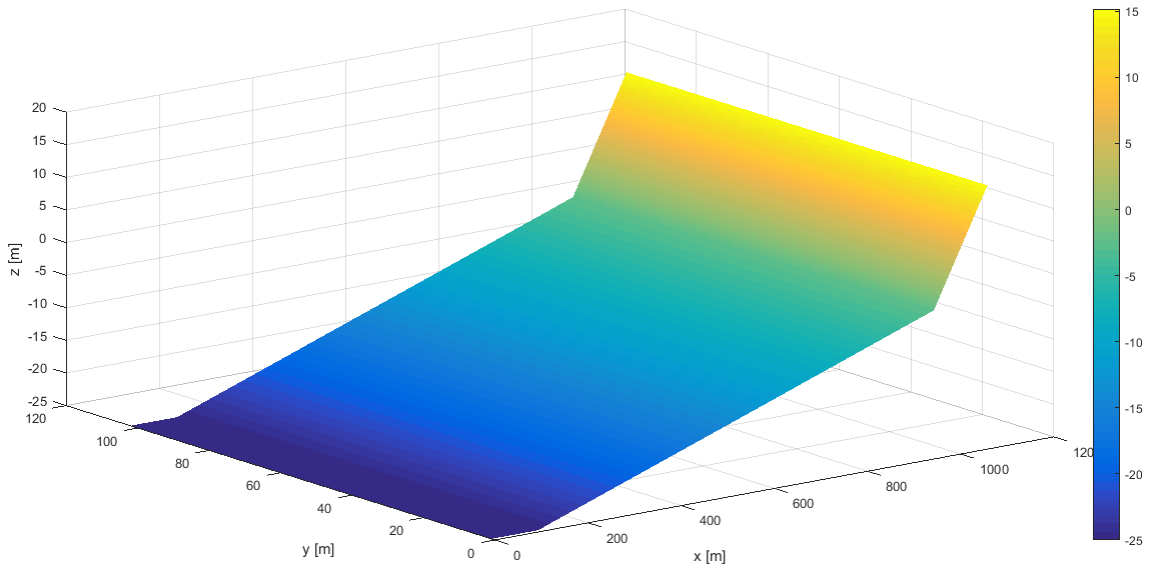

Figure 3-2: alongshore uniform bathymetry in 2DH

3.1.1.2 Beach cusps

The beach cusps are modelled with a certain length scale, which is described below. Furthermore the idealized bathymetry and the number of cusps in alongshore direction in a model computation is described.

Beach cusps can be applied on the alongshore uniform bathymetry. The input which is required for this option is the wave length of the beach cusp, number of beach cusps and angle of the cusps relative to the main slope of the uniform bathymetry.

Two ways are considered to generate beach cusps. This can be done with a constant sloped cusp and a varying sloped cusp. Both methods are compared with the survey of 2008. For this thesis the method of varying sloped cusps is chosen to model the beach cusps. The beach cusps are generated with the following formula:

$$\text{cuspheight} = zb_{x,1105} + (1.7 * -abs(\cos(k * y)) + 0.109) * (\text{x} - 1105) \tag{3.1}$$

In which $zb_{x,1105}$ is the height of the bathymetry at x=1105, 1.7 is the angle between a cusp horn and cusp embayment, k is the wave number, y is the alongshore distance, 0.109 is the slope of a cusp horn, x is the cross shore distance and x=1105 m is the starting point of the cusps.

In Appendix VI it is explained what the differences are between the two methods and which method approximates the survey of 2008 the best.

When a beach cusp system or crescentic bar is considered the width of the bathymetry in alongshore direction will depend on the wavelength of the beach cusp and the crescentic bar. Thus, when more beach cusps are considered in the bathymetry, the width of the bathymetry will be the number of cusps multiplied with the wave length of the beach cusp. The number of beach cusps which is going to be modelled is three. An analysis is made to determine the number of cusps which should be modelled next to each other. The concept of this analysis was to model nine cusps next to each other, seven, five and so on. The central cusp of each of these models is analysed. The results from the central cusp of the three cusp model showed similarities with the nine cusp model. This is the reason to model three cusps next to each other. The analysis can be found in Appendix VII . An example of beach cusps in 2DH can be seen in Figure 3-3.

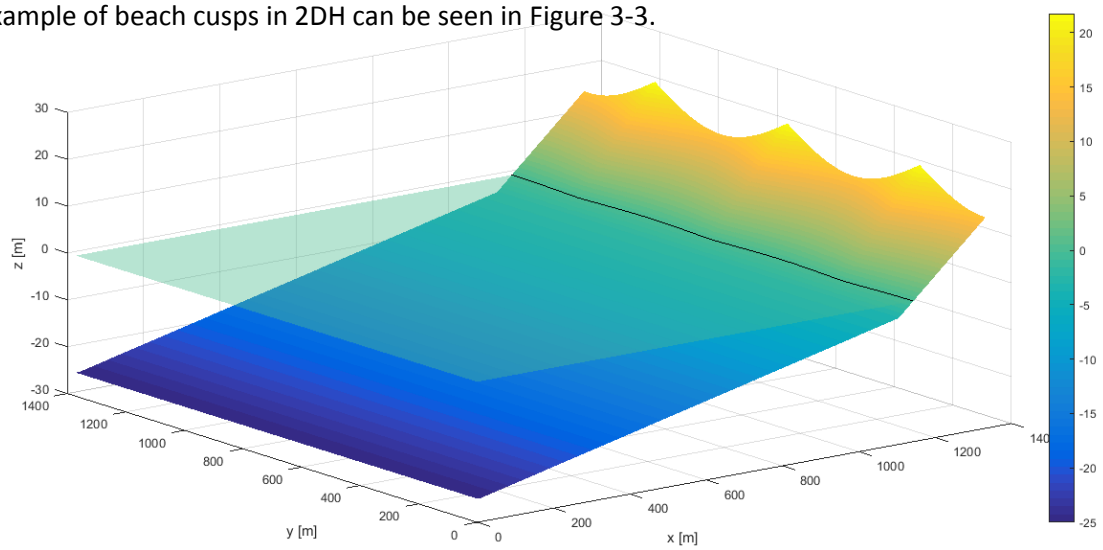

Figure 3-3: beach cusps, number of cusps: 3, cusp wavelength: 452 m and angle of 1.7 degree relative to the uniform bathymetry, the crescentic black line represents SWL at the beach

The lengths of the beach cusps which are most common at Anmok beach are 300 and 450 m [20]. Cusps of 100, 300 and 452 metres are modelled with XBeach. A cusp length of 452 m is used instead of 450 m such that the same grid size of dy=4 can be used.

The beach cusps contain a sharp gradient at the horns; this is the result due to the use of an absolute cosine function for the generation of the beach cusps. A sensitivity analysis is made to check whether this sharp gradient causes large influence on the results of the computation which are made in this thesis. The sharp gradient can be prevented by adding extra harmonics. This results in a more smooth horn, instead of a sharp peak. From this analysis it is concluded that extra harmonics are not added to the bathymetry. The analysis can be found in Appendix IX .

3.1.1.3 Beach cusps and offshore sandbar

In this thesis a cup bar system is modelled for a cusp length of 452 metres. The most common length scale at Anmok beach is chosen to model with a crescentic sandbar. The sandbar is schematized as a parabola, with a height of 2.5 metres. The width is 150 metres. These length scales are based on the survey of 2008. The amplitude in the horizontal cross shore plane is 45 metres. This length scale is based on the sandbar characteristics present at Anmok beach from a MSc Thesis of P. Athanasiou [20]. The cusp bar system is shown in Figure 3-4.

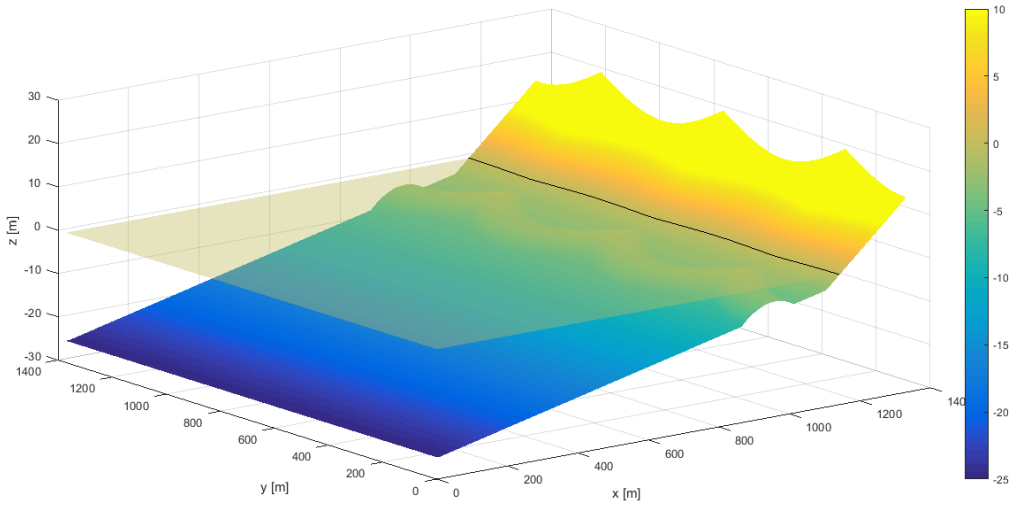

Figure 3-4: cusp bar system, number of cusps: 3, cusp wavelength: 452 m and angle of 1.7 degree relative to the uniform bathymetry, with crescentic sandbar. The black line represents SWL on the beach

3.1.1.4 Grid

In cross-shore direction a variable grid size is applied. In offshore direction the grid size will increase, as less detail is needed in the offshore region. In the swash zone the grid cells are smaller with a minimum value of 0.5 meter. The variable grid size is calculated based on a peak wave period of six seconds and thirty points per wave length. This will hold for every model simulation, reasoning that every calculation contains the same grid resolution in cross-shore direction. The period belonging to this grid resolution is a lower bound for waves which are going to be modelled, for this reason waves with a peak period of six seconds or less will not be modelled.

In alongshore direction a constant grid size of two metres is applied for the uniform bathymetry. For the beach cusps a grid resolution of four metres is applied. This is not equal to two metres because computational time is reduced with a length of four metres. In this case the cusps in different

calculations will have a variable relative grid resolution in alongshore direction when the wavelength of the cusps varies, because in every situation the grid points are defined at every four metres. With relative it is mentioned relative to the cusp length.

3.2 R2%, setup and swash

In this section the method is described how the R2%, setup and swash are calculated from an arbitrary water level time series at the waterline.

3.2.1 Output data

XBeach calculates the water level elevation at the waterline, for this a run-up gauge is selected in XBeach. The model will start to simulate waves, those waves are not immediately at the beach. Thus, for this reason a spin up time is removed, this is the time which is required to reach a certain 'equilibrium state'. For this time 500 seconds is selected. So the first 500 seconds are erased and data which are calculated after 500 seconds are analysed.

3.2.2 Run-up points

The water level time series at the waterline is analysed, a filter is applied on this data. Certain points are selected as run-up points and other points, local maxima, are ignored. How this works is explained in 0.

An example of run-up points is included in Figure 3-5, which gives the run-up points of the first 200 seconds from a water level elevation time series measured at the waterline. The run-up points are marked with a green + and surrounded with a red circle. The local maxima which are deleted are only marked with a green +. The horizontal magenta line is the mean water level. SWL is located at 0 metres. It can be seen that no run-up points are marked below SWL, which is in agreement with the filter conditions described in 0

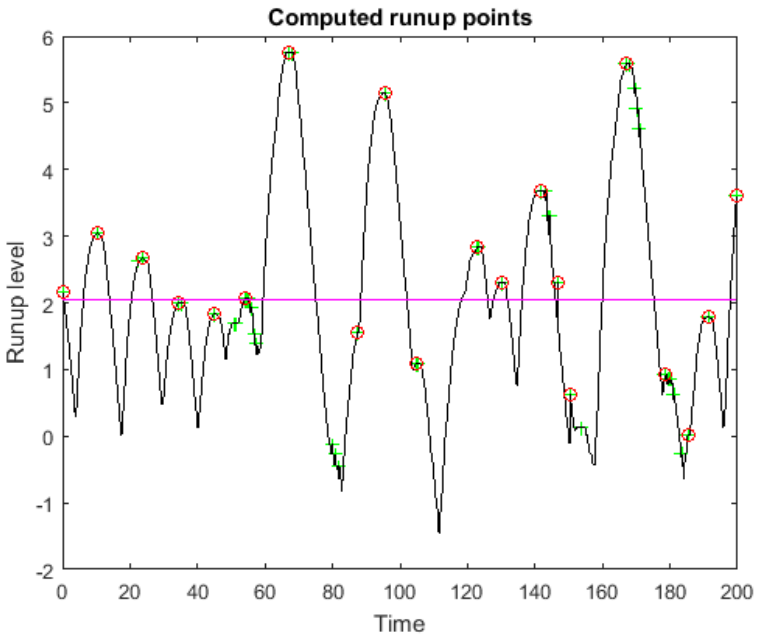

Figure 3-5: run-up points are marked with a green + surrounded by a red circle and local maxima which are erased are marked with a green +

With the filter rules all local maxima are analysed, resulting in run-up points and points which are erased due to filtering. The run-up points will be stored, ready for a new statistical analysis.

3.2.3 R2%

The statistical analysis could be calculating the R2% or the setup of the water level elevation. In this case the R2% is described. The two per cent run-up elevation, R2%, is defined as 'the run-up elevation above SWL that is exceeded by two per cent of the individual run-up elevations in the time series' [21]. With run-up elevation the points are mentioned which are selected as run-up points in the previous section.

The total amount of run-up points are counted and sorted from low to high. For example: if there are 100 run-up points, than the R2% is the 98th value. Or if there are 115 run-up points, the R2% value is calculated as follows: (115-115/100*2) = 112,7th value. The value belonging to this number is linearly interpolated between the 112th and 113th number.

To determine the R2%, a minimum amount of 50 run-up points is needed. Otherwise an interpolation would occur between the highest value of the dataset and an undetermined higher value, this is not possible. The first interpolation which is possible is between the highest run-up point and the second highest run-up point.

It is also possible to calculate R10%. To calculate this number 10 run-up points are needed. In general it is possible to calculate Rn%, in which n has a maximum value of 100. So whether R2% can be calculated or not depends from the amount of run-up points in the dataset. For this thesis R2% is calculated, this is in line with the EUROTOP manual [22].

3.2.4 Setup

The setup of the water level is calculated by taking the mean of the water level elevation time series. Thus, all the data points are taken into account and an averaged value is calculated from these numbers.

3.2.5 Swash

Swash is calculated with a different method compared to R2% and setup. Swash is calculated by integrating a variance density spectrum. The spectrum is created from the water level time series at the waterline.

From this signal a decomposition can be made for the incident band swash and the infragravity band swash. The variance is obtained by integrating the variance density spectrum from the water level elevation time series, which results in a value with metres squared as unit. Taking the squared root of this value and multiply this with four gives the significant swash value with the unit metres. Infragravity band swash is obtained by integrating over the low frequencies; incident band swash is obtained by integrating over the high frequency band. A split frequency is needed to obtain a difference in incident band swash and infragravity band swash. The split frequency is set on 0.0375 Hz, which is obtained from a previous study to wave run-up by K. Koudstaal [17]. In several studies a split frequency of 0.04 or 0.05 Hz is used.[2] To compare outcomes with the previous study, the same split frequency is chosen.

To create a spectrum the water level elevation is given as input together with the time values which belongs to each data point. A check is performed whether there are sufficient data points to satisfy

the frequency resolution. In this case the frequency resolution will be 0.0025 Hz. When this resolution is selected a data point is given at the split frequency. When there are not enough data points to satisfy the frequency resolution an interpolation is made of the values from the variance density spectrum in such a way that a data point is given at the split frequency of 0.0375 Hz. This problem could occur when the data set is split into sub sets, for instance to separate the data in different timeslots.

3.3 Research question 1

Sub research question 1 was: *'What is a useful definition of significant alongshore variance in wave run-up?'*

To answer this question different model simulations are made. The first step is to determine the number of waves which should be modelled, the goal is to minimize the computational time with this step. However, if a number of waves is selected, a certain error occurs compared to the situation in nature. This is due to a limited number of waves which is going to be modelled. To determine the number of waves a model simulation of 24 hours is made, which is seen as the reality in nature. One cross shore transect is used to determine the number of waves and to compute the error compared to the number of waves modelled in 24 hours. Two types of error are analysed, the random error and a bias. How these errors are computed is described in section 3.3.1.1.

When the number of waves is determined, the next step can be performed. This is an analysis to determine the $R_{2\%}$, setup and swash for different wave conditions. The different wave conditions are described in section 3.3.1.2. The model simulation is computed with the limited number of waves and not with a model time of 24 hours. The error or uncertainty which belongs to the number of waves which is selected holds also for these model simulations. Furthermore an analysis is made of the variation in $R_{2\%}$, setup and swash in alongshore direction. This analysis is based on multiple cross-shore transects in alongshore direction per wave condition. Multiple wave conditions are used to analyse whether the $R_{2\%}$, swash and setup together with the variation in these components in alongshore direction changes with for instance wave height, steepness of the waves etc.

3.3.1 Number of waves

To define the number of waves a model simulation of 24 hours is made with certain parameters, the wave condition, which are described further on in section 3.3.1.2. The longer the duration of the simulation, the better results will be obtained. A model simulation of 24 hours takes approximately 1.5 day of wall clock time. This is expensive and to perform more calculations it is desired to decrease the computational time. Furthermore it is not realistic that energetic storm condition will last for 24 hours. The first analysis is based on the determination of the number of waves to be modelled.

From XBeach a run-up gauge is placed in the middle of the model. It measures the water level elevation at the waterline and it provides a time series of the water level elevation. The time series can be split into different timeslots. For example in 24 hours fits 288 timeslots of 5 minutes and 144 timeslots of 10 minutes. In total 32 specific timeslots are selected to split the dataset, this is done by dividing 24 hours in timeslots which only gives an integer value. This gives for every timeslot an equal size in 24 hours. The first timeslot will be 5 minutes. So for instance in 24 hours fits 288 equal

sized timeslots of 5 min and a timeslot of 7 minutes is not selected because 24 hours divided by 7 minutes gives a non-integer value. The selected timeslots are given in Table 3-1.

Timeslot [min]	Nr. of time slots in 24 hr.	Timeslot [min]	Nr. of time slots in 24 hr.	Timeslot [min]	Nr. of time slots in 24 hr.
5	288	30	48	120	12
6	240	32	45	144	10
8	180	36	40	160	9
9	160	40	36	180	8
10	144	45	32	240	6
12	120	48	30	288	5
15	96	60	24	360	4
16	90	72	20	480	3
18	80	80	18	720	2
20	72	90	16	1440	1
24	60	96	15		

Table 3-1: selected timeslots

On this time series and the sub time slots of the time series different analysis can be performed, for instance to calculate the $R_{2\%}$, the setup or the swash components, incident band swash or infragravity band swash. How the $R_{2\%}$, setup and swash are calculated is described in section 3.2.

3.3.1.1 Error: random error and bias

An error will occur if a smaller timeslot is chosen compared to the 24 hour model simulation. A model simulation for 24 hours will be seen as reality, this is an assumption. This means for a computation of 24 hours there is no error. When a model duration is chosen which is less than 24 hours an error will occur. In this case two types of error can occur, these are the random error and a systematically error which is known as the bias.

3.3.1.1.1 Random error

A requirement will be set to determine a threshold value for the error in $R_{2\%}$, setup and swash. This requirement will be set on an error which should be less than 7.5%. In this case 7.5% is chosen due to practical reasons. If 1% is chosen, it would require a large computational time.

The random error is determined with a 95% confidence interval for the standard deviation of $R_{2\%}$, setup and swash. Thus, the standard deviation is multiplied with two and this number is normalized by dividing by the number of $R_{2\%}$, setup or swash of 24 hours. For this a remark is made, it requires the assumption that 24 hours of model simulation will be seen as the 'reality'.

The requirement holds for $R_{2\%}$, setup, incident band swash and infragravity band swash. From this requirement it follows how many waves should be modelled. This number of waves is going to be used for further calculations in this MSc thesis.

In formula the random error is calculated with formula (3.2).

$$\text{random error} = \frac{2*\text{std}(X_i)}{X_{24hr}} * 100\% \qquad (3.2)$$

In which X_i represents the R2%, setup or swash values for a certain timeslot, X_{24hr} represents R2%, setup or swash for the model simulation of 24 hours.

3.3.1.1.2 Bias

Furthermore there could be a bias present in the results of this analysis. This is determined by taking the mean of the R2% from a specified timeslot. For example: 288 timeslots of 5 minutes contain a value of R2%. The mean is determined of the R2% from these 288 values. This gives one value for a timeslot of 5 minutes. This is done for all the different timeslots. Then the value of R2% of 24 hours is subtracted from the mean of R2% of the different timeslots. These numbers are normalized by dividing these numbers by the value of R2% of 24 hours. The same is done for setup and swash. The same assumption holds for this case, it requires that 24 hours of model simulation will be seen as the 'reality'.

In formula the bias is calculated with formula (3.3).

$$\text{Bias} = \frac{\frac{1}{n}\sum_{i=1}^{n} X_i - X_{24hr}}{X_{24hr}} * 100\% \qquad (3.3)$$

In which X_i represents the R2%, setup or swash value for a subset of data i for one timeslot, X_{24hr} represents the value of R2%, setup or swash for 24 hours. This formula is applied for every timeslot.

3.3.1.2 Wave condition

The model simulation for 24 hours is computed with an energetic wave climate. A storm condition is selected which could be present on the location of Anmok beach, it is a realistic storm condition for Anmok Beach. The input for the wave condition can be seen in Table 3-2. In which H_{m0} represents the significant wave height, T_p the peak wave period, the main angle represents the angle of incidence of incoming waves, gamma-jsp defines the shape of the spectrum and s represents the directional spreading.

H_{m0} [m]	T_p [s]	Main angle θ[°]	Gamma-jsp γ-jsp [-]	s [-]
4,62480	10,3825	270	3.3	5,8208188

Table 3-2: primary storm condition for Anmok Beach

With these conditions the model simulation for 24 hours is made. The result of this calculation will be used to determine the number of waves which will be modelled.

3.3.2 R2%, setup and swash for multiple wave conditions

The method is described to define the number of waves together with the corresponding error. The next step is to perform different model simulations in which different wave conditions are applied. The goal is to define R2%, setup and swash for different wave conditions. Furthermore a definition of the variance in alongshore direction in R2%, setup and swash will be defined. Next to this a study is made whether trends can be shown in graphs between for instance the wave height and the variance in alongshore direction for different wave conditions.

To specify different wave conditions five parameters are changed. Several values are assigned to these parameters listed. In Table 3-3 an overview is given of the different parameters with their corresponding values.

Parameter	Description	Symbol	Value		
1	Wave height [m]	H	2	4	6
2	Wave steepness [-]	H/L	1	3	-
3	Wave direction	θ	270	290	-
4	Wave directional spread [-]	s	4	20	2000
5	Wave frequency spread [-]	Gamma-jsp (γ-jsp)	1	3.3	-

Table 3-3: Considered parameters with the assigned values

The wave height will contain three different values; this will be in the range of 2 to 6 meter. Two values will be used for the steepness of the waves; this will be in the order of 1% to 3%. Representing swell waves and more energetic storm conditions. If a larger wave height is considered it could give, in combination with the steepness of the waves, a period which is smaller than six seconds. This is an undesired situation which is already mentioned in section 3.1.1.4. Two directions of the waves will be considered, normal incident wave and a wave direction which is 20 degrees out of normal incident waves. The directional spread will contain three different values, with a very large value resulting in long-crested waves. The frequency spread will contain two different values. In total there are 12 different values belonging to the five parameters.

A combination of a wave height of 2 metres with a steepness of 3% is not taken into account. In XBeach this combination will give errors in the results, due to a large k*d number. Values of k*d above 1.5 are not considered. This is the case for a wave height of 2 metres and a steepness of 3%.

There are 60 combinations possible when the different parameters are combined. Thus, this results in 60 model simulations in which a specific wave condition is applied. The duration of the model simulation depends on the wave period considered in each case. The wave period is based on the steepness of the waves combined with the deep water condition for the dispersion relationship. The model duration is based on the number of waves multiplied by the wave period. In the appendix it is shown for every model simulation which wave condition is applied, see 0

For each model simulation the $R_{2\%}$, setup and swash is calculated with the method described in section 3.2. This is done for several run-up gauge output from XBeach. At every grid point in alongshore direction a run-up gauge is placed which calculate the water level elevation at the waterline. The grid points are situated two meter next to each other, resulting in 51 run-up gauges when the beach is 100 meter wide. The calculation of $R_{2\%}$, setup and swash results in 51 values per model simulation, thus a 51x60 matrix for $R_{2\%}$, setup and swash. A mean value for $R_{2\%}$, setup and swash components is calculated from the run-up gauges, this result in a mean value per model simulation for $R_{2\%}$, setup and swash.

3.3.3 Define standard deviation in alongshore direction

A definition of the variance or standard deviation will be given for $R_{2\%}$, setup and swash in alongshore direction. The 60 model simulations with uniform bathymetry are analysed to calculate the variance or the standard deviation in alongshore direction. This gives 60 numbers which can be

compared as reference situation for other bathymetries which include for instance beach cusps and an offshore bar.

For every run-up gauge an analysis is made for R2% for each model simulation, which is already described in section 3.3.2. This is done for 60 model simulations, in which each model simulation contains 51 R2% values for the uniform bathymetry. The standard deviation is taken from the 51 values of R2% from one model simulation out of 60. Thus, this is the standard deviation in alongshore direction. This is done for each model simulation, so in this case 60 values of the standard deviation are obtained. These values of the standard deviation in alongshore direction are normalized by dividing over the mean of the R2% from the 51 run-up gauges per model simulation. Thus, this is the mean of the R2% in alongshore direction. The same method is applied for the normalized standard deviation in alongshore direction of setup, infragravity band swash, incident band swash and total swash. Formula (3.4) represents this method.

$$\text{normalized standard deviation in alongshore direction} = \frac{\text{std}(X_i)}{\frac{1}{n}\sum_{i=1}^{n} X_i} * 100\% \qquad (3.4)$$

In which X_i represents the R2%, setup or standard deviation for the swash, n will be 51, because there are 51 run-up gauges. This formula will be applied for 60 model simulations.

The numbers obtained by this method results in 60 values per model simulation for R2%, setup and swash. These will be considered as the reference numbers which will be used for comparison with other bathymetries. It is chosen to specify this in the format of the standard deviation, in this case the unit of metres is obtained.

3.4 Research question 2

Sub research question 2 was: *'How does the magnitude and the alongshore variance in wave run-up vary relative to cusp characteristics and are there any dependencies visible? '*
To answer this question first of all the 60 wave conditions are applied to the model with a bathymetry which contains beach cusps. Three cusp lengths are modelled. These are the 452, 300 and 100 metres cusps. Every four metres a run-up gauge output is stored, which give a water level time series. Thus, data is analysed at every four meters from the central cusp. From this data the R2%, setup and swash is calculated as described in section 3.2.

3.4.1 Magnitude

Firstly, the alongshore averaged values of R2%, setup and swash components are determined. Secondly, the alongshore maximum along the central cusp of R2%, setup and swash components is determined. This is done for each cusp length, resulting in 60 values for each of these parameters for each bathymetry. This is also done for the uniform bathymetry. In this case the alongshore averaged value is calculated from the 100 metres wide uniform beach together with the alongshore maximum from the same beach, this is also done for R2%, setup and swash components.

The next step is to plot these results. The alongshore averaged values (60 in total) are presented in scatterplots for setup, swash components and R2%. Two cusps lengths are compared in this way. A comparison is made for the 452 metres cusp with the 300 and 100 metres cusp. Furthermore the 300 and 100 metres cusps are also compared with each other. The same is done for the alongshore

maximum values. With these scatterplots the differences in magnitude between the cusp lengths are visible.

To check the differences with the uniform bathymetry, also scatterplots are made which compare the results of a cusp system with the results of the uniform bathymetry. Thus, a scatterplot is presented of a cusps length of 452 metres versus the uniform bathymetry, a cusp length of 300 metres versus the uniform bathymetry and a cusp length of 100 metres versus the uniform bathymetry. This is done for the alongshore averaged values of $R_{2\%}$, setup and swash components and also for the alongshore maximum values of run-up and all components.

The alongshore maximum value is determined with the following method. From the data set of a certain parameter, in this case for instance $R_{2\%}$, the mean value is determined. When this mean is plotted along the data set, with on y-axis $R_{2\%}$ and on x-axis the alongshore distance of the cusp, a division is made in vertical sense. Thus, two subsets are created. One subset of data points below the mean value, called subset A. And one subset of data points above the mean value, subset B. From subset B a mean value is determined. Furthermore the standard deviation is determined of subset B. To determine the alongshore maximum with a 95% confidence interval the standard deviation of subset B is multiplied by two and added to the mean of subset B. This gives the alongshore maximum of $R_{2\%}$. The same holds for setup and the swash components. In Appendix X it is shown why the standard deviation is taken from subset B instead of the standard deviation of the whole dataset. This method resembles the maximum values better.

3.4.2 Trend along the central cusp

Once the magnitude is determined an analysis is made to make patterns visible of $R_{2\%}$, setup and swash components along the central cusp. Scatterplots are made to compare the different wave conditions and the different cusp lengths. The plots include the values of $R_{2\%}$, setup and swash components versus the alongshore varying slope in a cusp. The scatterplot is not readable anymore if all data points of the 60 wave conditions are present in this plot. Thus, trend lines are plotted in scatterplots for a wave height of 6 metres and a wave height of 2 metres with both a steepness of 1%. In the scatterplots the location of the horn and embayment is shown with a text label. A slope of $\tan(\beta)=0.079$ represents an embayment and a slope of $\tan(\beta)=0.109$ represents a horn. For each component (setup, swash components and run-up) a scatterplot is shown for a cusp of 100 metres together with data points and a trend line and another scatterplot in which the trend lines of the 100 and 452 metres cusp are compared for certain wave conditions.

3.5 Research question 3

Sub research question 3 was: *'How does the magnitude and the alongshore variance in wave run-up vary on bar characteristics in combination with cusp characteristics and is this different from that found for question 2?'*

To answer this question the same methods are applied as described for research question 2. One cusp bar system is modelled. This is a cusp length of 452 metres including a crescentic sandbar which is also 452 metres long. The 60 wave conditions are applied at the bathymetry of the cusp bar system. Every four metres a run-up gauge output is stored, which give a water level time series. Thus, data is analysed at every four meters from the central cusp. From this data the $R_{2\%}$, setup and swash is calculated as described in section 3.2.

3.5.1 Magnitude

The alongshore averaged and alongshore maximum values are determined along the central cusp for setup, infragravity band swash, incident band swash, total swash and finally total run-up $R_{2\%}$. The same method is applied as described in section 3.4.

The magnitudes are presented in scatter plots. This is done for the alongshore averaged values (60 in total) for setup, swash components and $R_{2\%}$. The cusp bar system is compared with the cusp system for a length scale of 452 metres within a scatterplot. The same is done for the alongshore maximum values. With these scatterplots the differences in magnitude between the cusp bar system and the cusp system is visible.

To check the differences with the uniform bathymetry, also scatterplots are made which compare the results of the cusp bar system with the results of the uniform bathymetry. Thus, a scatterplot is presented of a cusp bar system with a length of 452 metres versus the uniform bathymetry. This is done for the alongshore averaged values of $R_{2\%}$, setup and swash components and also for the alongshore maximum value of run-up and all components.

3.5.2 Trend along the central cusp

Once the magnitude is determined an analysis is made to make patterns visible of $R_{2\%}$, setup and swash components along the central cusp of the cusp bar system. Scatterplots are made to compare the different wave conditions and cusp bar system with the cusp system. The plots include the values of $R_{2\%}$, setup and swash components versus the alongshore varying slope in a cusp. Trend lines are plotted in the scatterplots. The results are shown which contain differences in trends compared to the cusp system of a cusp length of 452 metres. In the scatterplots the location of the horn and embayment is shown with a text label. For each component (setup, swash components and run-up) a scatterplot is made in which the trend lines of the cusp bar system are compared with the cusp system if differences are observed.

4 Uniform bathymetry

In this section the results are described of sub research question 1, with the methods described in section 0 considering a uniform bathymetry.

To give an answer on sub research question 1 the number of waves is defined as a first step together with the random error and the bias which occurs if a limited number of waves is selected. Subsequently the results for $R_{2\%}$, setup and swash are given for multiple wave condition. Finally the alongshore standard deviation is determined for each model simulation with a different wave condition.

4.1 Number of waves

In this section the number of waves is determined. The method is described in section 3.3.1. The random error is defined and the bias which occurs if a smaller timeslot (number of waves) is chosen compared to 24 hours (number of waves in 24 hours). The method of calculating the random error and the bias are described in section 3.3.1.1.

4.1.1 Confidence interval and random error

In this section the results are shown of the random error which is normalized of the $R_{2\%}$, setup and swash. The random errors are defined as taking the standard deviation of the subsets and multiply this with two as described in section 3.3.1.1.1. This gives a 95.5% confidence interval. It can be seen that the value for 24 hours or 8322 waves contains always a random error equal to zero. This is because the assumption holds that the model duration of 24 hours is seen as reality. The following requirement holds: the error should be smaller than 7.5%, this is the threshold value. A lower value would require too many waves to simulate, so for practical reasons this is not in the order of 1% or 2%.

4.1.1.1 Random error $R_{2\%}$

In Figure 4-1 it can be seen that the requirement of 7.5% coincides with the graph at 426 waves. In this case a minimum of 426 waves need to be modelled to obtain an error less than 7.5%. At x=462 waves an error of 6.769% occurs and at x=520 waves an error of 7.233% is seen. The random error at the vertical axis is plotted versus the number of waves on the horizontal axis. The timeslots of 5, 6, 8 and 9 minutes are not available for the calculation of $R_{2\%}$. As described in section 3.2.3, there are too few run-up points to calculate $R_{2\%}$ for these timeslots. For a timeslot of 10 minutes and larger it is possible to compute $R_{2\%}$.

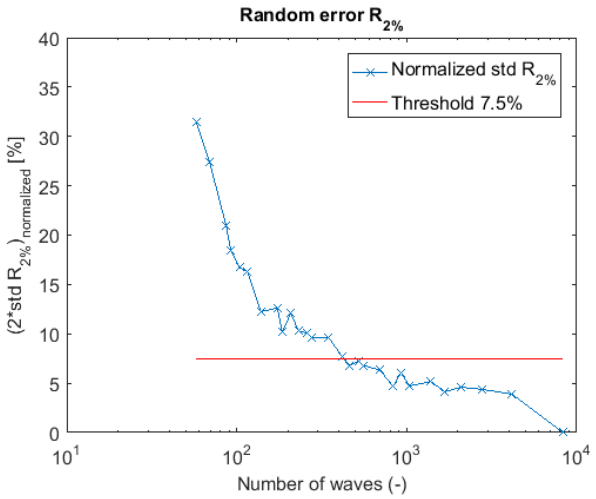

Figure 4-1: two times the normalized standard deviation for $R_{2\%}$, plotted against number of waves

4.1.1.2 Random error setup

In Figure 4-2 it can be seen that the requirement of 7.5% coincides with the graph at 122 waves. In this case a minimum of 122 waves need to be modelled to obtain an error less than 7.5%. At x=462 waves an error of 4.22% occurs and at x=520 waves an error of 4.00% is seen.

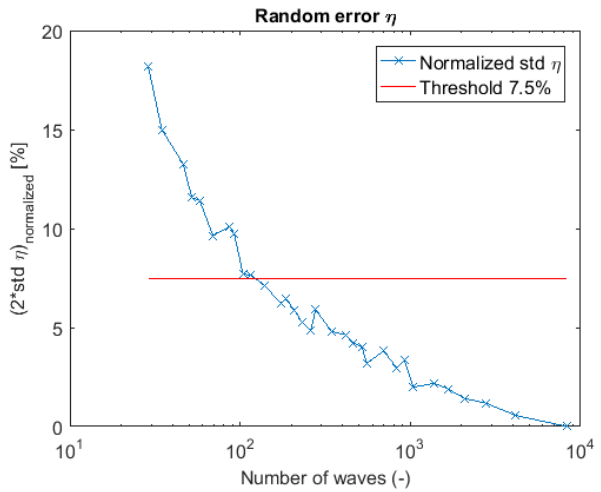

Figure 4-2: two times the normalized standard deviation for setup, plotted against number of waves

4.1.1.3 Random error swash

In Figure 4-3 it can be seen that the requirement of 7.5% coincides with the graph at 416 waves. In this case a minimum of 416 waves need to be modelled to obtain an error less than 7.5%. A further decrease of the error is seen in the graph from this point. At x=462 waves an error of 5.278% occurs and at x=520 waves an error of 5.606% is seen. The values obtained in this case are the standard deviations from the swash signal. For example, a five minute timeslots gives 288 variance values after integrating the variance density spectra. The squared root of this gives the swash values or the standard deviations. The standard deviation of this set of values (288 in total) is the standard deviation for the 5 minute timeslot. Thus, it is a measure of the standard deviation of the standard deviation.

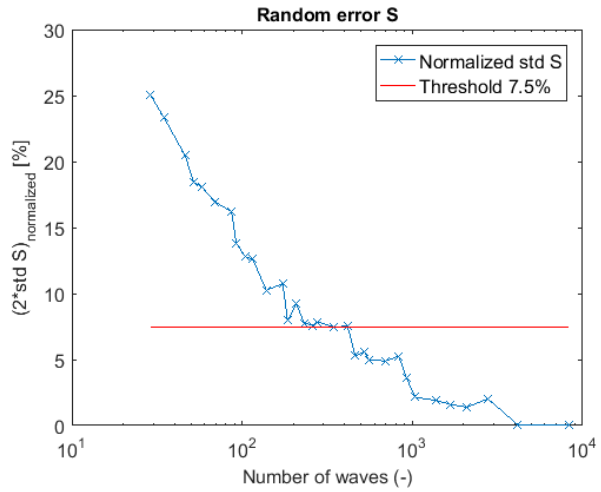

Figure 4-3: two times the normalized standard deviation for swash plotted against number of waves

4.1.1.4 Random error infragravity band swash

In Figure 4-4 it can be seen that the requirement of 7.5% coincides with the graph at 450 waves. In this case a minimum of 450 waves need to be modelled to obtain an error less than 7.5%. However, a small increase in error can be seen between 462 and 520 waves. This is still lower compared to the threshold value of 7.5%. At 462 waves an error of 6.578% occurs and at 520 waves an error of 7.377% is seen. After 520 waves the error decreases again. On average a total number of 500 waves should be modelled.

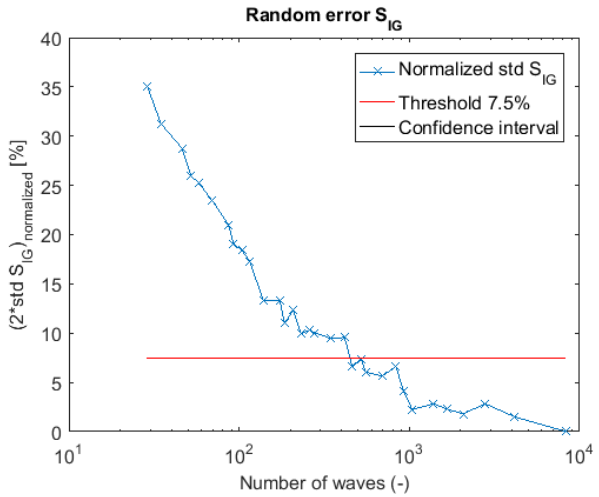

Figure 4-4: two times the normalized standard deviation for infragravity band swash, plotted against number of waves

4.1.1.5 Random error incident band swash

In Figure 4-5 it can be seen that the requirement of 7.5% coincides with the graph at 346 waves. In this case a minimum of 346 waves need to be modelled to obtain an error less than 7.5%. A further decrease of the error is seen in the graph from this point. At x=462 waves an error of 6.376% occurs and at x=520 waves an error of 5.486% is seen.

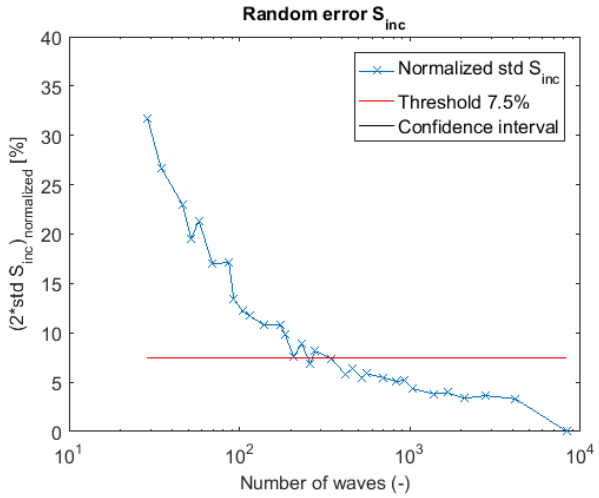

Figure 4-5: two times the normalized standard deviation for incident band swash, plotted against number of waves

4.1.1.6 *Number of waves*

In Table 4-1 an overview is given of the minimum number of waves to be modelled for each computation.

	Intersection of requirement 7.5% with number of waves [-]	Minimum number of waves to be modelled [-]	Random error for minimum nr. of waves [%]	Error at 500 waves [%]
$R_{2\%}$	426	462	6.769	7.07
Setup	122	139	7.117	4.07
Swash	416	462	5.278	5.50
Infragravity band swash	450	462	6.578	7.11
Incident band swash	346	347	7.397	5.78

Table 4-1: overview of minimum number of waves to be modelled

From Figure 4-1 to Figure 4-5, it can be concluded that the minimum number of waves should be equal to 462 waves or more. Figure 4-4 contains the largest error and determines the number of waves. In the same figure it can be seen that the error is slightly increasing but remains under the threshold value of 7.5%. This happens between 462 and 520 waves. It is chosen to model 500 waves for further calculations. This results in a reduction of computational time, in which the error is lower than 7.5% or even more in some cases with a 95% confidence interval.

4.1.2 Bias

There could also be a systematic error beside the random error which occurs at the 95% confidence interval obtained in section 4.1.1, the error mentioned in this section is the bias. The normalized bias is calculated for the $R_{2\%}$, setup and swash and represented in Figure 4-6 to Figure 4-10. It is a deviation compared to the expected value of a parameter, in which parameter is referring to $R_{2\%}$, setup or swash components. It can be seen that the value for 24 hours or 8322 waves is always zero. This is because the assumption holds that the model duration of 24 hours is seen as reality. The bias could be positive or negative, indicating an overestimation or underestimation respectively.

4.1.2.1 Bias R2%

In Figure 4-6 the normalized bias is shown for R2%. For 500 waves the bias is equal to approximately 1.38 %. The values are in the range of 0.55% to 1.5% around 500 waves.

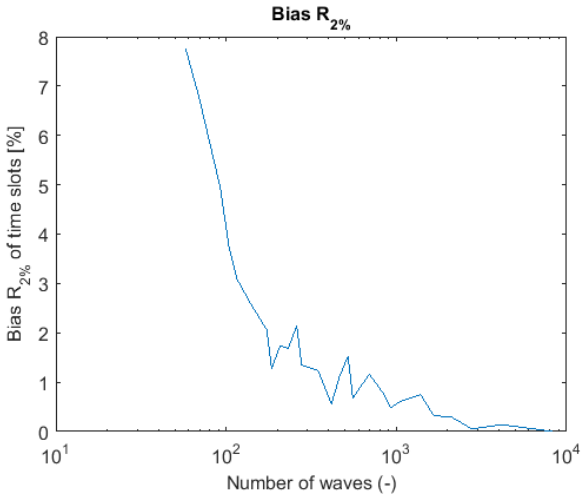

Figure 4-6: normalized bias R2%, plotted against the number of waves

4.1.2.2 Bias setup

In Figure 4-7 the normalized bias is shown for setup. For 500 waves the bias is equal to approximately -2.65E-4 %. The values are in the range of -0.0005125% to 0.001336% around 500 waves.

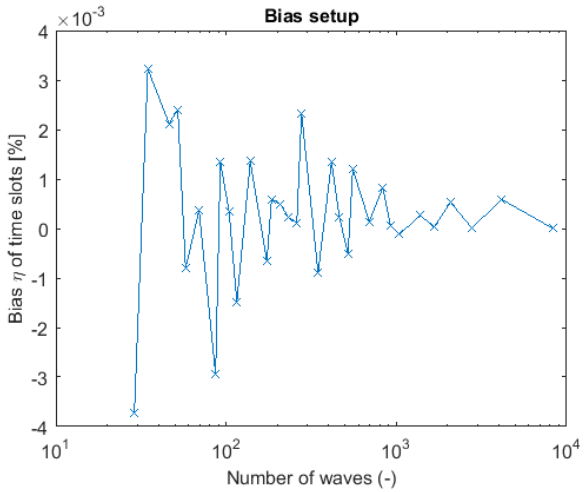

Figure 4-7: normalized bias setup, plotted against the number of waves

4.1.2.3 Bias swash

In Figure 4-8 the normalized bias is shown for swash. For 500 waves the bias is equal to approximately -0.09 %. This is the same value around 500 waves. The negative value means an underestimation of the expected value.

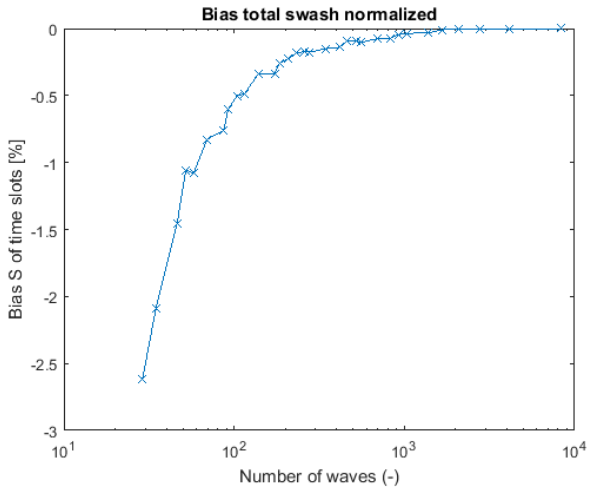

Figure 4-8: normalized bias swash, plotted against the number of waves

4.1.2.4 Bias infragravity band swash

In Figure 4-9 the normalized bias is shown for infragravity band swash. For 500 waves the bias is equal to approximately -0.138 %. The values are in the range of -0.0765% to -0.2609% around 500 waves. In this case also an underestimation of the expected value is found.

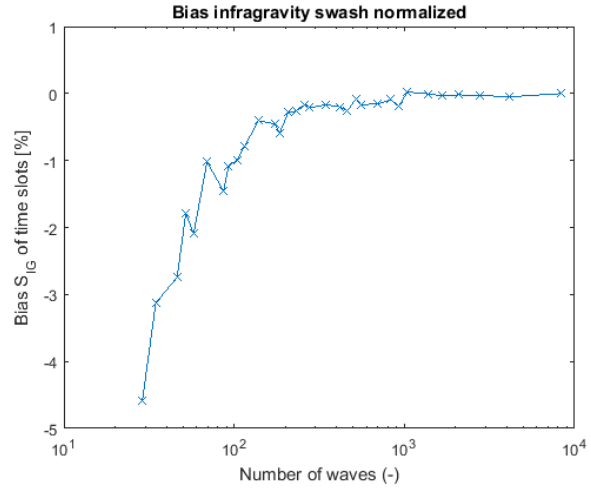

Figure 4-9: normalized bias infragravity band swash, plotted against the number of waves

4.1.2.5 Bias incident band swash

In Figure 4-10 the normalized bias is shown for incident band swash. For 500 waves the bias is equal to approximately -0.05 %. The bias is in the range of 0.24% to -0.19% around 500 waves.

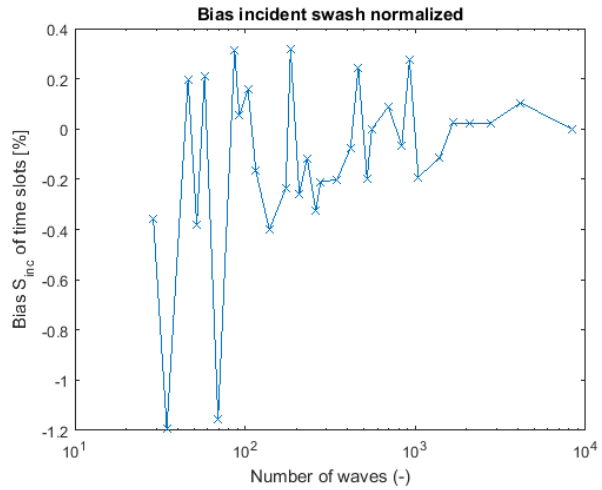

Figure 4-10: normalized bias incident band swash, plotted against the number of waves

4.1.2.6 Overview bias

In Table 4-2 an overview is given of the different values for the bias in the different calculations.

	Bias at 500 waves [%]
$R_{2\%}$	1.38
Setup	-2.65E-4
Swash	-0.09
Infragravity band swash	-0.138
Incident band swash	-0.05

Table 4-2: overview bias for 500 waves

From Table 4-2 it can be seen that the bias is almost 0% for each situation. $R_{2\%}$ contains the largest bias. From Figure 4-6 - Figure 4-10 it can be seen that the absolute value of the bias is decreasing to zero. The values are below 2% and thus 500 waves are maintained for the model simulations. One could argue when the bias is approximately 8% for $R_{2\%}$ that there should be more waves to be modelled, but this is not the case.

4.2 Rn%

Now it is known how many waves are going to be modelled, now a figure is made in which the Rn% is plotted versus the exceedance. In this thesis the value of $R_{2\%}$ will be used for further analysis. However, for specific cases it is desired to know for instance $R_{0.1\%}$, this could be a relevant value to check safety for structures in the hinterland or on the beach. Figure 4-11 gives the results for the data set of 24 hours. The data sets for 462 and 520 waves, which are respectively 80 and 90 minutes, are also shown. A data set of 500 waves is not given because this does not correspond to a integer value for a timeslot as described in section 3.3.1.

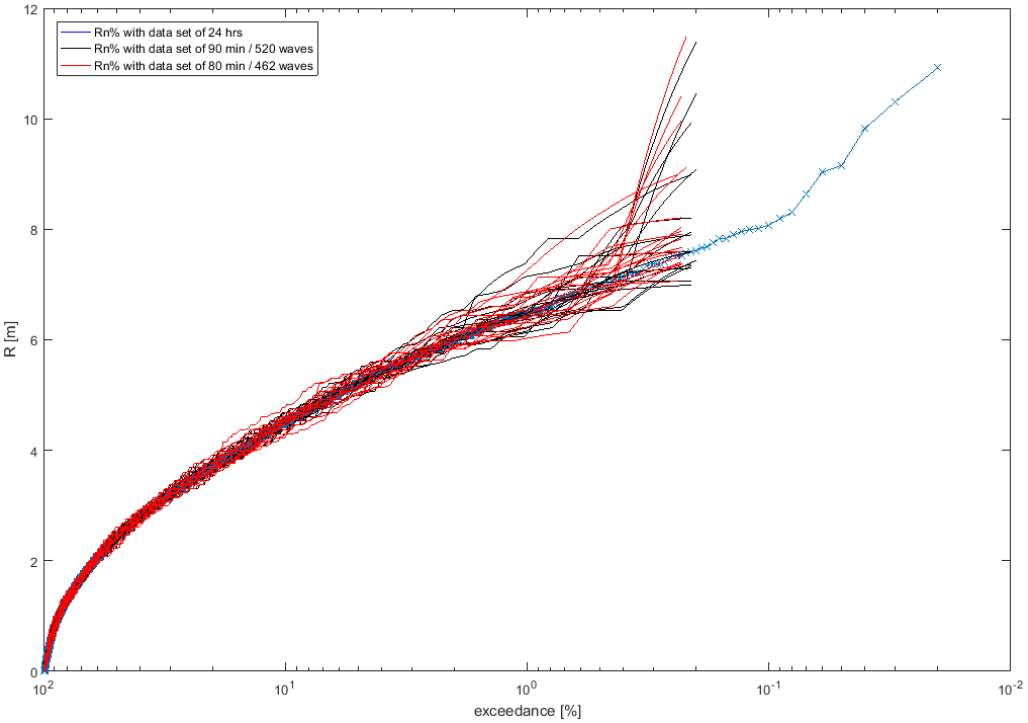

Figure 4-11: $R_{n\%}$ versus percentage of exceedance

From Figure 4-11 it can be seen that the points are almost on one line for all the three datasets. The dataset of 24 hours follows a 'smooth' line. However, suddenly an interruption occurs, $R_{n\%}$ values lie above the 'smooth' line. This happens for n smaller than 0.08. This could be explained due to less extreme run-up points, the same is the case for the datasets considered with 462 and 520 waves for n is smaller than 0.5. A spread (in the vertical) is present around $R_{2\%}$ for all the timeslots of 520 waves and 462 waves. The standard deviation for this value which represents a measure of the spread is respectively 0.2165 meter (3.62%) and 0.2026 meter (3.38%). The values between brackets are the normalized values, in which the standard deviation is divided by the $R_{2\%}$ value of 24 hours. These values are in agreement with the normalized values found in section 4.1.1.1 when they are multiplied by two for a 95% confidence interval.

4.3 Analysis uniform bathymetry

In this section an analysis is given of the uniform bathymetry regarding to the absolute values of $R_{2\%}$, setup and the swash components, together with the interpretation of the standard deviation in alongshore direction of the before mentioned terms.

4.3.1 $R_{2\%}$, setup and swash components

$R_{2\%}$, setup and swash is calculated for 60 model simulation from every run-up gauge in alongshore direction (51 transects). The mean value is determined from these 51 transects in one model simulation, resulting in five values for each model simulation: $R_{2\%}$, setup, swash, infragravity band swash and incident band swash. For the swash components the squared root of the signal is obtained to give an answer in the unit of metres. The results are shown in Appendix III .

The mean values of $R_{2\%}$, setup, swash, infragravity band swash and incident band swash in alongshore direction are compared together with the different parameters such as wave height, steepness, angle of incidence, frequency spreading and directional spreading.

In general an increase in $R_{2\%}$, setup and swash can be seen when the wave height goes up for all the wave conditions. When a distinction is made between swell waves and a more energetic condition, in this case a steepness of 1% and 3% respectively, a decrease can be seen in $R_{2\%}$, setup and swash components if the steepness increases. This can be seen when a wave height of 4 m and 6 m are considered together with a steepness of 1% and 3%. Swell waves results in a larger $R_{2\%}$, setup and swash in this case. Breaking incident waves could be an explanation, where the infragravity waves will dominate which results in larger values for $R_{2\%}$, setup and swash components when a steepness of 1% is considered. A comparison with a wave height of 2 m cannot be made. The combination with a wave height of 2 m and a steepness of 3% resulted in a k*d value which is larger than 1.5, which causes errors in the results of XBeach.

There is no pattern observed in a significant increase or decrease when the angle of incidence is changed from 270 to 290 degrees. The same holds for the difference in frequency spreading and directional spreading. It can be seen that waves with an angle of 270 degrees gives a slightly larger run-up compared with 290 degrees, this holds for the long-crested waves.

The results of the mean values of $R_{2\%}$, setup and swash components in scatterplots can be seen in Appendix V .

4.3.2 Standard deviation in alongshore direction

In alongshore direction the standard deviation is calculated for the 60 different model simulations specified in section 3.3.1.2. This is done for $R_{2\%}$, setup, swash, incident band swash and infragravity band swash components. The values are normalized which gives a picture of the variation in alongshore direction. It is chosen to express this in the standard deviation, with this method the same unit is obtained from the specific parameters which are analysed. For the method how this is calculated with the corresponding formula a reference is made to section 3.3.3.

In Table 4-3 a summary is given of the normalized minimum and maximum values of the standard deviation in alongshore direction.

1*std of:	$R_{2\%}$	Setup	Swash	Infragravity band swash	Incident band swash
Min [%]	0.171	0.023	0.037	0.055	0.056
Median [%]	1.548	0.478	0.561	0.682	0.854
Max [%]	4.614	2.038	1.891	2.320	3.350

Table 4-3: minima and maxima of normalized standard deviation $R_{2\%}$, setup and swash components

It can be seen that the variations contains a maximum of 4.61% for $R_{2\%}$. Swash contains a minimal variation when maximal values are considered of at most 1.89%. Incident band swash contains a larger value for the maximum normalized standard deviation compared with infragravity band swash, 3.35% and 2.32% respectively.

The above mentioned values hold for all wave conditions. If only long-crested waves are considered the mean values of the normalized standard deviation are much lower. This is 0.36% for R2% and around 0.11% for setup, swash, infragravity band swash and incident band swash.

The actual values of the 60 normalized standard deviations of the different components are given in Appendix IV in Table IV-1. Furthermore the normalized standard deviation is analysed with respect to different hydrodynamic forcing components, this is described in chapter 7.

4.4 Conclusion

A first step was made to define the number of waves to be used in the calculations. This resulted in 500 waves, with a random error lower than 7.5% within a confidence interval of 95%. The bias was found to be lower than 1.38%. The goal was to limit the computational time, which is achieved by choosing 500 waves to simulate in further model simulations.

In total 60 model simulations are made for an alongshore uniform bathymetry. This resulted in 60 mean values for $R_{2\%}$, setup and swash components. The calculations were made for 51 transects with two metre spacing.

It can be concluded that wave height and steepness are the two dominant parameters which influence the results of the $R_{2\%}$, setup and swash components. A wave height of 2 meters result in lower values for run-up compared to a wave height of 6 metres. Furthermore when waves with a steepness of 1% are considered the magnitude is larger compared to waves which contain a steepness of 3%. A change in the angle of incidence, from 270 to 290 degrees, gives slightly larger values for an angle of 270 degrees. This holds for long crested waves without directional spreading. No clear pattern can be observed when a difference is applied in frequency spreading and directional spreading.

From the $R_{2\%}$, setup and swash the standard deviation in alongshore direction is calculated, the squared root of the variance. It is chosen to express the numbers in the standard deviations, with this method the same units are obtained for $R_{2\%}$, setup and swash. This resulted in 60 definitions of the variance in alongshore direction for $R_{2\%}$, setup, swash, infragravity band swash and incident band swash. These numbers are the reference situation, used for comparison when the same calculations are made for other bathymetries, for instance a bathymetry with beach cusps or a cusp bar system. The normalized standard deviation ranges between 0.17% and 4.61% for $R_{2\%}$, between 0.02% and 2.04% for setup, between 0.037% and 1.89% for swash, between 0.05% and 2.32% for infragravity band swash and between 0.06% and 3.35% for incident band swash.

5 Beach cusps

In this section an analysis is made of the results of the beach cusps which are modelled with a cusp length of 452, 300 and 100 metres.

5.1 Alongshore mean run-up and components

In alongshore direction the mean value of R2%, setup and swash components is calculated for each central cusp. This is done for all wave conditions and for all cusp lengths. These mean values for the different cusp lengths are compared with each other and the mean values of each cusp length are compared with the alongshore mean from the uniform bathymetry. In this section scatterplots are presented to show the results of the comparison between the different cusp lengths in section 5.1.1. Furthermore a comparison with the uniform bathymetry is made in section 5.1.2.

5.1.1 Alongshore mean of run-up and components for all cusp lengths

In this section a comparison is made of the alongshore mean of setup, infragravity band swash, incident band swash, total swash and R2% between the different cusp lengths. A comparison is made between a cusp length of 452m and 100m, a cusp length of 300m and 100m and finally between a cusp length of 452m and 300m.

5.1.1.1 Setup

In Figure 5-1 the results are shown of the alongshore mean values of setup for the different cusp lengths.

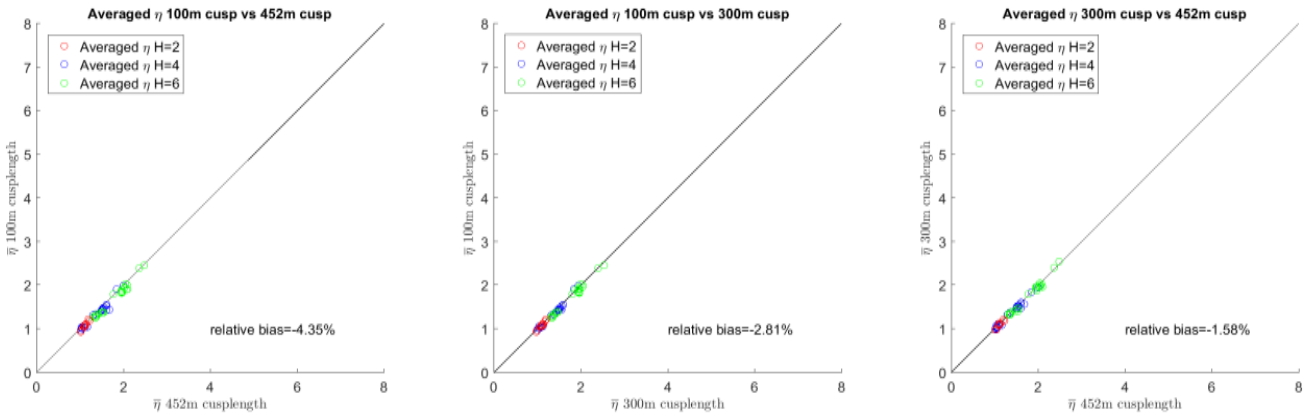

Figure 5-1: alongshore mean of setup compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 300m cusp vs 100m cusp, right: 452m cusp vs 300m cusp. The black line represents the 1:1 line.

The alongshore averaged values are in the order of 1 to 2.5 metres. It can be seen that there is no large difference between the mean values of setup for a cusp length of 452 meter and 100 meter, a cusp of 452 metres gives slightly larger mean values. This is also represented by the relative bias of -4.35%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is -2.81%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar mean values for setup.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres gives the largest mean values of setup. Two groups can be seen for a wave height of 6

and 4 metres. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.1.1.2 Infragravity band swash

In Figure 5-2 the results are shown of the alongshore mean values of infragravity band swash for the different cusp lengths.

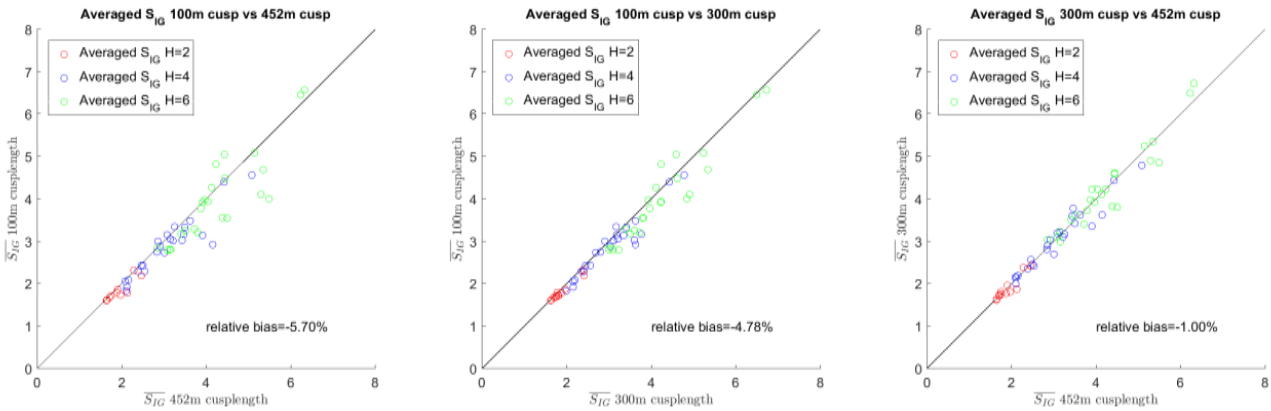

Figure 5-2: alongshore mean of infragravity band swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 300m cusp vs 100m cusp, right: 452m cusp vs 300m cusp. The black line represents the 1:1 line.

The alongshore mean values are in the order of 1.5 to 6.5 metres. It can be seen that the mean values are larger than the setup. Furthermore, the results show larger mean values for a cusp length of 452 metres compared with a cusp length of 100 metres. This is represented by the relative bias of -5.70%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is -4.78%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar mean values for infragravity band swash, with slightly larger mean values for a cusp length of 452 metres.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres gives the largest mean values for infragravity band swash.

5.1.1.3 Incident band swash

In Figure 5-3 the results are shown of the alongshore mean values of incident band swash for the different cusp lengths.

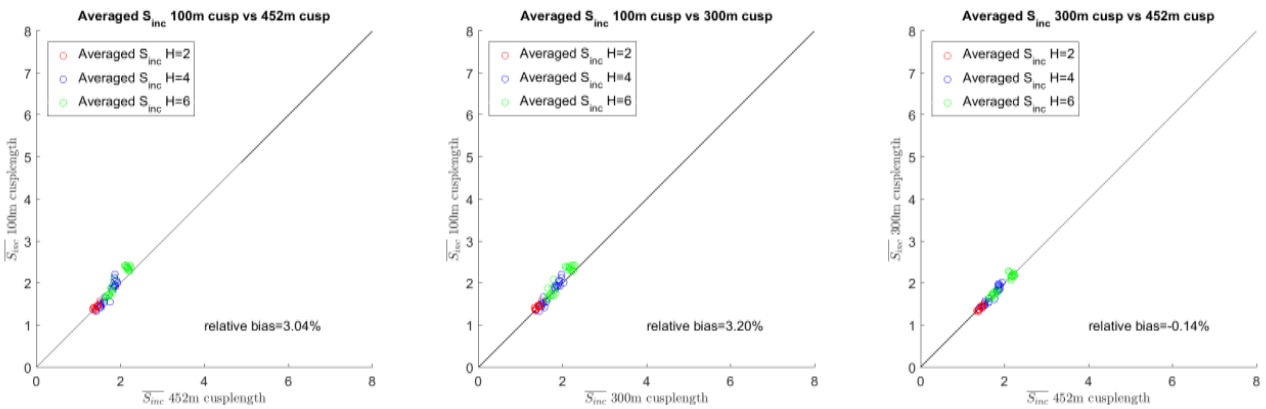

Figure 5-3: alongshore mean of incident band swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 300m cusp vs 100m cusp, right: 452m cusp vs 300m cusp. The black line represents the 1:1 line.

The alongshore mean values are in the order of 1.3 to 2.3 metres. The range is in the same order compared with setup and smaller compared with infragravity band swash. It can be seen that there is no large difference between the mean values of incident band swash for a cusp length of 452 meter and 100 meter, a cusp of 100 metres gives slightly larger mean values. This is also represented by the relative bias of 3.04%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is 3.2%. The comparison between the 452 metres and 300 metres cusp gives similar mean values for incident band swash. In this case the relative bias is only -0.14%.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres gives the largest mean values of incident band swash. Two groups of a wave height of 6 and 4 metres can be seen. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.1.1.4 Total swash

In Figure 5-4 the results are shown of the alongshore mean values of total swash for the different cusp lengths.

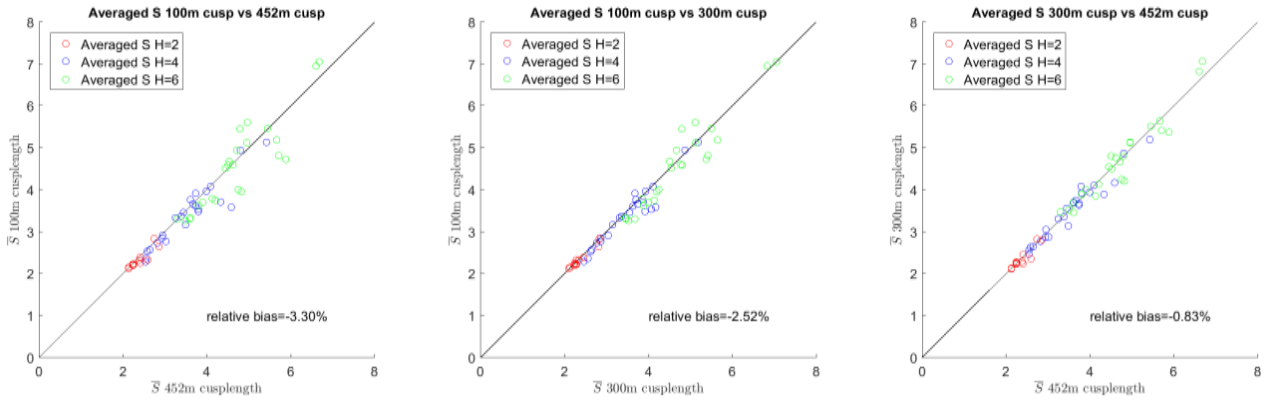

Figure 5-4: alongshore mean of total swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 300m cusp vs 100m cusp, right: 452m cusp vs 300m cusp. The black line represents the 1:1 line.

The alongshore mean values are in the order of 2 to 7 metres. It can be seen that the mean values are larger compared to setup. Furthermore the results show larger mean values for a cusp length of 452 metres compared with a cusp length of 100 metres. This is represented by the relative bias of -3.30%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is -2.52%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar mean values for total swash, with slightly larger mean values for a cusp length of 452 metres. In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres gives the largest mean values of total swash.

5.1.1.5 R2%

In Figure 5-5 the results are shown of the alongshore mean values of R2% for the different cusp lengths.

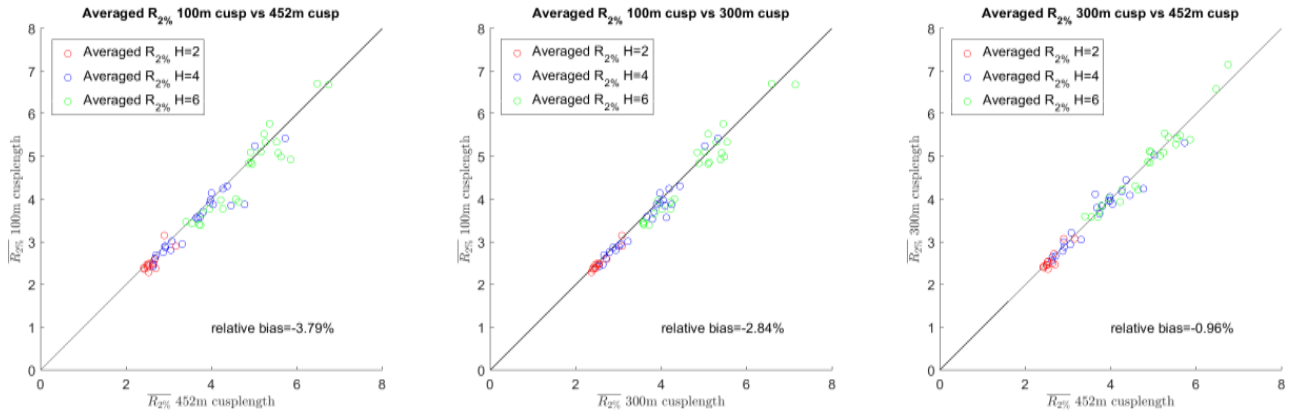

Figure 5-5: alongshore mean of R2% compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 300m cusp vs 100m cusp, right: 452m cusp vs 300m cusp. The black line represents the 1:1 line.

The alongshore mean values are in the order of 2.5 to 7 metres. It can be seen that there is no large difference between the mean values of R2% for a cusp length of 452 meter and 100 meter, a cusp of 452 metres gives slightly larger mean values. This is also represented by the relative bias of -3.79%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is -2.84%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar mean values for R2%.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres gives the largest mean values of R2%. Two groups can be observed, for a wave height of 6 and 4 metres. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.1.1.6 Conclusion mean values run-up and components, compared with cusp lengths

R2% is influenced by setup and infragravity band swash and incident band swash. In this case infragravity band swash is one of the largest components. Setup and incident band swash are both in the order of 1 to 2.3 metres and infragravity band swash is in the order of 1.5 to 6.5 metres. The averaged value for total run-up does not show large differences between the different cusp lengths. A 452 metres cusp length shows somewhat larger mean values compared to a cusp length of 100 metres and a cusp length of 300 metres shows similar results compared to a cusp length of 452 metres.

5.1.2 Alongshore mean of run-up and components for cusps and uniform bathymetry

In this section a comparison is made of the alongshore mean of setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$ between the different cusp lengths and the uniform bathymetry. A cusp length of 452, 300 and finally 100 metres is compared with the uniform bathymetry. The uniform bathymetry is represented in the scatter plots as a cusp with infinite length.

5.1.2.1 Setup

In Figure 5-6 the results are shown of the alongshore mean values of setup for the different cusp lengths and uniform bathymetry.

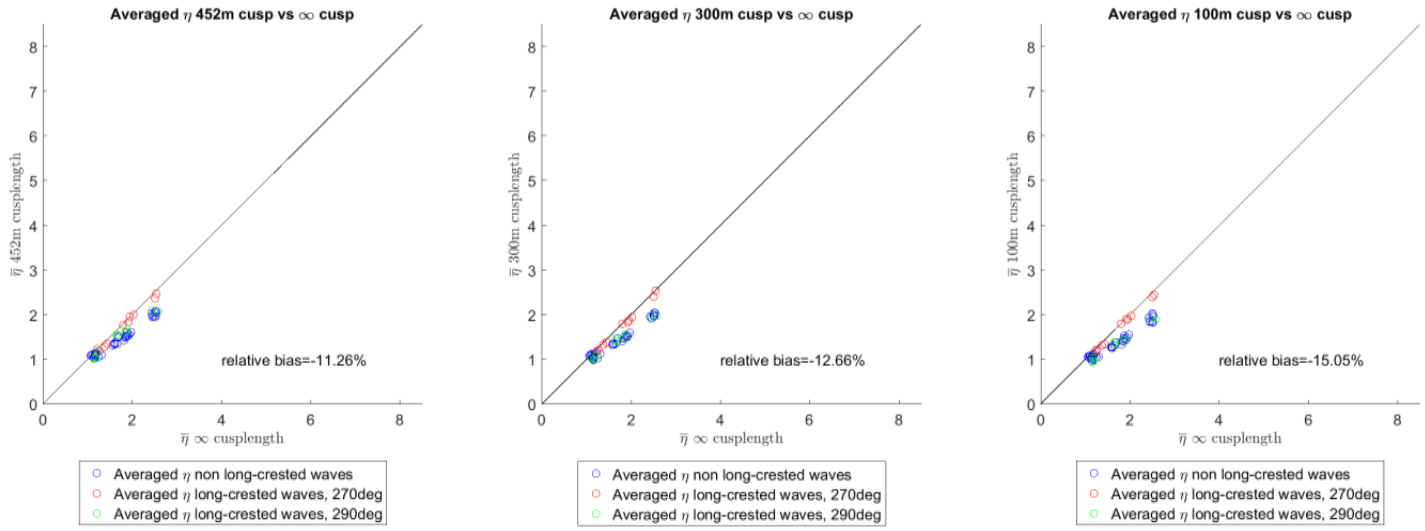

Figure 5-6: alongshore mean setup for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

In this scatterplot it can be seen that the alongshore mean values of all cusp lengths, 452, 300 and 100 metres are smaller compared to the alongshore mean values of setup from the uniform bathymetry. This is also observed in the magnitude of the relative bias. For a cusp length of 100 metres the largest difference between the mean value of setup from the cusps and the mean value of setup from the uniform bathymetry is found. In this case the absolute value of the relative bias is the largest, to be specific 15.05%.

Long-crested waves, without directional spreading and with an angle of incidence of 270 degrees, shows equal values for the mean value of setup from the cusps and the mean value of setup from the uniform bathymetry.

5.1.2.2 *Infragravity band swash*

In Figure 5-7 the results are shown of the alongshore mean values of infragravity band swash for the different cusp lengths and uniform bathymetry.

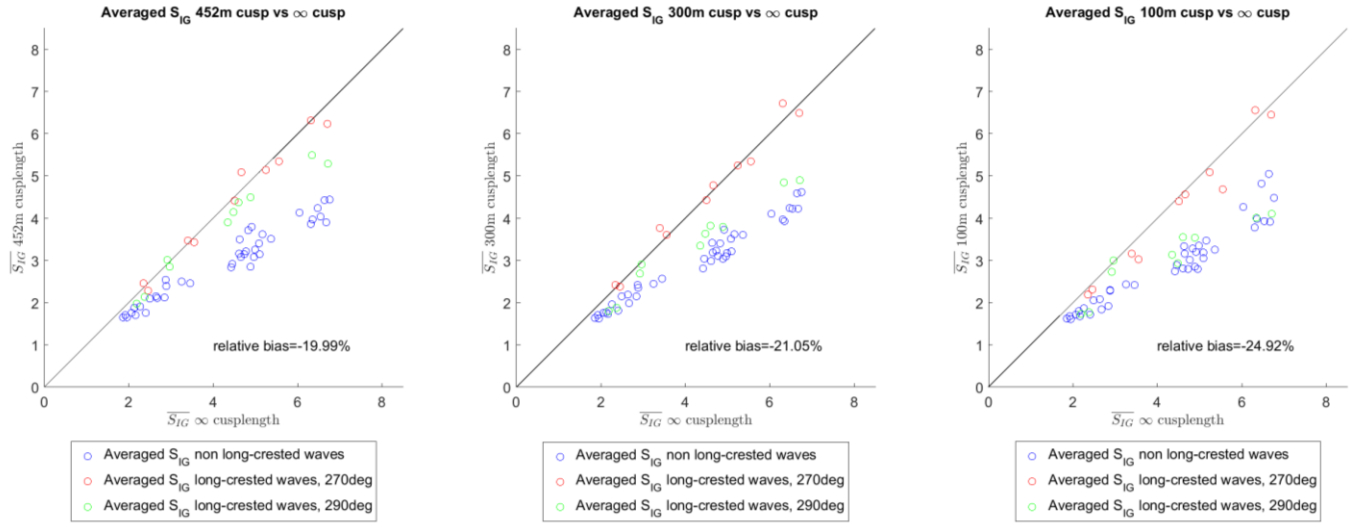

Figure 5-7: alongshore mean infragravity band swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

In this scatterplot it can be seen that the mean values for infragravity band swash are higher for the uniform bathymetry. It can be observed that long-crested waves contain almost the same mean values for infragravity band swash in the case of the uniform bathymetry and the beach cusps. However, this is not the case for a cusp length of 300 and 100 metres when long-crested waves are considered with an angle of incidence of 290 degrees.

Furthermore it can be seen that the higher the wave height, the larger the difference is in the alongshore mean value for infragravity band swash between the uniform bathymetry and the cusp lengths. For a wave height of 2 metres the values are lying close to the reference line (black 1:1 line), but for a wave height of 6 metres the values are more located in the lower right corner of the scatterplot. Thus, a wave height of 6 metres contains a larger difference between mean values for infragravity band swash for the uniform bathymetry and beach cusps compared with conditions with a wave height of 2 metres. In this case the long-crested waves with an angle of incidence of 270 degrees are an exception.

5.1.2.3 Incident band swash

In Figure 5-8 the results are shown of the alongshore mean values of incident band swash for the different cusp lengths and uniform bathymetry.

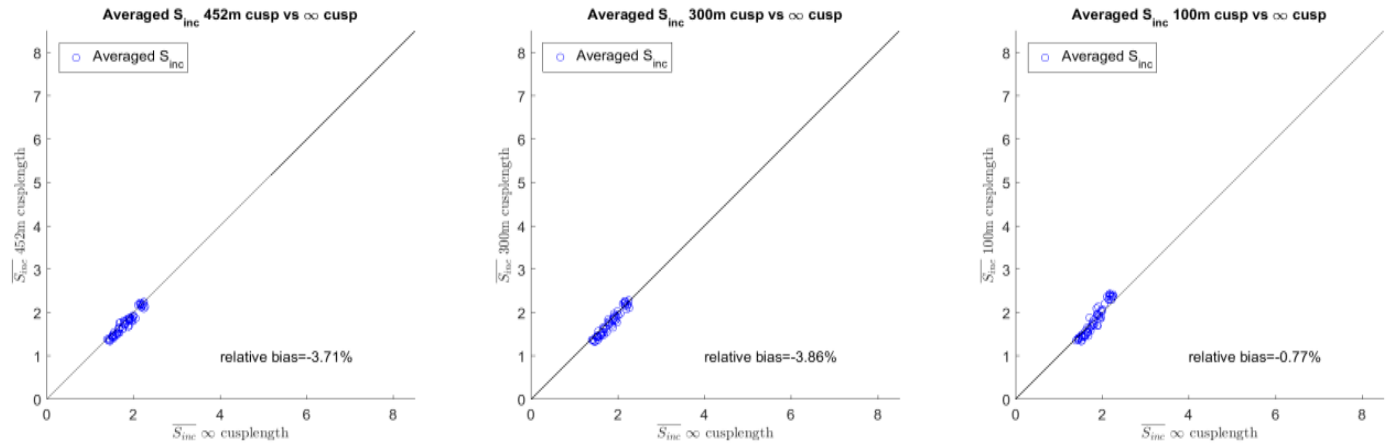

Figure 5-8: alongshore mean incident band swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

In this scatterplot it can be seen that the alongshore mean values of all cusp lengths, 452, 300 and 100 metres are almost equal to the alongshore mean values of incident band swash from the uniform bathymetry. This holds especially for the comparison between a cusp length of 100 metres and the uniform bathymetry. The relative bias is in this case almost zero. In the case of a cusp length of 452 and 300 metres the alongshore mean values of incident band swash are somewhat larger for the uniform bathymetry.

5.1.2.4 Total swash

In Figure 5-9 the results are shown of the alongshore mean values of total swash for the different cusp lengths and uniform bathymetry.

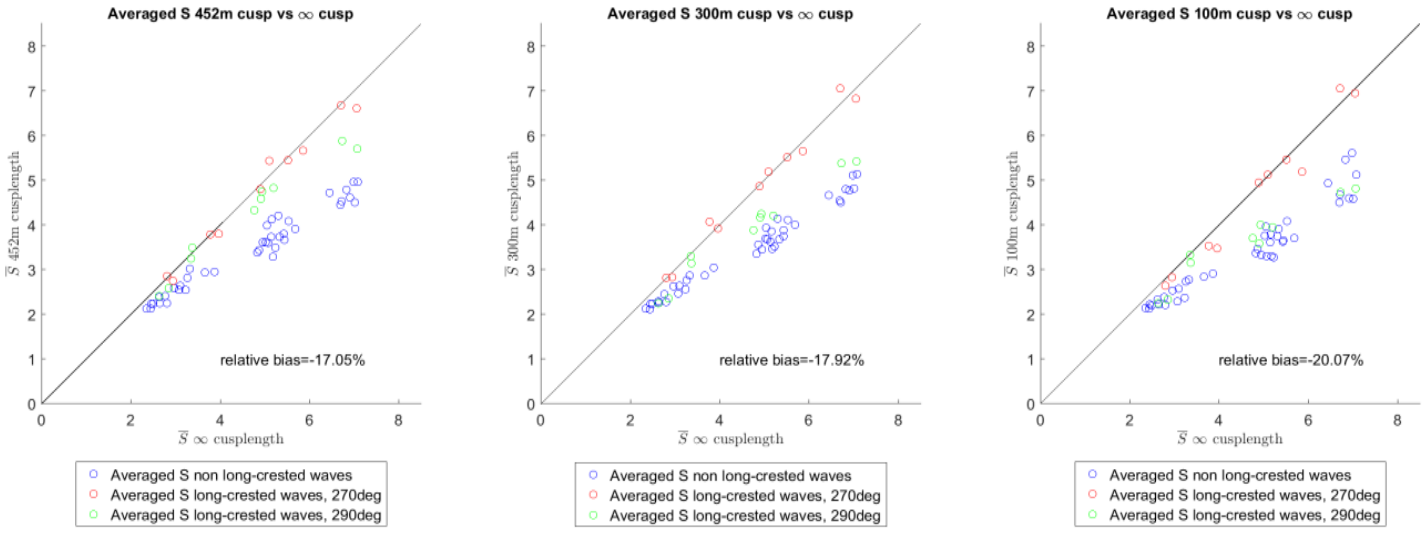

Figure 5-9: alongshore mean total swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

If total swash is considered it can be seen that the same conclusion can be drawn compared with infragravity band swash. The long-crested waves contain almost the same alongshore mean values for total swash in the case of the uniform bathymetry and the different cusp lengths. This holds not for the long-crested waves with an angle of incidence of 290 degrees together with a cusp length of 300 and 100 metres. All other wave conditions contain larger mean values for the uniform bathymetry compared to the beach cusps.

5.1.2.5 R2%

In Figure 5-10 the results are shown of the alongshore mean values of R2% for the different cusp lengths and uniform bathymetry.

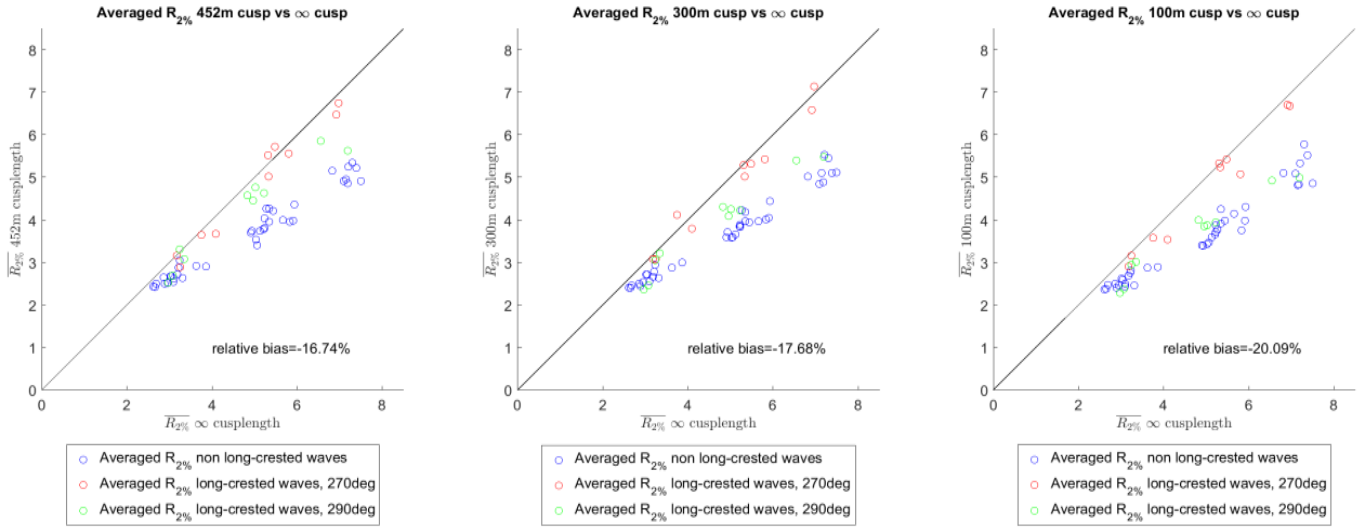

Figure 5-10: alongshore mean R2% for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

If R2% is considered it can be seen that the mean value in alongshore direction contain larger values in the case of the uniform bathymetry compared to the different cusp lengths. A wave height of 2 metres contains mean values which are slightly larger for the uniform bathymetry, the values are lying close to the 1:1 line. If the wave height increases a larger difference can be seen. The uniform bathymetry contains in this case a larger mean value. Long-crested waves, with an angle of incidence of 270 degrees, contain mean values which are similar for the uniform bathymetry and the beach cusps.

5.1.2.6 Conclusion mean values run-up and components, compared with uniform bathymetry

Infragravity band swash is one of the largest components of the total run-up for both bathymetries. Infragravity band swash contains mean values which are larger for the uniform bathymetry, this holds also for setup. However, the difference between the uniform bathymetry and the cusps for infragravity band swash is larger compared with setup. Incident band swash shows equal values between the uniform bathymetry and the beach cusps. For total run-up the same behaviour is seen as concluded for infragravity band swash, due to this dominant component. This does not hold for long-crested waves. Long-crested waves show similar results for a uniform bathymetry and for the cusp systems.

5.2 Alongshore maximum run-up and components

From the central cusp the alongshore maximum value of R2%, setup and swash components is calculated for all wave conditions and for each cusp length. These alongshore maximum values for the different cusp lengths are compared with each other and the maximum values of each cusp length are compared with the maximum values from the uniform bathymetry. In this section scatterplots are presented to show the results of the comparison between the different cusp lengths and the comparison with the uniform bathymetry.

5.2.1 Alongshore maximum of run-up and components for all cusp lengths

In this section a comparison is made of the alongshore maximum values of setup, infragravity band swash, incident band swash, total swash and R2% between the different cusp lengths. A comparison is made between a cusp length of 452m and 100m, a cusp length of 300m and 100m and finally between a cusp length of 452m and 300m.

5.2.1.1 Setup

In Figure 5-11 the results are shown of the alongshore maximum values of setup for the different cusp lengths.

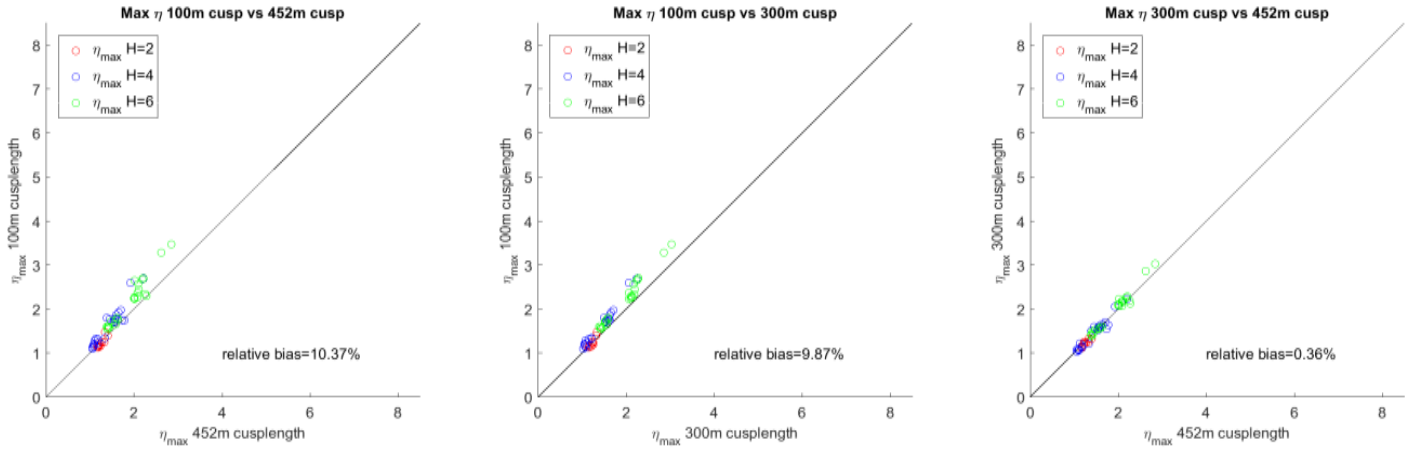

Figure 5-11: alongshore maximum setup compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 452m cusp vs 300m cusp, right: 300m cusp vs 100m cusp. The black line represents the 1:1 line

The alongshore maximum values are in the order of 1 to 3.5 metres. It can be seen that there is no large difference between the maximum values of setup for a cusp length of 452 meter and 100 metres, a cusp of 100 metres gives slightly larger maximum values. This is also represented by the relative bias of 10.37%. This is a contradiction compared with the mean values written in section 5.1.1.1. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is 9.87%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar maximum values for setup, which is represented by a relative bias of 0.36%.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres results in the largest alongshore maximum values for setup. Two groups can be seen for

a wave height of 6 and 4 metres. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.2.1.2 *Infragravity band swash*

In Figure 5-12 the results are shown of the alongshore maximum values of infragravity band swash for the different cusp lengths.

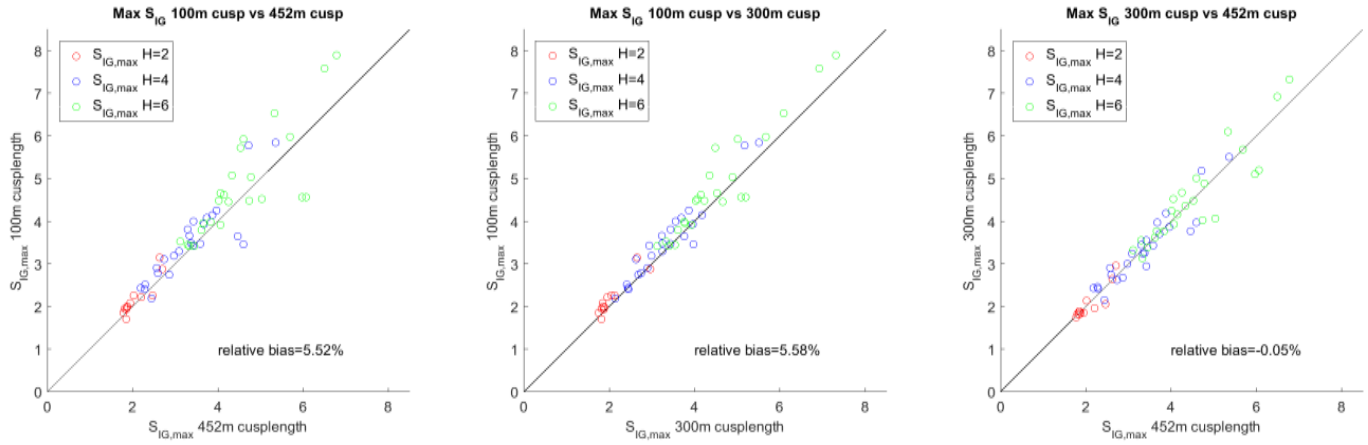

Figure 5-12: alongshore maximum infragravity band swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 452m cusp vs 300m cusp, right: 300m cusp vs 100m cusp. The black line represents the 1:1 line

The alongshore maximum values are in the order of 2 to 8 metres. It can be seen that the maximum values are larger compared to setup. Furthermore the results show larger maximum values for a cusp length of 100 metres compared with a cusp length of 452 metres. This is represented by the relative bias of 5.52%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is 5.58%. Thus, a cusp length of 100 metres gives larger alongshore maximum values compared to a cusp length of 452 and 300 metres, this is not the case when alongshore mean values are considered as described in section 5.1.1.2. The comparison between the 452 metres and 300 metres cusp gives similar maximum values for infragravity band swash. The relative bias in this case is -0.05%.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres results in the largest maximum values of infragravity band swash.

5.2.1.3 *Incident band swash*

In Figure 5-13 the results are shown of the alongshore maximum values of incident band swash for the different cusp lengths.

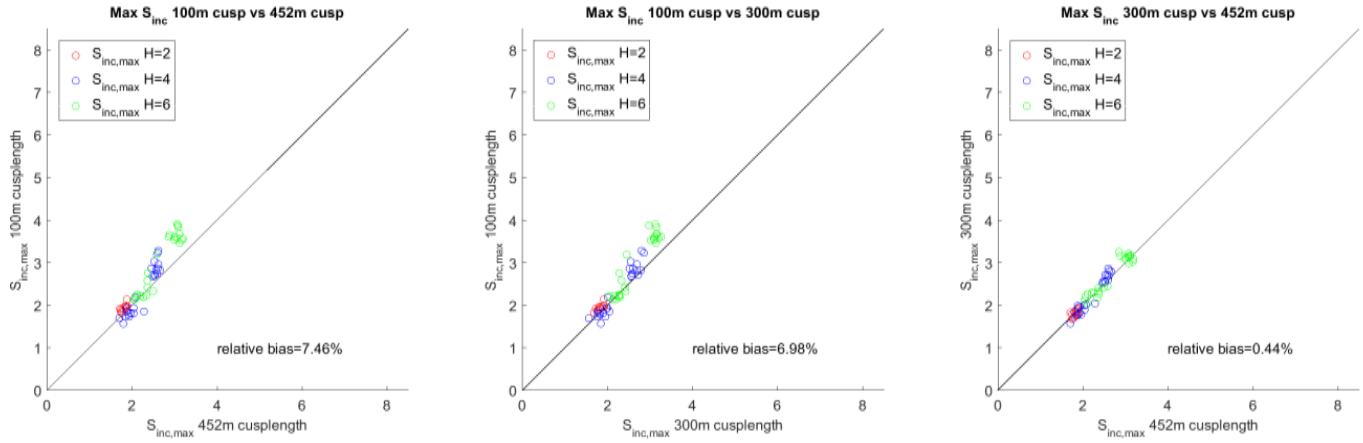

Figure 5-13: alongshore maximum incident band swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 452m cusp vs 300m cusp, right: 300m cusp vs 100m cusp. The black line represents the 1:1 line

The maximum values are in the order of 1.5 to 4 metres. The range is in the same order compared with setup and smaller compared with infragravity band swash. It can be seen that there is no large difference between the maximum values of incident band swash for a cusp length of 452 metres and 100 metres. A cusp of 100 metres gives slightly larger maximum values. This is also represented by the relative bias of 7.46%. The difference increases if larger wave heights are considered. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is 6.98%. The same pattern can be seen for the alongshore mean values as described in section 5.1.1.3. The comparison between the 452 metres and 300 metres cusp gives similar maximum values for incident band swash. In this case the relative bias is 0.44%.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres results in the largest maximum values of incident band swash. Two groups can be seen for a wave height of 6 and 4 metres. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.2.1.4 Total swash

In Figure 5-14 the results are shown of the alongshore maximum values of total swash for the different cusp lengths.

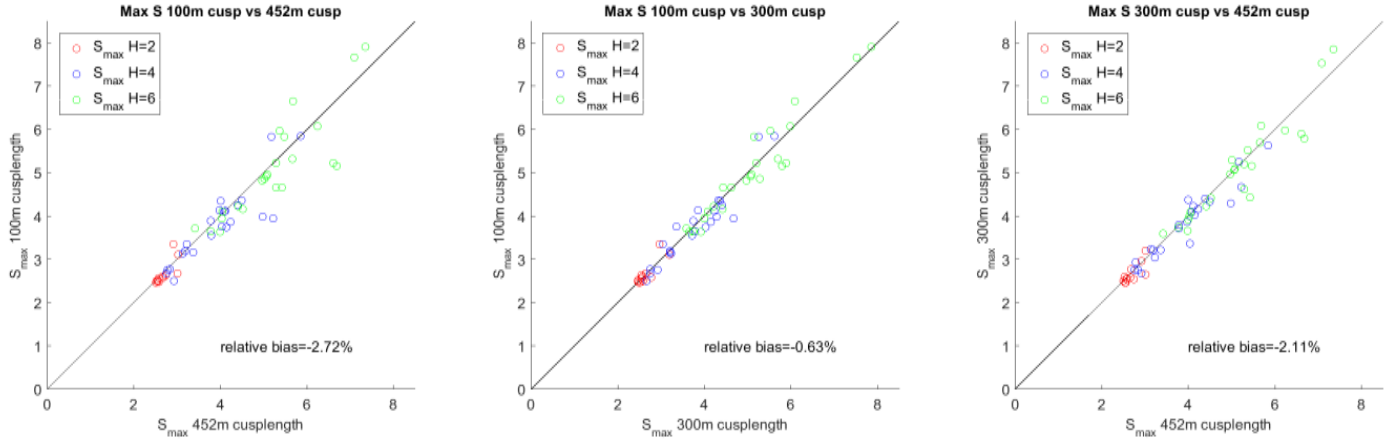

Figure 5-14: alongshore maximum total swash compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 452m cusp vs 300m cusp, right: 300m cusp vs 100m cusp. The black line represents the 1:1 line

The maximum values are in the order of 2.5 to 8 metres. It can be seen that the maximum values are larger compared to setup. Furthermore the results show larger maximum values for a cusp length of 452 metres compared with a cusp length of 100 metres. This is represented by the relative bias of -2.72%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is -0.63%, indicating that the values are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar maximum values for total swash, with slightly larger maximum values for a cusp length of 452 metres. In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres results in the largest mean values of total swash.

5.2.1.5 R2%

In Figure 5-15 the results are shown of the alongshore maximum values of R2% for the different cusp lengths.

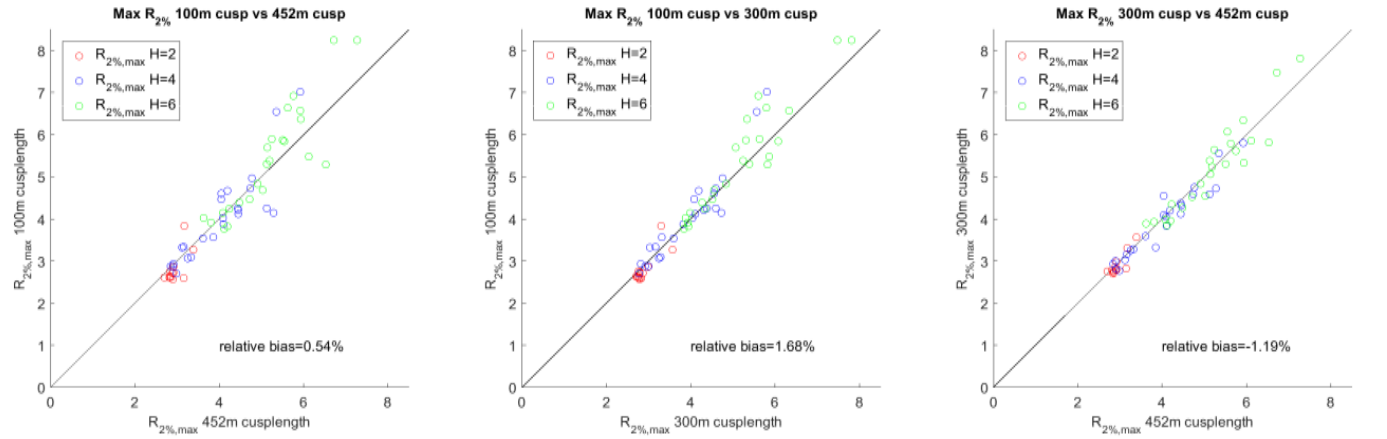

Figure 5-15: alongshore maximum R2% compared for cusp lengths. Left: 452m cusp vs 100m cusp, centre: 452m cusp vs 300m cusp, right: 300m cusp vs 100m cusp. The black line represents the 1:1 line

The maximum values are in the order of 2.5 to 8 metres. It can be seen that there is no large difference between the maximum values of $R_{2\%}$ for a cusp length of 452 metres and 100 metres, a cusp of 452 metres gives slightly smaller maximum values. This is also represented by the relative bias of 0.54%. The same is observed when a cusp length of 300 metres is compared with a cusp length of 100 metres. In this case the relative bias is 1.68%. The values from the comparison of the 452 metres cusp and the 100 metres cusp are more closely located to the reference 1:1 line in the scatterplot, shown by the black line. The comparison between the 452 metres and 300 metres cusp gives similar maximum values for $R_{2\%}$.

In the scatter plots a difference is made between a wave height of 2, 4 and 6 metres. A wave height of 6 metres results in the largest maximum values of $R_{2\%}$. Two groups can be seen for a wave height of 6 and 4 metres. Waves with a steepness of 1% gives larger values compared with waves with a steepness of 3%.

5.2.1.6 Conclusion maximum values run-up and components, compared with cusp lengths

$R_{2\%}$ is composed of setup and infragravity band swash and incident band swash. In this case infragravity band swash is one of the largest components. Setup and incident band swash are both in the order of 1 to 4 metres and infragravity band swash is in the order of 2 to 8 metres. The maximum values for total run-up does not show large differences between the different cusp lengths. A 452 metres cusp show somewhat smaller maximum values compared to a cusp length of 100 metres and a cusp length of 300 metres shows similar results compared to a cusp length of 452 metres.

5.2.2 Alongshore maximum of run-up and components for beach cusps and uniform bathymetry

In this section a comparison is made of the alongshore maximum values of setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$ between the different cusp lengths and the uniform bathymetry. The uniform bathymetry is represented in the scatter plots as a cusp with infinite length.

5.2.2.1 Setup

In Figure 5-16 the results are shown of the alongshore maximum values of setup for the different cusp lengths and uniform bathymetry.

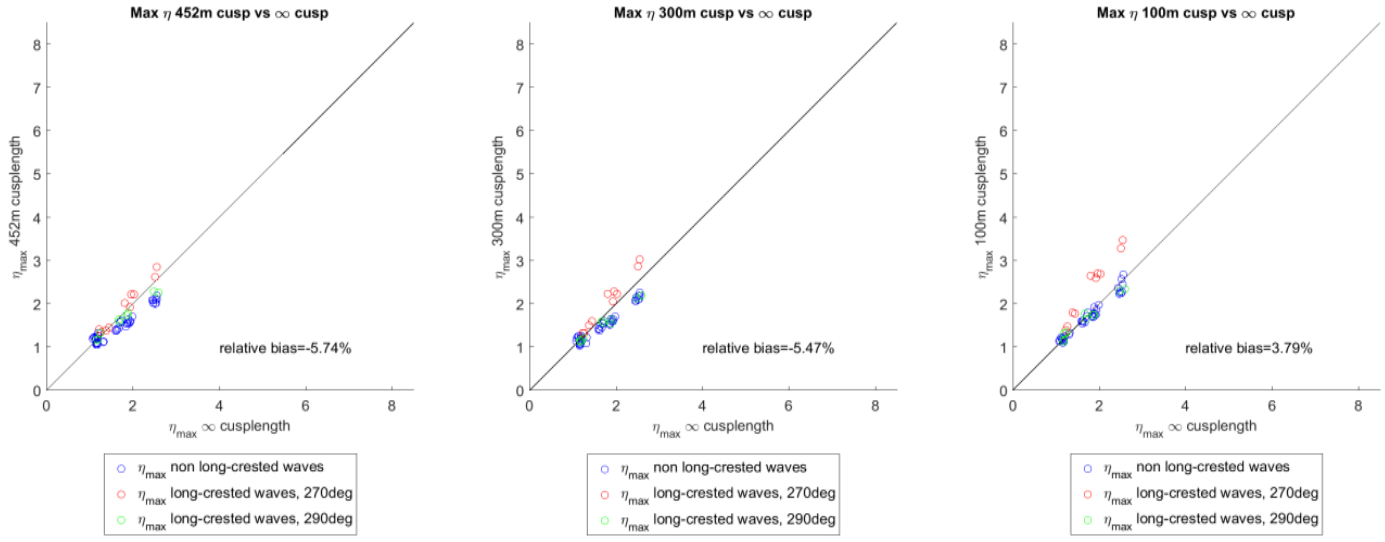

Figure 5-16: alongshore maximum setup for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line

In Figure 5-16 it can be seen that the maximum values for cusp lengths of 452 and 300 metres are smaller compared to the alongshore maximum values of setup from the uniform bathymetry. This is also observed in the magnitude of the relative bias. The relative bias is -5.74% and -5.47% for a cusp length of 452 and 300 metres respectively. This does not hold for long-crested waves with an angle of incidence of 270 degrees. These waves contain larger maximum values for all beach cusps. For a cusp length of 100 metres all waves condition give equal maximum values for the uniform bathymetry and the beach cusps, except for the long-crested waves with an angle of 270 degrees.

There are differences in behaviour between the alongshore maximum values and the mean values. Long-crested waves with an angle of incidence of 270 degrees give larger alongshore maximum values for the cusps. When mean values are considered it gives equal values for the uniform bathymetry and the beach cusps as described in section 5.1.2.1. Other wave conditions give larger values for the uniform bathymetry, this holds for all cusp lengths when mean values are considered. Furthermore this is valid for a cusp length of 452 and 300 metres when maximum values are considered.

5.2.2.2 *Infragravity band swash*

In Figure 5-17 the results are shown of the alongshore maximum values of infragravity band swash for the different cusp lengths and uniform bathymetry.

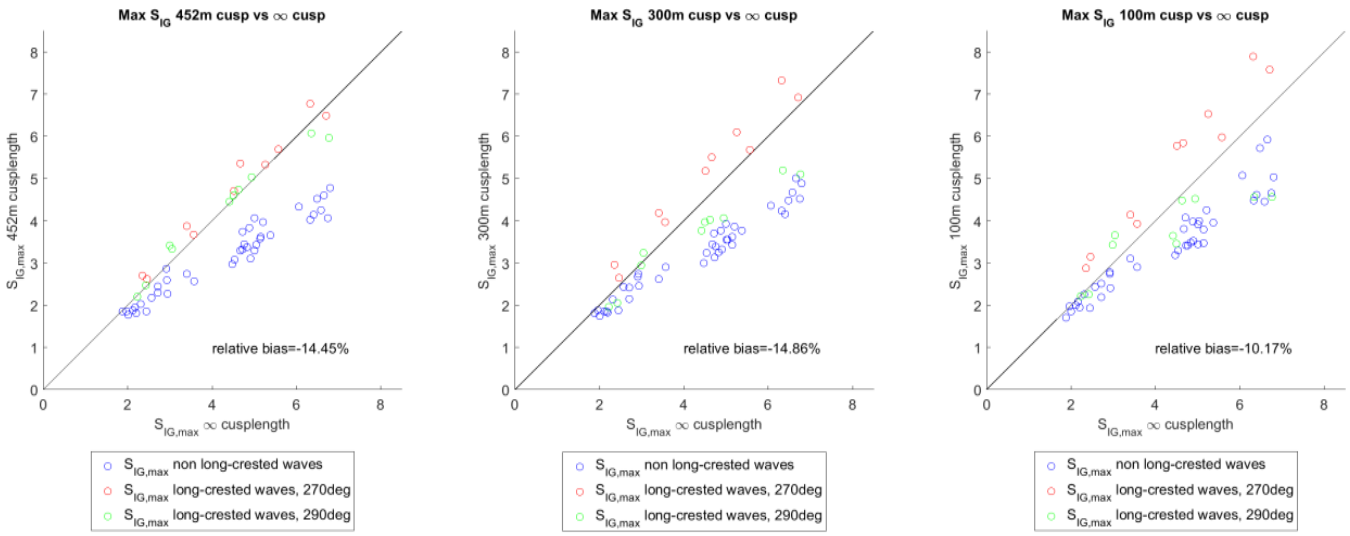

Figure 5-17: alongshore maximum infragravity band swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

In Figure 5-17 it can be seen that the maximum values for infragravity band swash are higher for the uniform bathymetry. It can be observed that long-crested waves contain almost the same maximum values for infragravity band swash in the case of the uniform bathymetry and a beach cusp of 452 metres. However, this is not the case for a cusp length of 300 and 100 metres when long-crested waves are considered with an angle of incidence of 270 and 290 degrees. Long-crested waves with an angle of incidence of 270 degrees give larger alongshore maximum values for the beach cusps instead of the uniform bathymetry.

Furthermore it can be seen that the higher the wave height, the larger the difference is in the maximum value for infragravity band swash between the uniform bathymetry and the cusp lengths. For a wave height of 2 metres the values are lying close to the reference line (black 1:1 line). However, for a wave height of 6 metres the values are more located in the upper left corner of the scatterplot. Thus, a wave height of 6 metres contains a larger difference between maximum values for infragravity band swash for the uniform bathymetry and beach cusp compared with a wave height of 2 metres. In this case the long-crested waves with an angle of incidence of 290 degrees for a cusp length of 300 and 100 metres are an exception.

The behaviour is the same compared to the mean values, as described in section 5.1.2.2. However, the long-crested waves with an angle of 270 degrees results in same values for a uniform bathymetry and all beach cusps considering the mean values. This is not the case when maximum values are considered for a cusp length of 300 and 100 metres.

5.2.2.3 *Incident band swash*

In Figure 5-18 the results are shown of the alongshore maximum values of incident band swash for the different cusp lengths and uniform bathymetry.

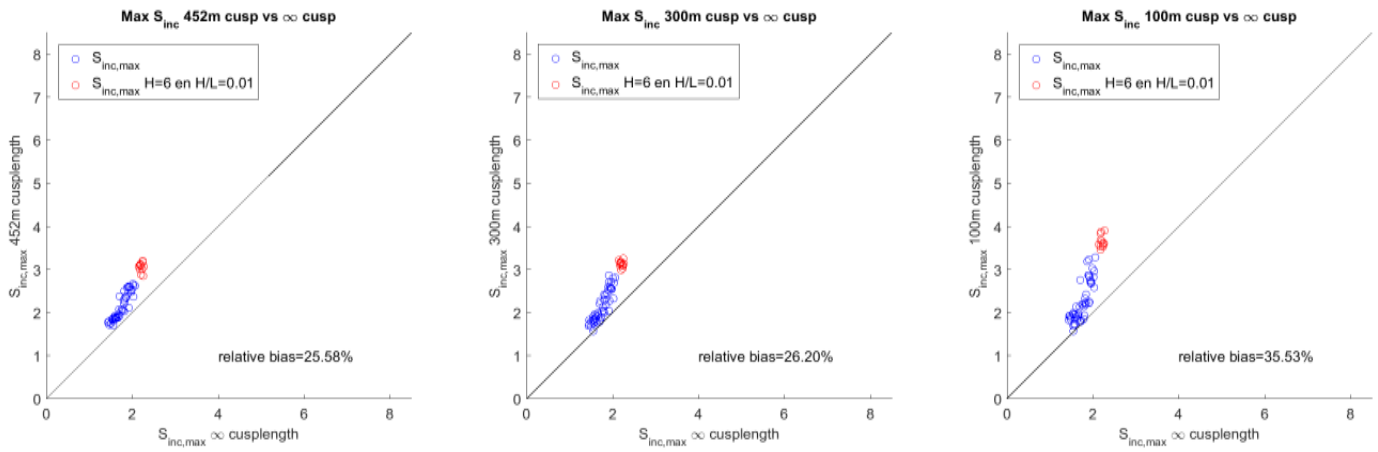

Figure 5-18: alongshore maximum incident band swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

In this scatterplot it can be seen that the alongshore maximum values of all cusp lengths, 452, 300 and 100 metres are larger compared with the alongshore mean values of incident band swash from the uniform bathymetry. This holds especially for the comparison between a cusp length of 100 metres and the uniform bathymetry. The relative bias is in this case 35.53%. Incident band swash for waves with a wave height of 6 metres and a steepness of 1% gives larger values as indicated in the scatterplot.

The behaviour is different when mean values are considered. Mean values give almost equal results for the uniform bathymetry and the beach cusps, as described in section 5.1.2.3. Alongshore maximum values of incident band swash is higher for a cusp system because an alongshore trend is visible along a cusp. In this trend a large difference is seen between a horn and embayment, this is described in section 5.3.3. When a mean value is taken along a cusp, this mean value is close to the value of incident band swash given at the mean slope between a horn and embayment. This slope is equal to the mean slope of the uniform bathymetry. This clarifies the similar values for the alongshore averaged incident band swash and the difference between the alongshore maximum values between a cusp system and a uniform bathymetry.

5.2.2.4 Total swash

In Figure 5-19 the results are shown of the alongshore maximum values of total swash for the different cusp lengths and uniform bathymetry.

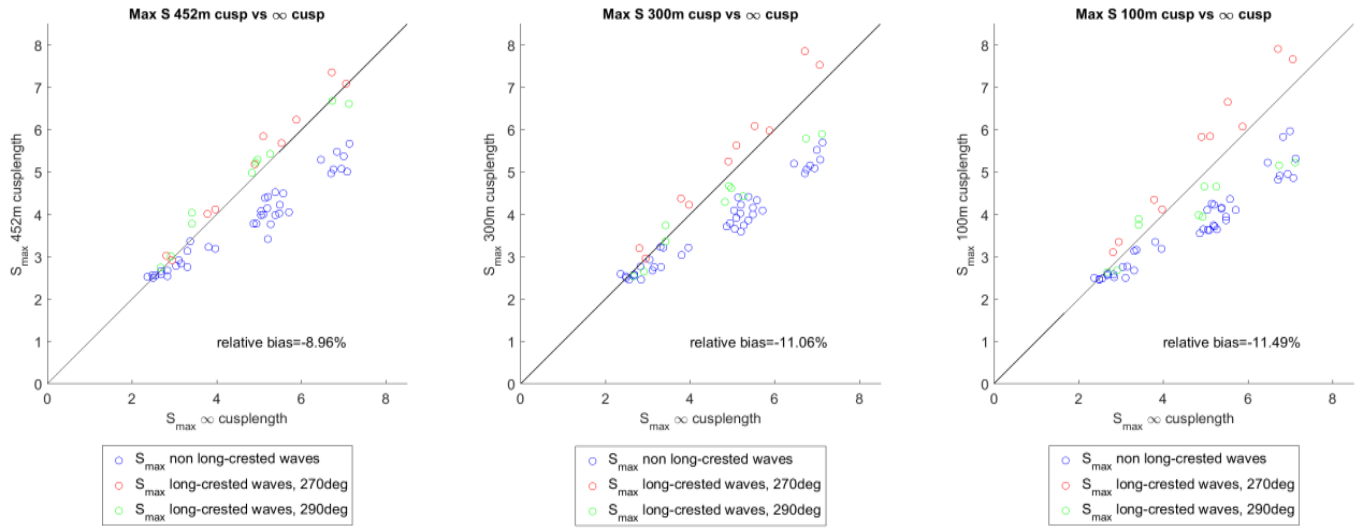

Figure 5-19: alongshore maximum total swash for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

If total swash is considered it can be seen that the same conclusion can be drawn compared with infragravity band swash. The long-crested waves contain almost the same maximum values for total swash in the case of the uniform bathymetry and a cusp length of 452 metres. This holds not for the long-crested waves with an angle of incidence of 290 degrees together with a cusp length of 300 and 100 metres. All other wave conditions contain larger maximum values for the uniform bathymetry compared to the beach cusps.

The behaviour compared with the mean values as described in section 5.1.2.4 is almost the same. However, the long-crested waves with an angle of 270 degrees results in the same values for a uniform bathymetry and all beach cusps considering the mean values. This is not the case when maximum values are considered for a cusp length of 300 and 100 metres.

5.2.2.5 R2%

In Figure 5-20 the results are shown of the alongshore maximum values of R2% for the different cusp lengths and uniform bathymetry.

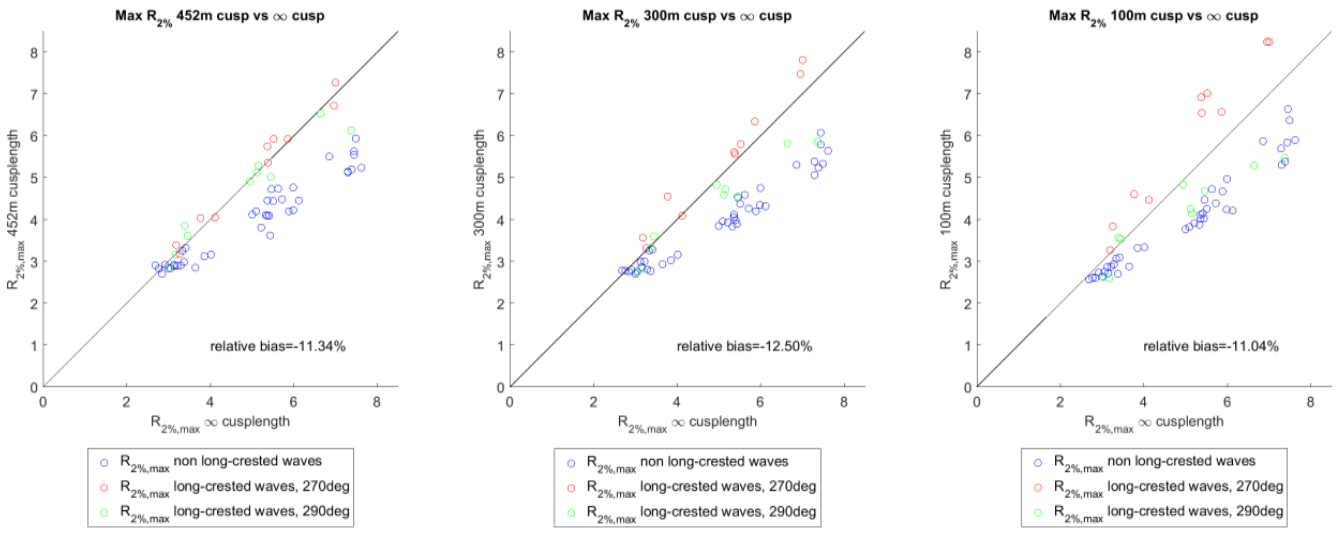

Figure 5-20: alongshore maximum R2% for different cusp lengths compared with the uniform bathymetry. Left: 452m cusp vs uniform bathymetry, centre: 300m cusp vs uniform bathymetry, right: 100m cusp vs uniform bathymetry. The black line represents the 1:1 line.

When R2% is considered it can be seen that the maximum values contain larger values in the case of the uniform bathymetry compared to the different cusp lengths. However, this is not the case for long-crested waves with an angle of incidence of 270 degrees. A wave height of 2 metres contains maximum values similar for the uniform bathymetry and beach cusps. If the wave height increases a larger difference can be seen. The uniform bathymetry contains in this case a larger alongshore maximum value. Long-crested waves, with an angle of incidence of 270 degrees, contain alongshore maximum values which are smaller for the uniform bathymetry and larger for the beach cusps in the case of a cusp length of 300 and 100 metres. For a cusp length of 452 metres similar results are found between the uniform bathymetry and the cusp system when long-crested waves are considered.

The behaviour is similar compared with the mean values as described in section 5.1.2.5. A difference is observed, long-crested waves give larger maximum values for beach cusps.

5.2.2.6 Conclusion maximum values run-up and components, compared with uniform bathymetry

Infragravity band swash is one of the largest components of the total run-up. Infragravity band swash contains alongshore maximum values which are larger for the uniform bathymetry. When long-crested waves are not taken into account, this holds also for setup. However, the difference between the uniform bathymetry and the cusps for infragravity band swash is larger compared with setup. This can be seen in the relative bias. Infragravity band swash contains a larger relative bias compared with setup. Incident band swash shows larger values for beach cusps compared with the uniform bathymetry. For total run-up the same behaviour is seen as concluded for infragravity band swash, due to this dominant component. Thus, long-crested waves results in similar values for run-up when the uniform bathymetry and cusp system is compared. Non long-crested waves give larger alongshore maximum values for run-up on a uniform bathymetry.

5.3 Alongshore variation in run-up and components cusp system

This section considers the results of $R_{2\%}$, setup and swash components along the central cusp for different cusp lengths and different wave conditions.

Three cusps are modelled, 452, 300 and 100 metres. In total 60 wave conditions are modelled in XBeach on each of these cusp lengths. Every four metres a calculation is made of $R_{2\%}$, setup and the swash components. Scatterplots are made to compare the different wave conditions and the different cusp lengths. The plots include the values of $R_{2\%}$, setup and swash components against the alongshore varying slope in a cusp. The scatterplot is not readable anymore if all data points of the 60 wave conditions are present in this plot. Thus, trend lines are plotted in scatterplots for each wave height and steepness. So a trend line for a wave height of 2 metres and a steepness of 1%, for a wave height of 4 metres and a steepness of 1%, for 4 metres and a steepness of 3% and so on. The data points are based on the central cusp. The left and right cusps are not taken into account due to the influence of boundary conditions. In the scatterplots the location of the horn and embayment is shown with a text label. A slope of tan(β)=0.079 represents an embayment and a slope of tan(β)=0.109 represents a horn. For each component a scatterplot is shown for a cusp of 100 metres together with data points and a trend line. Another scatterplot is presented in which the trend lines of the 100 and 452 metres cusp are compared for certain wave conditions.

5.3.1 Setup

In this section setup is represented in scatterplots with trend lines.

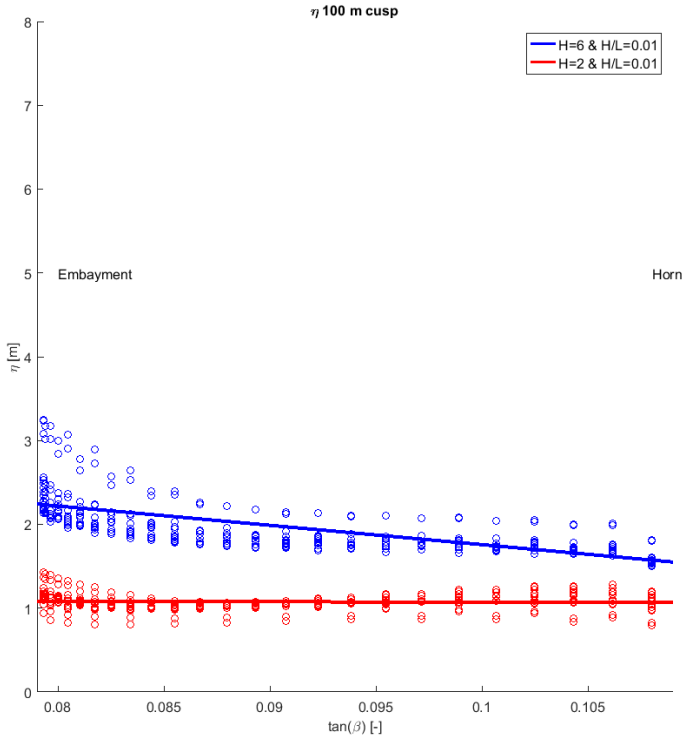

Figure 5-21: trend line for setup along beach slope, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

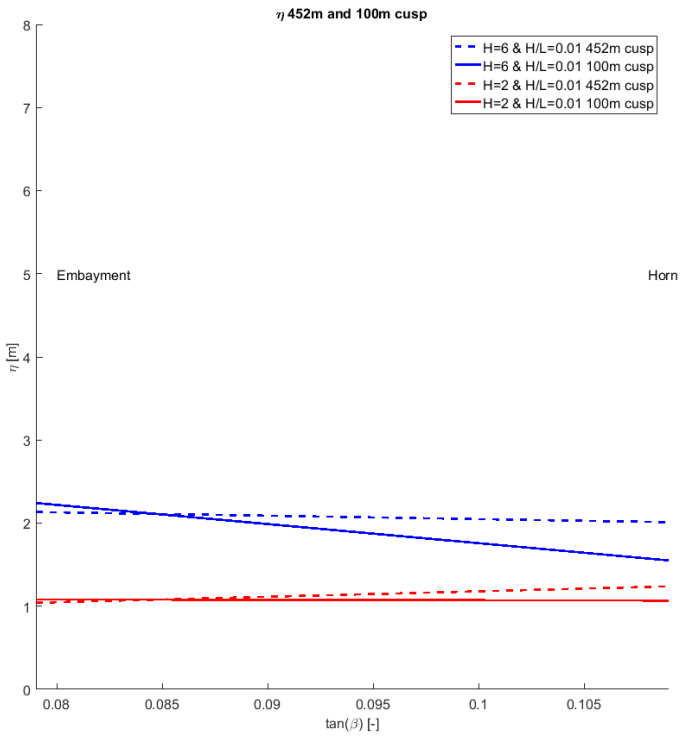

Figure 5-22: trend line for setup along beach slope, solid lines 452 m cusp, dashed lines 100 m cusp, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

In Figure 5-21 a scatterplot is shown for the 100 metres cusp. For a wave height of 6 metres and a steepness of 1% it can be seen that setup is decreasing when the slope increases. Thus, in an embayment setup is larger compared to the horn. A wave height of 6 metres with a steepness of 3%

and a wave height of 4 metres and a steepness of 1% and 3% gives similar results considering the trend lines. However, the magnitude is different compared with the results shown in this figure, which is also concluded in section 5.1.1.1 and 5.2.1.1 where scatterplots were shown of the alongshore maximum and alongshore averaged values for setup. Waves with a steepness of 3% gives in general smaller results compared to waves with a steepness of 1%. Furthermore for a wave height of 4 metres the trend line is less steep.

A wave height of 2 metres and a steepness of 1% give other results compared with a wave height of 6 metres and a steepness of 1%. In this case a slight decrease can be seen for setup when the slope is increasing. However, there are almost no differences between a horn and embayment. Thus, in an embayment setup is comparable to setup in a horn.

In the same figure it can be observed that a group of data points is present around the trend line, above this group a second group is present. This holds especially for a wave height of 6 metres (blue data points). These are the long-crested waves, which does not contain a directional spreading and contains an angle of incidence of 270 degrees.

In Figure 5-22 a comparison is made for a cusp of 100 metres and a cusp of 452 metres. In this case it can be seen that a wave height of 2 metres shows a positive slope considering the pattern of the trend line. Thus, setup is larger at the horn for a 452 metres cusp compared with a 100 metres cusp.

A different behaviour is found for a wave height of 6 metres together with a steepness of 1%. When a cusp length of 452 metres is considered a more or less straight line can be found for the trend line. Thus, an increasing slope does not give significantly smaller setup.

For the 452 metres cusp it also holds that the trend lines gives similar results when a wave height of 6 metres is considered together with a steepness of 3% and a wave height of 4 metres together with a steepness of 1% and 3%. The magnitude is in this case lower and the trend lines are less steep for a wave height of 4 metres. A cusp length of 300 metres gives similar results as the 452 metres cusp.

5.3.2 Infragravity band swash

In this section infragravity band swash is represented in scatterplots with trend lines.

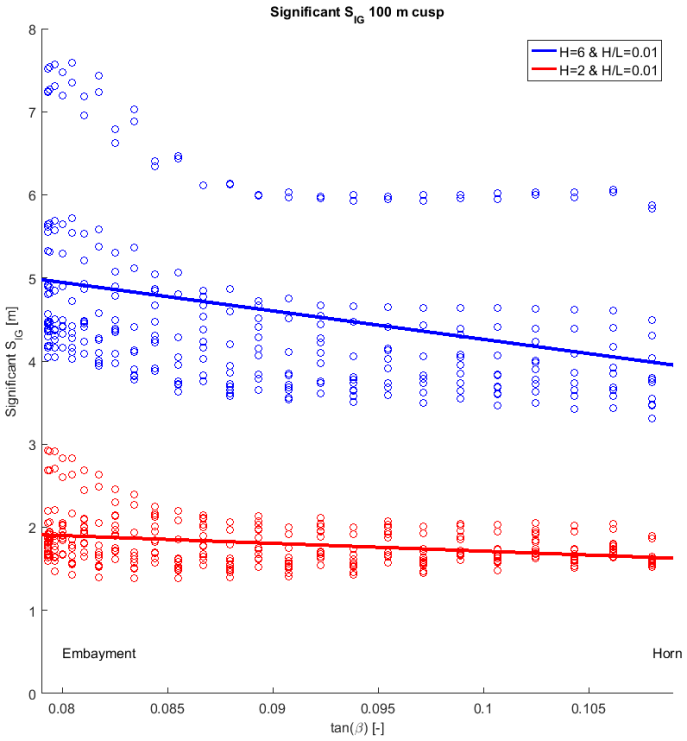

Figure 5-23: trend line for infragravity band swash along beach slope, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

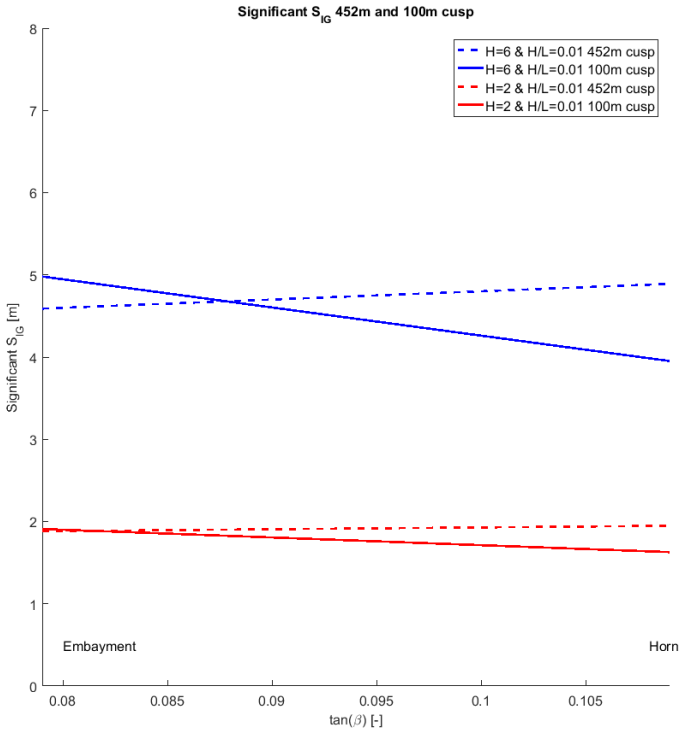

Figure 5-24: trend line for infragravity band swash along beach slope, solid lines 452 m cusp, dashed lines 100 m cusp, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

In Figure 5-23 a scatterplot is shown for the 100 metres cusp. For a wave height of 6 metres and a steepness of 1% it can be seen that infragravity band swash is decreasing when the slope increases. Thus, in an embayment infragravity band swash is larger compared to the horn. A wave height of 6 metres with a steepness of 3% and a wave height of 4 metres and a steepness of 1% and 3% gives similar results considering the trend lines. However, the magnitude is different compared with the results shown in these figures, which is also concluded in section 5.1.1.2 and 5.2.1.2 where scatterplots were shown of the maximum and alongshore averaged values for infragravity band swash. Waves with a steepness of 3% gives in general smaller results compared to waves with a steepness of 1%. Furthermore for a wave height of 4 metres the trend line is less steep.

A wave height of 2 metres and a steepness of 1% give similar results compared with a wave height of 6 metres and a steepness of 1%. However, the trend line is less steep in this case. Thus, in an embayment infragravity band swash is still larger compared to a horn.

Furthermore the data points which lie above the blue grouped data points are clearly present. These are the long-crested waves with an angle of incidence of 270 degrees and no directional spreading.

In Figure 5-24 a comparison is made for a cusp of 100 metres and a cusp of 452 metres. In this case it can be seen that a wave height of 2 metres shows a slightly decreasing trend line for a 100 metres cusp. However, for a 452 metres cusp the trend line is almost a straight line. Thus, infragravity band

swash is lower at the horn compared with an embayment for a 100 metres cusp and for a 452 metres cusp there is no significant difference between the horn and embayment.

A different behaviour is found for a wave height of 6 metres together with a steepness of 1%. When a 452 metres cusp is considered, the trend line contains a positive slope. This indicates a reversed behaviour between a horn and embayment compared with the 100 metres cusp. Infragravity band swash is lower at an embayment compared with a horn for the 452 metres cusp. This is a contradiction compared with the 100 metres cusp.

For the 452 metres cusp it also holds that the trend lines show similar results when a wave height of 6 metres is considered together with a steepness of 3%, though the trend line is less steep in this case and the magnitude is smaller. The same holds for a wave height of 4 metres together with a steepness of 1% and 3%. The magnitude is in this case lower and the trend lines are less steep.

A 300 metres cusp gives similar results for a wave height of 2 and 6 metres with a steepness of 1% compared with the 452 metres cusp. For a wave height of 4 and 6 metres with a steepness of 3% this is not the case. The slope of the trend line is in this case negative whereas it is positive in the case of the 452 metres cusp.

5.3.3 Incident band swash

In this section incident band swash is represented in scatterplots with trend lines.

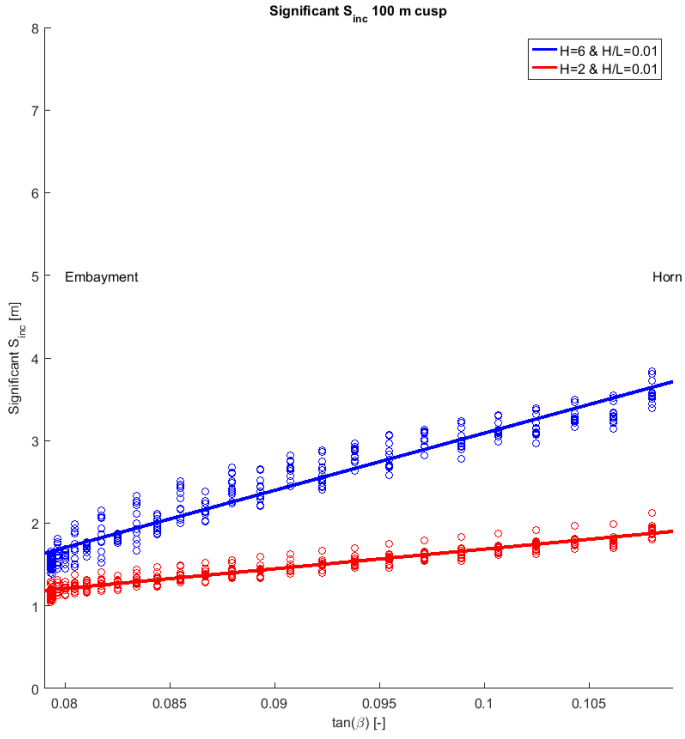

Figure 5-25: trend line for incident band swash along beach slope, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

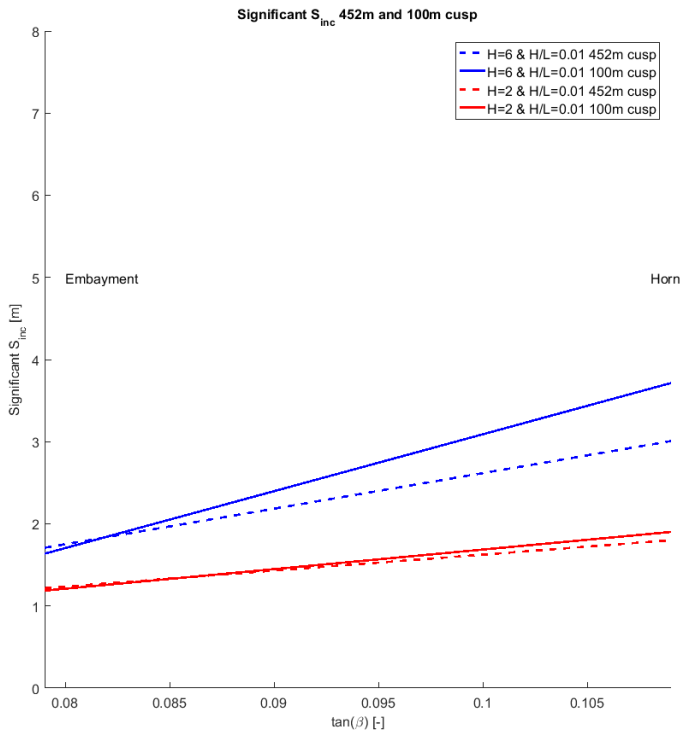

Figure 5-26: trend line for incident band swash along beach slope, solid lines 452 m cusp, dashed lines 100 m cusp, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

In Figure 5-25 a scatterplot is shown for the 100 metres cusp. For a wave height of 6 metres and a steepness of 1% it can be seen that incident band swash is increasing when the slope increases. Thus, in an embayment incident band swash is smaller compared to the horn. A wave height of 6 metres

with a steepness of 3% and a wave height of 4 metres and a steepness of 1% and 3% gives similar results considering the trend lines. However, the magnitude is different compared with the results shown in these figures, furthermore the trend lines are less steep. The difference in magnitude is also concluded in section 5.1.1.3 and 0 where scatterplots were shown of the maximum and alongshore averaged values for incident band swash. Waves with a steepness of 3% contain in general smaller values compared to waves with a steepness of 1%.

A wave height of 2 metres and a steepness of 1% give similar results compared with a wave height of 6 metres and a steepness of 1%. However, the trend line is less steep in this case. Thus, in an embayment incident band swash is also smaller compared to a horn.

In Figure 5-26 a comparison is made for a cusp of 100 metres and a cusp of 452 metres. In this case it can be seen that for both wave heights 6 and 2 metres similar results are found between a cusp length of 452 and 100 metres. However, when a cusp length of 452 metres is considered the trend lines are less steep. Thus, a 100 metres cusp contains larger incident band swash at the horn compared with a 452 metres cusp. For the 452 metres cusp it also holds that the trend lines gives similar results when a wave height of 6 metres is considered together with a steepness of 3% and a wave height of 4 metres together with a steepness of 1% and 3%. The magnitude is in this case lower and the trend lines are less steep for these wave conditions. A 300 metres cusp gives similar results compared with a 452 metres cusp.

5.3.4 Total swash

In this section total swash is represented in scatterplots with trend lines.

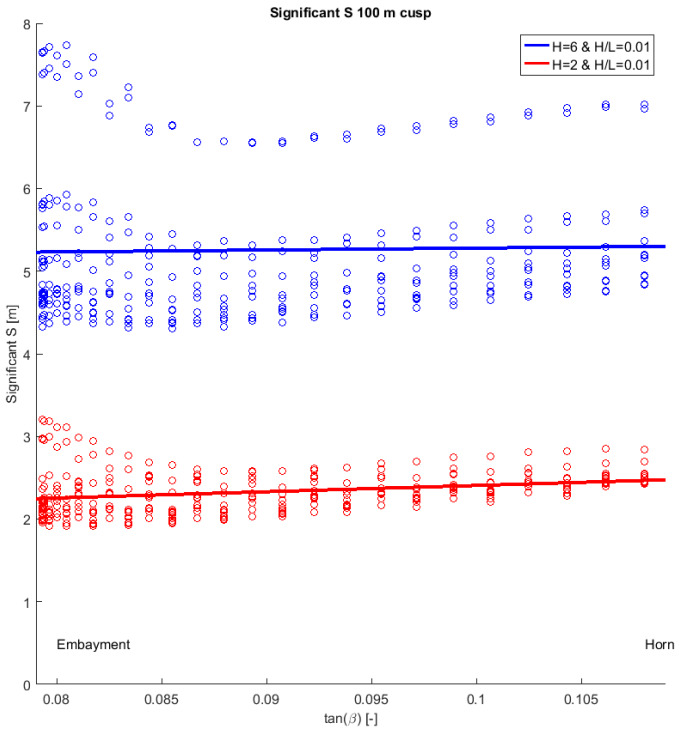

Figure 5-27: trend line for total swash along beach slope, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

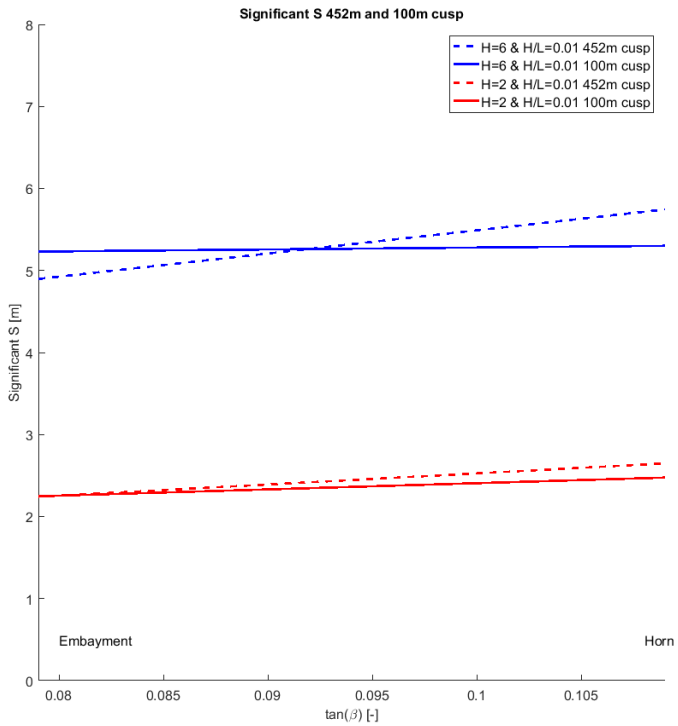

Figure 5-28: trend line for total swash along beach slope, solid lines 452 m cusp, dashed lines 100 m cusp, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

In Figure 5-27 a scatterplot is shown for the 100 metres cusp. For a wave height of 6 metres and a steepness of 1% it can be seen that total swash is slightly increasing when the slope increases, however, the trend line shows more or less a straight line. Thus, in an embayment total swash is smaller compared to the horn. Considering the trend line there are no large differences. A wave height of 4 metres with a steepness of 3% shows similar results compared with a wave height of 6 metres and 1% steepness. However, the magnitude is different compared with the results shown in these figures, which is also concluded in section 5.1.1.4 and 0 where scatterplots were shown of the maximum and alongshore averaged values for total swash. A wave height of 6 and 4 metres with a steepness of 3% shows different results. Those two conditions are shown in Figure 5-29 and are described later on.

A wave height of 2 metres and a steepness of 1% give similar results compared with a wave height of 6 metres and a steepness of 1%. However, the trend line is steeper in this case. Thus, in an embayment total swash is smaller compared to a horn.

Furthermore the data points which lie above the blue grouped data points are clearly present. These are the long-crested waves with an angle of incidence of 270 degrees and no directional spreading.

In Figure 5-28 a comparison is made for a cusp of 100 metres and a cusp of 452 metres. In this case it can be seen that a wave height of 2 metres shows a slightly increasing trend line for a 100 metres cusp. This is similar for a 452 metres cusp which contains a steeper sloped trend line. Thus, total swash is lower at the embayment compared with a horn for a 100 metres cusp and for a 452 metres cusp.

The same pattern can be seen when a wave height of 6 metres is considered together with a steepness of 1%. Thus, the embayment contains a smaller value for total swash compared to a horn. The 100 metres cusp contains a trend line which is almost straight for a wave height of 6 metres.

For the 452 metres cusp it also holds that the trend line gives similar results when a wave height of 6 metres is considered together with a steepness of 3%, though the trend line is less steep in this case and the magnitude is lower. The same holds for a wave height of 4 metres together with a steepness of 1% and 3%. The magnitude is in this case lower and the trend lines are less steep.

A 300 metres cusp gives similar results compared with a cusp length of 452 metres.

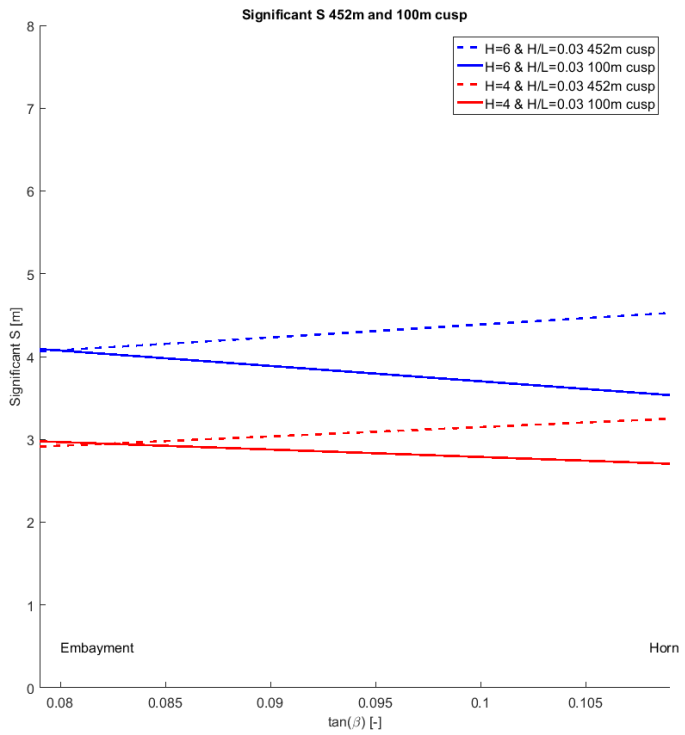

Figure 5-29: trend line for total swash along beach slope, blue lines 452 m cusp, red lines 100 m cusp, short waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

As said earlier waves with a height of 4 and 6 metres combined with a steepness of 3% contains different results when the 452 metres and 100 metres cusps are compared. This can be seen in Figure 5-29. When a cusp of 100 metres is considered and a wave height of 6 metres it results in a trend line with a negative slope. Thus, an embayment contains larger total swash compared with the horn. This behaviour is opposite for a 452 metres cusp. In this case total swash is smaller in an embayment compared with a horn. The same holds for a wave height of 4 metres and a steepness of 3% as shown in Figure 5-29.

5.3.5 $R_{2\%}$

In this section total run-up is represented in scatterplots with trend lines.

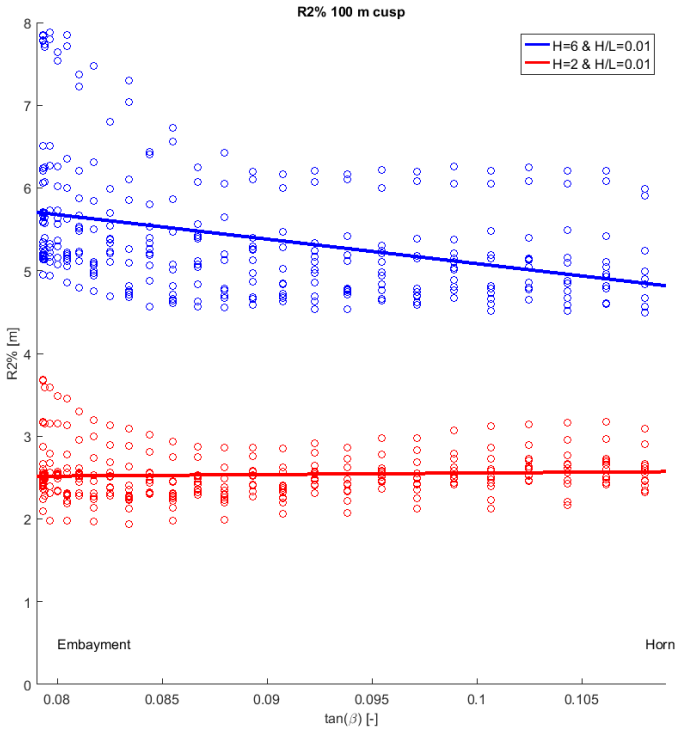

Figure 5-30: trend line for $R_{2\%}$ along beach slope, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

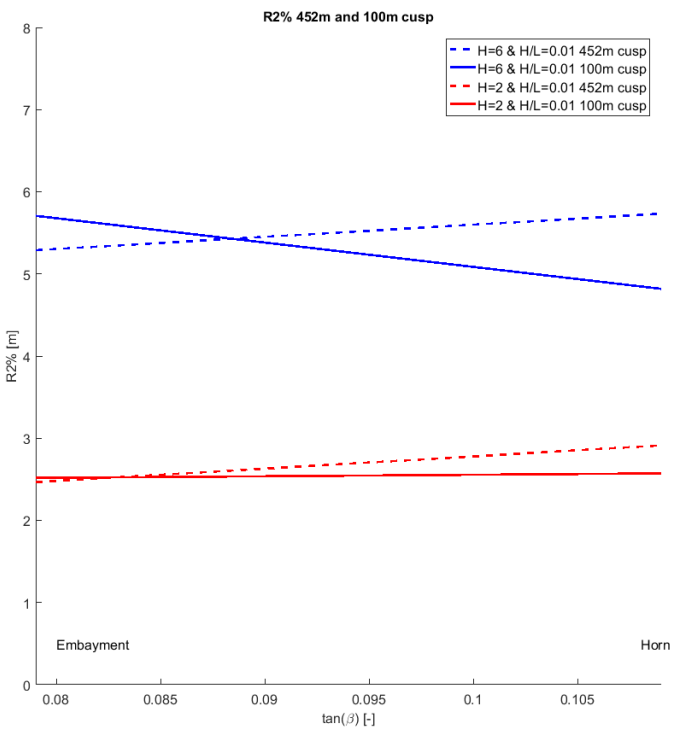

Figure 5-31: trend line for $R_{2\%}$ along beach slope, solid lines 452 m cusp, dashed lines 100 m cusp, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

In Figure 5-30 a scatterplot is shown for the 100 metres cusp. For a wave height of 6 metres and a steepness of 1% it can be seen that $R_{2\%}$ is decreasing when the slope increases. In a horn total run-up is 15.5% smaller compared to an embayment. A wave height of 6 metres with a steepness of 3% and a wave height of 4 metres and a steepness of 1% and 3% gives similar results considering the trend lines. However, the magnitude is different compared with the results shown in these figures, which is also concluded in section 5.1.1.5 and 5.2.1.5 where scatterplots were shown of the maximum and alongshore averaged values for $R_{2\%}$. Waves with a steepness of 3% gives in general smaller results compared to waves with a steepness of 1%. Furthermore for a wave height of 4 metres the trend line is less steep.

A wave height of 2 metres and a steepness of 1% give a different result compared with a wave height of 6 metres and a steepness of 1%. The trend line contains a positive slope, and the slope of the trend line is less steep. Total run-up is 2.23% larger at a horn compared to an embayment.

Furthermore the data points which lie above the blue grouped data points are also for total run-up clearly present. These are the long-crested waves with an angle of incidence of 270 degrees and no directional spreading. It can also be observed for a wave height of 2 metres, plotted with red data points.

In Figure 5-31 a comparison is made for a cusp of 100 metres and a cusp of 452 metres. In this case it can be seen that a wave height of 2 metres shows a slightly increasing trend line for a 100 metres cusp. A cusp of 452 metres does also contain a positive sloped trend line, in which the slope is steeper. Thus, run-up is lower at the embayment compared with a horn for a 452 and 100 metres cusp. For the 452 metres cusp, total run-up is 18.13% larger at a horn compared with an embayment.

A different behaviour is found for a wave height of 6 metres together with a steepness of 1%. When a 452 metres cusp is considered, the trend line contains a positive slope. This indicates a reversed behaviour between a horn and embayment compared with the 100 metres cusp. Total run-up is 8.41% larger at a horn compared with an embayment in the case of a 452 metres cusp. This is a contradiction compared with the 100 metres cusp.

For the 452 metres cusp it also holds that the trend lines gives similar results when a wave height of 6 metres is considered together with a steepness of 3%, though the trend line is less steep in this case and the magnitude is lower. The same holds for a wave height of 4 metres together with a steepness of 1% and 3%. The magnitude is in this case lower and the trend lines are less steep.

A 300 metres cusp gives similar results compared with a cusp length of 452 metres.

5.3.6 Conclusion alongshore trend total run-up and components

When setup is considered, a 300 metres cusp shows similar results compared with a 452 metres cusp. For a 452 metres cusp there is no large difference between the horn and embayment. The trend lines are almost straight lines. This is not the case for a 100 metres cusp. In this case setup is larger in the embayment and smaller at a horn, except for a wave height of 2 metres. In this case setup does not contain differences between a horn and embayment.

Infragravity band swash does not show a clear trend compared with the alongshore varying slope for the 452 metres cusp. The trend lines are slightly increasing. Thus, the infragravity band swash is

smaller in an embayment compared with a horn. This is different compared with a 100 metres cusp. In this case it can be seen that infragravity band swash is decreasing when the slope increases. Thus, the embayment contains larger infragravity band swash compared with the horn. This holds for all wave conditions. A 300 metres cusp gives similar results as the 452 metres cusp. However, waves with a steepness of 3% shows a decreasing trend line. Thus, the embayment contains slightly larger values for infragravity band swash compared with the horn.

The results of incident band swash are the same when a cusp of 300 metres is compared with a cusp of 452 metres. In this case it can be seen that incident band swash increases when the slope increases. Thus, in an embayment incident band swash is smaller compared with a horn. The same holds for a cusp of 100 metres. However, the trend lines are steeper in this case. Thus, incident band swash is larger at a horn of a 100 metres cusp compared with the horn of a 452 metres cusp.

Total swash shows similar results when a cusp of 300 and 452 metres is compared. It can be concluded that all wave conditions contain smaller total swash in the embayment compared with the horn. Different results are found for a 100 metres cusp. Waves with a steepness of 3% contain decreasing trend lines. Thus, total swash is larger at an embayment compared with the horn.

When total run-up is considered a main conclusion can be made that a cusp of 300 metres and a cusp of 452 metres give similar results. A 100 metres cusp shows different behaviour. Total run-up in an embayment is lower compared to a horn for a 452 metres cusp and this is reversed for a 100 metres cusp. Except for the case when a wave height of 2 metres is considered at a 100 metres cusp, in this case total run-up is also lower at an embayment compared with a horn.

For large wave height the horn contains 8.4% larger run-up compared with the embayment in the case of a 452 metres cusp. Whereas the horn contains 15.5% smaller run-up compared with the embayment in the case of a 100 metres cusp.

For small wave heights the horn contains 18.1% larger run-up compared with the embayment in the case of a 452 metres cusp. However, the difference is smaller for a 100 metres cusp, the horn contains 2.22% larger run-up compared with the embayment.

6 Beach cusps and crescentic sandbar

In this section an analysis is made of the results of the beach cusps together with a crescentic sandbar which are modelled with a cusp length of 452 metres. This cusp length is chosen because this is one of the most common cusp lengths at Anmok Beach.

6.1 Alongshore mean of run-up and components

In alongshore direction the mean value of R2%, setup and swash components is calculated for the central cusp. This is done for all wave conditions and for a cusp bar system with a length scale of 452 metres. The mean values for a cusp length of 452 metres with sandbar are compared with the results of a bathymetry containing only a beach cusp of 452 metres. Furthermore the mean values from the cusp bar system are compared with the alongshore mean from the uniform bathymetry. In this section scatterplots are shown to show the results of the comparison between the cusp sandbar system and the system with a beach cusp only.

6.1.1 Alongshore mean of run-up and components for cusp bar system

In this section a comparison is made of the alongshore mean of setup, infragravity band swash, incident band swash, total swash and R2% between the cusp system and the cusp bar system. A comparison is made between a cusp length of 452m and a cusp length of 452 metres including a crescentic sandbar.

6.1.1.1 Setup

In Figure 6-1 the results are shown of the alongshore mean values of setup for the cusp system and cusp bar system.

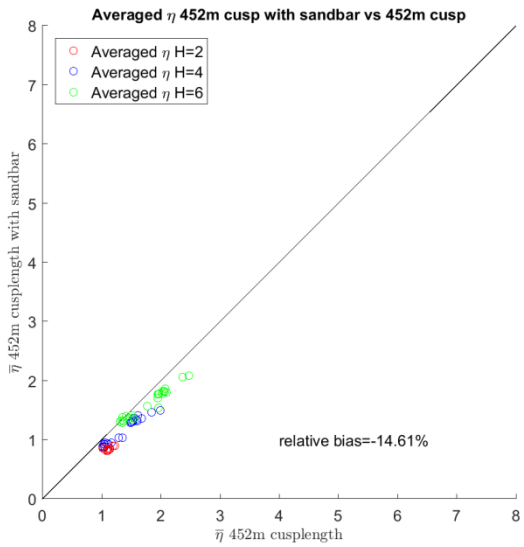

Figure 6-1: alongshore mean of setup compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The alongshore mean values for setup are in the range of 1 to 2.5 metres. It can be seen that the mean values are larger for the system with only a cusp compared to the system in which a cusp and a crescentic sandbar is present. This is also represented by a relative bias of -14.61%.

6.1.1.2 *Infragravity band swash*

In Figure 6-2 the results are shown of the alongshore mean values of infragravity band swash for the cusp system and cusp bar system.

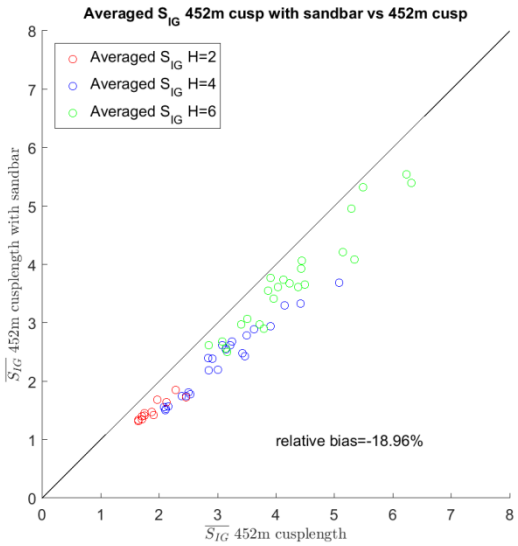

Figure 6-2 alongshore mean of infragravity band swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The alongshore mean values for infragravity band swash are in the range of 1.3 to 6.3 metres. It can be seen that the mean values are larger for the system with only a cusp compared to the system in which a cusp and a crescentic sandbar is present. This is also represented by a relative bias of -18.96%.

6.1.1.3 *Incident band swash*

In Figure 6-3 the results are shown of the alongshore mean values of incident band swash for the cusp system and cusp bar system.

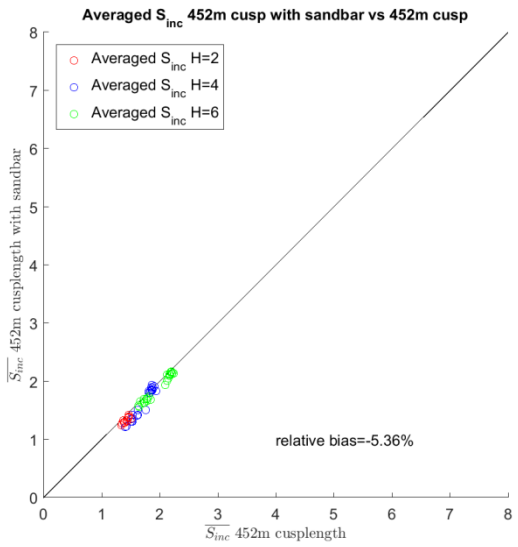

Figure 6-3: alongshore mean of incident band swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The alongshore mean value of incident band swash ranges from 1.2 to 2 metres. It does not show clear differences between a system with and without sandbar. However, the system without sandbar shows slightly larger values for the alongshore averaged mean of incident band swash, the relative bias is -5.36%

6.1.1.4 Total swash

In Figure 6-4 the results are shown of the alongshore mean values of total swash for the cusp system and cusp bar system.

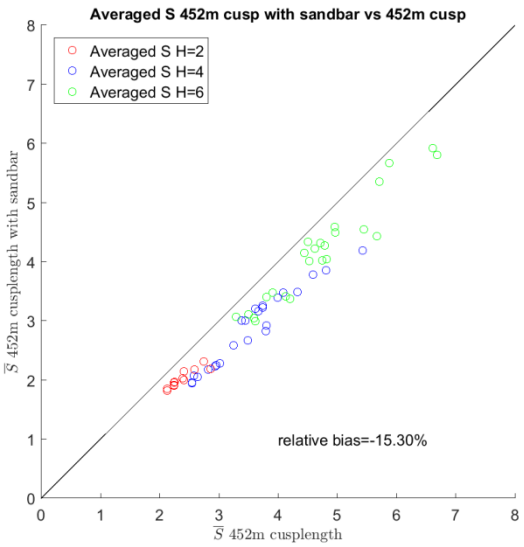

Figure 6-4: alongshore mean of total swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

When total swash is considered it can be seen that the alongshore mean values are larger for a system without a sandbar compared with a system with sandbar. The alongshore mean values are in the range of 1.8 to 6.5 metres. The same pattern is observed compared to infragravity band swash, due to this dominating component.

6.1.1.5 R2%

In Figure 6-5 the results are shown of the alongshore mean values of R2% for the cusp system and cusp bar system.

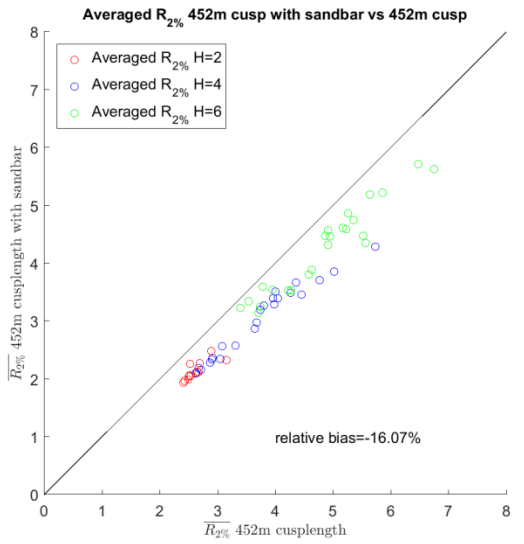

Figure 6-5: alongshore mean of R2% compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

When R2% is considered it can be seen that the alongshore mean values are larger for a system without a sandbar. This is also represented by a relative bias of -16.07%. The alongshore mean values of run-up range from 2 metres to 7 metres.

6.1.1.6 Conclusion mean values run-up and components, cusp bar system

The effect of the sandbar is visible in the results, in such a way that the alongshore mean values for R2% are lower for a system with a sandbar. This effect is also visible for the other components. However, it is less visible for incident band swash. Incident band swash gives alongshore mean values which are close to the 1:1 line, thus similar results for a system with a sandbar compared with a system without a sandbar. In all scatterplots it can be seen that a wave height of 2 metres gives smaller values for R2%, setup and swash compared to a wave height of 6 metres.

6.1.2 Alongshore mean of run-up and components for cusp bar system and uniform bathymetry

In this section a comparison is made of the alongshore mean of setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$ between the cusp bar system, with a length scale of 452 metres, and the uniform bathymetry. For comparison also the 452 metres cusp is added. The uniform bathymetry is represented in the scatter plots as a cusp with infinite length.

6.1.2.1 Setup

In Figure 6-6 the results are shown of the alongshore mean values of setup for the cusp bar system and the uniform bathymetry.

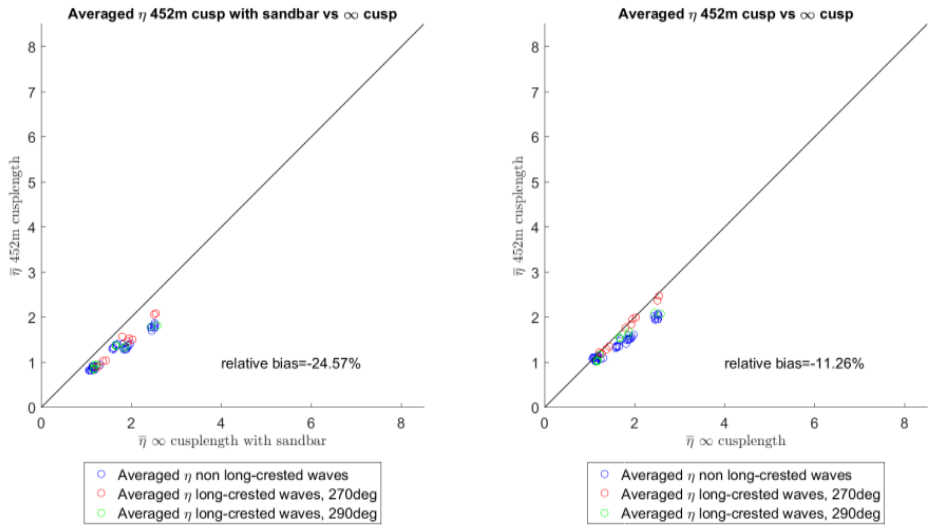

Figure 6-6: alongshore mean setup for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

For setup it can be seen that alongshore mean values are larger for the uniform bathymetry compared to the cusp bar system. The same conclusion was drawn for a cusp system. There is no difference in long-crested waves and non long-crested wave in the case of a cusp bar system. The relative bias is -24.57%, which also indicate that the uniform bathymetry gives larger values for the alongshore averaged setup.

6.1.2.2 *Infragravity band swash*

In Figure 6-7 the results are shown of the alongshore mean values of infragravity band swash for the cusp bar system and the uniform bathymetry.

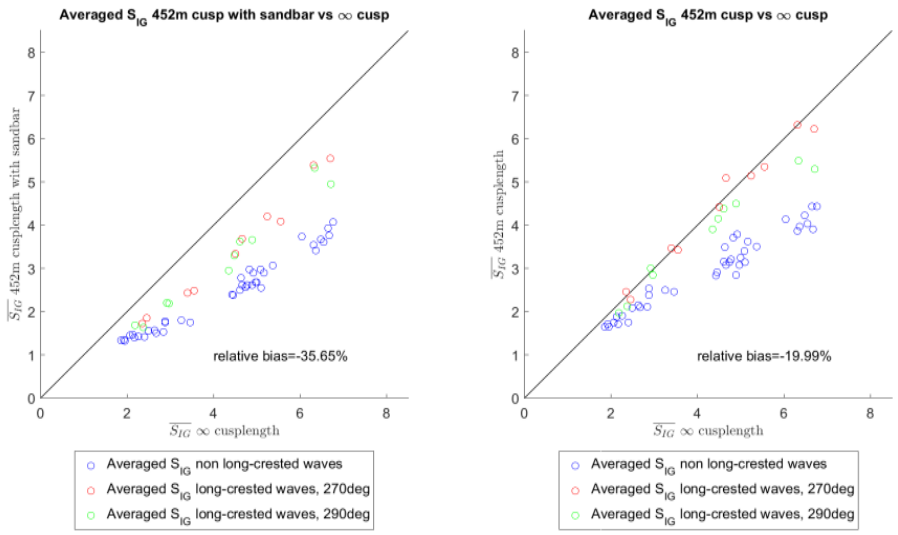

Figure 6-7: alongshore mean infragravity band swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

The alongshore mean for infragravity band swash is smaller for a cusp bar system compared with the uniform bathymetry. This is represented by a relative bias of -35.65%. Thus, the uniform bathymetry gives larger values. There is a difference in long-crested waves and non long-crested waves. The long-crested waves give larger values for the uniform bathymetry. However, the difference between the uniform bathymetry and the cusp bar system is smaller compared with the non long-crested waves. This can be observed by the data points of the non long-crested waves which are located more closely to the 1:1 line. In the case of the cusp system only the long-crested waves resulted in similar outcomes compared with the uniform bathymetry.

6.1.2.3 *Incident band swash*

In Figure 6-8 the results are shown of the alongshore mean values of incident band swash for the cusp bar system and the uniform bathymetry.

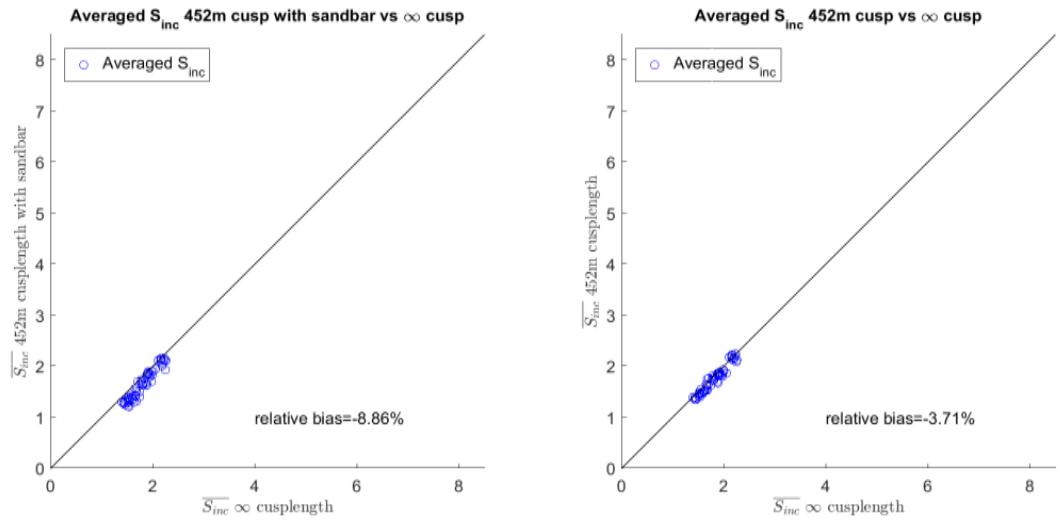

Figure 6-8: alongshore mean incident band swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

Alongshore mean values for incident band swash seems to be larger for the uniform bathymetry compared with a cusp bar system. The relative bias is in this case -8.86%. However, the results are close to the 1:1 line, indicating that the results are almost similar to the cusp bar system. This holds especially when a cusp system without a sandbar is compared with the uniform bathymetry.

6.1.2.4 Total swash

In Figure 6-9 the results are shown of the alongshore mean values of total swash for the cusp bar system and the uniform bathymetry.

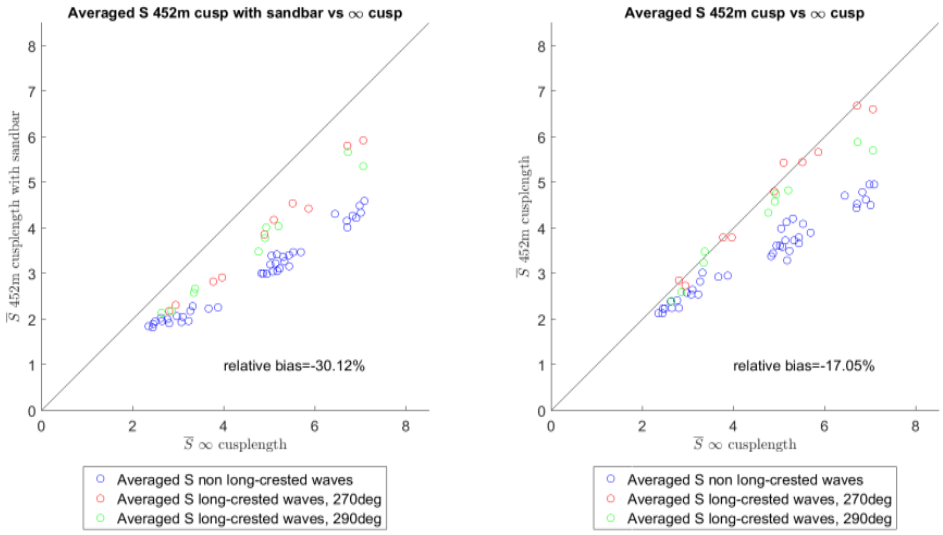

Figure 6-9: alongshore mean total swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

When the mean values for total swash are considered it shows the same pattern as infragravity band swash. Infragravity band swash is the largest components of the total swash. It can be seen that the values are smaller for a cusp bar system compared with the uniform bathymetry. This is also represented by a relative bias of -30.12%. Also the long-crested waves contain smaller alongshore mean values for a cusp bar system compared with the uniform bathymetry.

6.1.2.5 R2%

In Figure 6-10 the results are shown of the alongshore mean values of R2% for the cusp bar system and the uniform bathymetry.

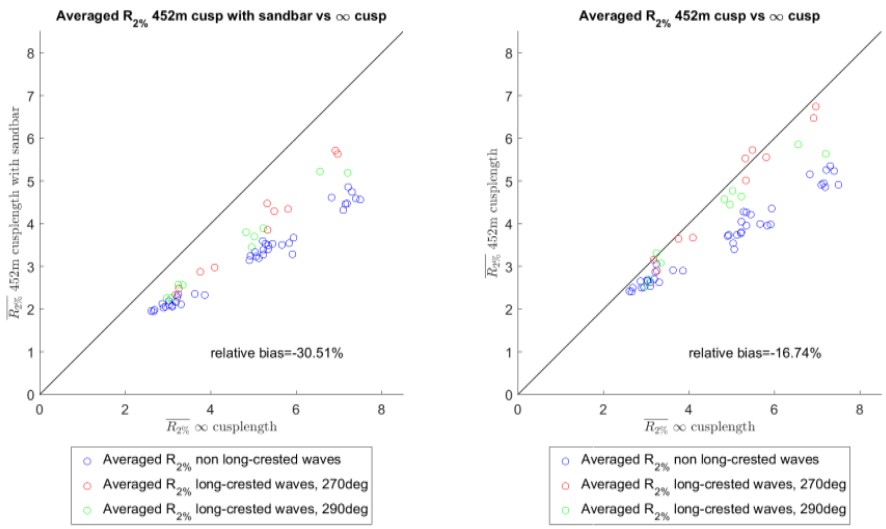

Figure 6-10: alongshore mean R2% for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

For total R2% the alongshore mean values are lower for a cusp bar system. Thus, a uniform bathymetry contains larger total run-up. The relative bias is in this case -30.51%. The long-crested waves does not show a large different pattern compared with the non long-crested waves. When the cusp system only is considered, the long-crested waves, with an angle of incidence of 270 degrees, gives equal values for the alongshore mean value of R2% for the uniform bathymetry.

6.1.2.6 Conclusion mean values run-up and components, cusp bar system compared with uniform bathymetry

The mean values of total run-up are smaller for a cusp bar system. Thus, the uniform bathymetry contains larger values for total run-up. This holds for both long-crested and non long-crested waves. Furthermore, it holds for all the components. However, incident band swash gives almost equal values between the uniform bathymetry and the cusp bar system. The uniform bathymetry gives still slightly larger values.

6.2 Maximum run-up and components

From the central cusp/sandbar the maximum value of R2%, setup and swash components is calculated for all wave conditions and for a cusp/bar length of 452 metres. These maximum values for a cusp bar system are compared with a cusp system only. Furthermore the maximum values of the cusp bar system are compared with the maximum values from the uniform bathymetry. In this section scatterplots are presented to show the results of the comparison between the different cusp lengths and the uniform bathymetry.

6.2.1 Maximum of run-up and components for cusp bar system

In this section a comparison is made of the maximum values of setup, infragravity band swash, incident band swash, total swash and R2% between the cusp system and the cusp bar system. A comparison is made between a cusp length of 452m and a cusp length of 452 metres including a crescentic sandbar.

6.2.1.1 Setup

In Figure 6-11 the results are shown of the alongshore maximum values of setup for a cusp bar system.

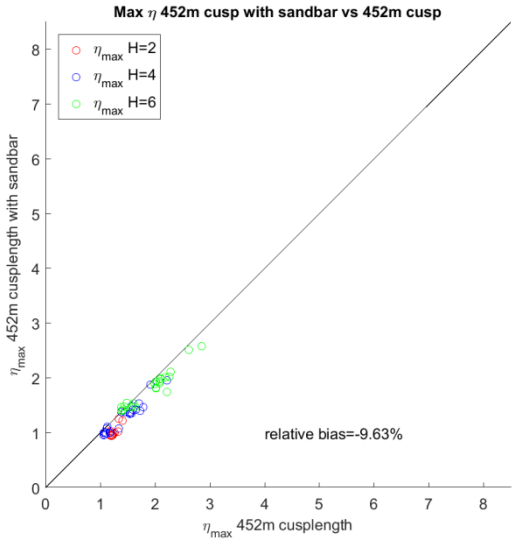

Figure 6-11: alongshore maximum setup compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The maximum values for setup are in the range of 1 to 3 metres. It can be seen that the maximum values are larger for the system with only a cusp compared to the system in which a cusp and a crescentic sandbar is present. This is also represented by a relative bias of -9.63%. Compared with the alongshore mean values the absolute relative bias is smaller. Thus, the difference between the maximum values for a cusp system and a cusp bar system is smaller compared to the difference for the alongshore mean values.

6.2.1.2 *Infragravity band swash*

In Figure 6-12 the results are shown of the alongshore maximum values of infragravity band swash for a cusp bar system.

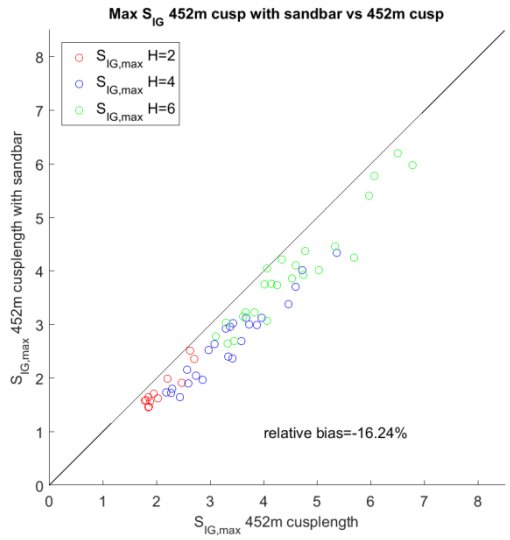

Figure 6-12: alongshore maximum infragravity band swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The maximum values for infragravity band swash are in the range of 1.5 to 7 metres. It can be seen that the maximum values are larger for the system with only a cusp compared to the system in which a cusp and a crescentic sandbar is present. This is also represented by a relative bias of -16.24%. Compared with the alongshore mean values the absolute relative bias is almost the same, however, it is slightly smaller. Thus, the difference between the maximum values for a cusp system and a cusp bar system is smaller compared to the difference for the alongshore mean values, this is not clearly visible in the scatterplots due to a small difference.

6.2.1.3 *Incident band swash*

In Figure 6-13 the results are shown of the alongshore maximum values of incident band swash for a cusp bar system.

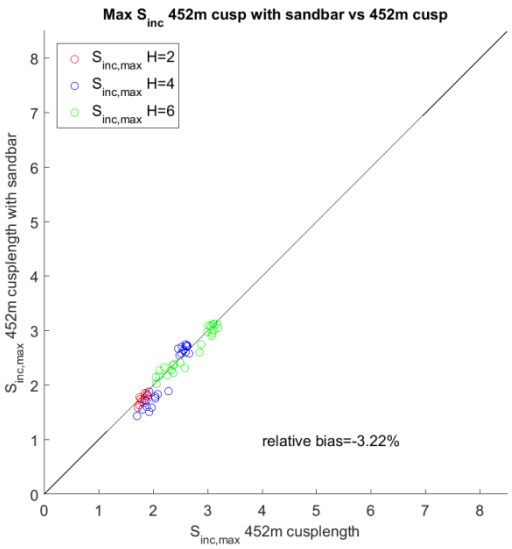

Figure 6-13: maximum incident band swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

The maximum value of incident band swash ranges from 1.5 to 3.2 metres. It does not show clear differences between a system with and without a sandbar. However, the system without sandbar shows slightly larger values for the maximum values of incident band swash. Again the relative bias is in absolute value smaller compared to the alongshore mean values of incident band swash.

6.2.1.4 Total swash

In Figure 6-14 the results are shown of the alongshore maximum values of total swash for a cusp bar system.

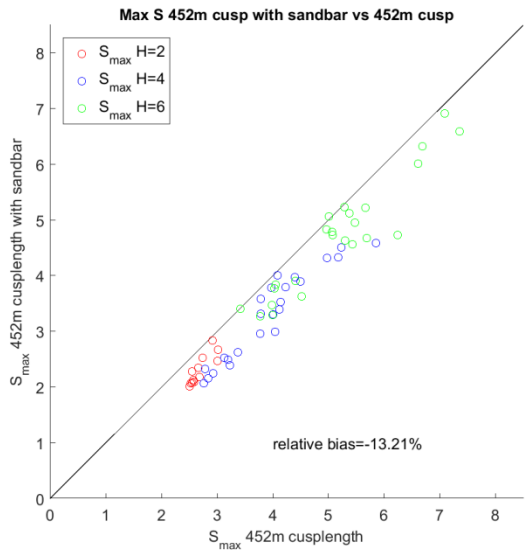

Figure 6-14: alongshore maximum total swash compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

When total swash is considered it can be seen that the maximum values are larger for a system without a sandbar compared with a system with sandbar. The maximum values are in the range of 2 to 7.5 metres. The same pattern is observed compared to infragravity band swash, due to this dominating component. The absolute relative bias, which is 13.21%, is slightly smaller compared with the alongshore mean values.

6.2.1.5 R2%

In Figure 6-15 the results are shown of the alongshore maximum values of R2% for a cusp bar system.

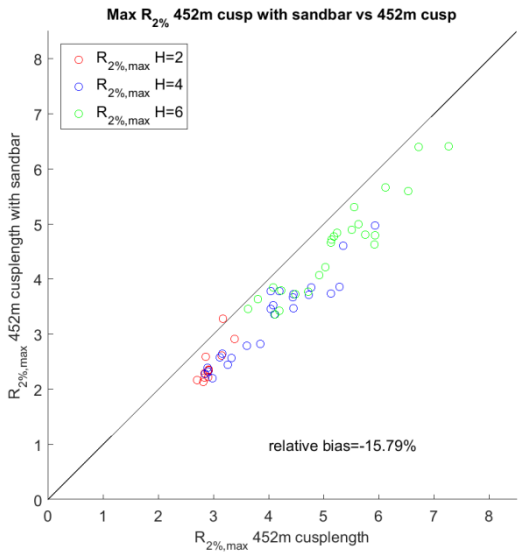

Figure 6-15: alongshore maximum R2% compared for a cusp system and a cusp bar system, with a length scale of 452 metres. The black line represents the 1:1 line.

When R2% is considered it can be seen that the maximum values are larger for a system without a sandbar. This is also represented by a relative bias of -15.79%. The maximum values ranges from 2 metres to 7.2 metres. The relative bias is almost the same compared with the alongshore mean value of R2%.

6.2.1.6 Conclusion maximum values run-up and components, cusp bar system

It is observed that the maximum values are lower for a cusp bar system compared with a cusp system considering total run-up and all the components. However, for incident band swash the results are almost the same for a cusp bar system compared with a cusp system. The dominating part of the total run-up is infragravity band swash. Thus, R2% shows similarities compared with the infragravity band swash. In all scatterplots it can be seen that the maximum values increases if the wave height increases from 2 to 6 metres. This holds for R2%, setup and swash components.

6.2.2 Maximum of run-up and components for cusp bar system and uniform bathymetry

In this section a comparison is made of the maximum values of setup, infragravity band swash, incident band swash, total swash and R2% between the cusp bar system, with a length scale of 452 metres, and the uniform bathymetry. For comparison also the 452 metres cusp is added. The uniform bathymetry is represented in the scatter plots as a cusp with infinite length.

6.2.2.1 Setup

In Figure 6-16 the results are shown of the alongshore maximum values of setup for a cusp bar system and the uniform bathymetry.

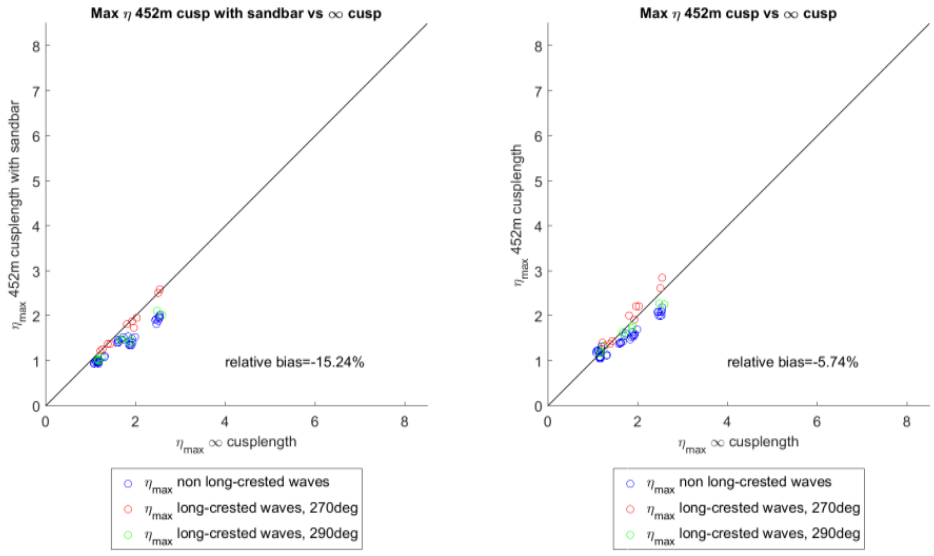

Figure 6-16: alongshore maximum setup for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

For setup it can be seen that maximum values are larger for the uniform bathymetry compared to the cusp bar system. The same conclusion can be made for a cusp system. Equal results are found for the uniform bathymetry and the cusp bar system when long-crested waves, with an angle of incidence of 270 degrees, are considered. The relative bias is -15.24%, which also indicate that the uniform bathymetry gives larger values for the alongshore maximum setup. The difference between long-crested waves and non long-crested waves in the case of maximum values is not seen at the alongshore mean values of setup described in section 6.1.2.1.

6.2.2.2 Infragravity band swash

In Figure 6-17 the results are shown of the alongshore maximum values of infragravity band swash for a cusp bar system and the uniform bathymetry.

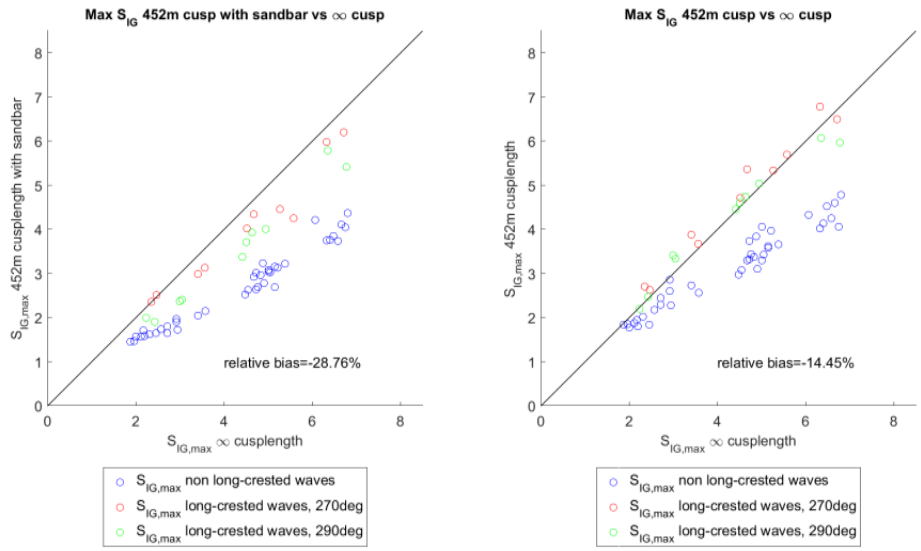

Figure 6-17: alongshore maximum infragravity band swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

The maximum values for infragravity band swash is smaller for a cusp bar system compared with the uniform bathymetry. This is represented by a relative bias of -28.76%. Thus, the uniform bathymetry gives larger values. There is a difference in long-crested waves and non long-crested waves. The long-crested waves give larger alongshore maximum values for the uniform bathymetry. However, the difference between the uniform bathymetry and the cusp bar system is smaller compared with the non long-crested waves. In the case of the cusp system only the long-crested waves gives similar results of the alongshore maxima compared with the uniform bathymetry.

6.2.2.3 Incident band swash

In Figure 6-18 the results are shown of the alongshore maximum values of incident band swash for a cusp bar system and the uniform bathymetry.

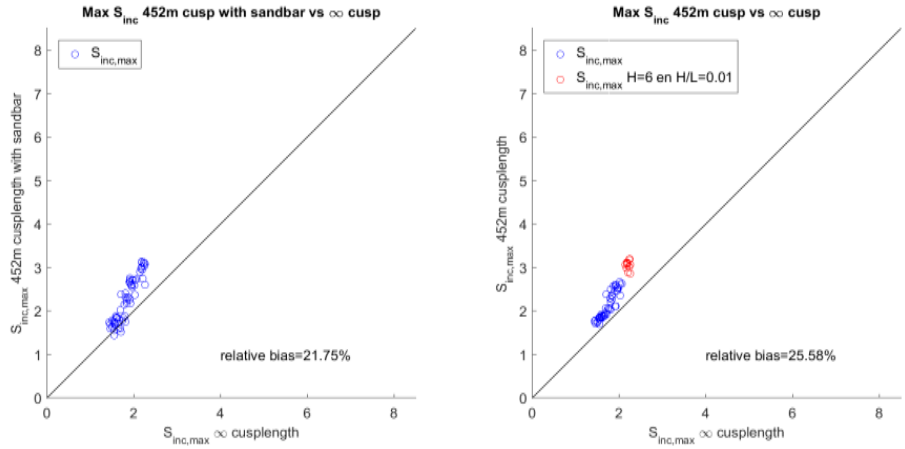

Figure 6-18: alongshore maximum incident band swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

Alongshore maximum values for incident band swash are larger for a cusp bar system compared to the uniform bathymetry. The relative bias is in this case 21.75%. The same can be observed for a system which contains only a beach cusp. These results are in contradiction compared to the alongshore averaged incident band swash. Equal results were found for the alongshore averaged values for a cusp bar system and a uniform bathymetry. This difference is explained in section 5.2.2.3, due to an alongshore trend for incident band swash along a cusp.

6.2.2.4 Total swash

In Figure 6-19 the results are shown of the alongshore maximum values of total swash for a cusp bar system and the uniform bathymetry.

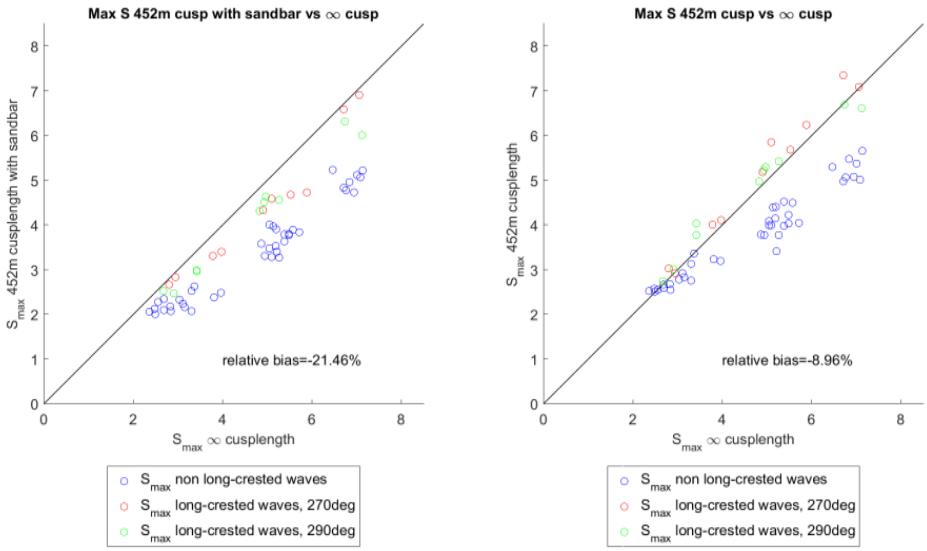

Figure 6-19: alongshore maximum total swash for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

When the maximum values for total swash are considered it shows the same pattern as infragravity band swash. Infragravity band swash is the largest components of the total swash. It can be seen that the alongshore maximum values are smaller for a cusp bar system compared with the uniform bathymetry. This is also represented by a relative bias of -21.46%. Also the long-crested waves contain smaller maximum values for a cusp bar system compared with the uniform bathymetry. This does not hold for a system with a cusp only.

6.2.2.5 R2%

In Figure 6-20 the results are shown of the alongshore maximum values of R2% for a cusp bar system and the uniform bathymetry.

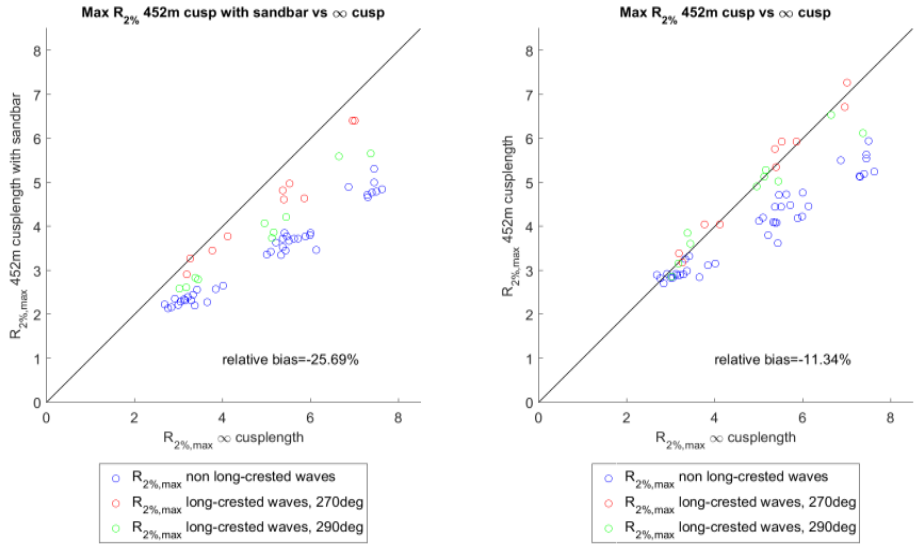

Figure 6-20: alongshore maximum R2% for cusp bar system compared with the uniform bathymetry. Left: 452m cusp with sandbar vs uniform bathymetry, right: 452m cusp vs uniform bathymetry. The black line represents the 1:1 line.

For total R2% the alongshore maximum values are lower for a cusp bar system. Thus, a uniform bathymetry contains larger total run-up. The relative bias is in this case -25.69%. The long-crested waves does not show a large different pattern compared with the non long-crested waves. When the cusp system is considered, the long-crested waves, with an angle of incidence of 270 and 290 degrees, gives equal values for the alongshore mean value of R2% for the uniform bathymetry

6.2.2.6 Conclusion maximum values run-up and components, cusp bar system compared with uniform bathymetry

The maximum values for total run-up are lower for a cusp bar system compared with the uniform bathymetry. This is also observed for the other components, except for incident band swash. Incident band swash shows larger maximum values if a cusp bar system is present compared with a uniform bathymetry. However, this does not result in larger values for total run-up in the case of a cusp bar system. Long-crested waves contains just as non long-crested waves also larger values for the uniform bathymetry compared with the cusp bar system.

6.3 Alongshore variation in run-up and components cusp bar system

This section considers the results of $R_{2\%}$, setup and swash components along a cusp for a cusp bar system compared with a cusp system considering different wave conditions.

One cusp bar system is modelled; this is the 452 metres cusp including a crescentic bar. In total 60 wave conditions are modelled. Every four metres a calculation is made of $R_{2\%}$, setup and the swash components. Scatterplots are made to compare the different wave conditions and the two different systems, a cusp bar system and a cusp only system. The plots include the values of $R_{2\%}$, setup and swash components against the alongshore varying slope in a cusp. The scatterplot is not readable anymore if all data points of the 60 wave conditions are present in this plot. Thus, trend lines are plotted in scatterplots for each wave height and steepness. So a trend line for a wave height of 2 metres and a steepness of 1%, a trend line for a wave height of 4 metres and a steepness of 1% and so on. The data points are based on the central cusp. The left and right cusps are not taken into account due to the influence of boundary conditions. In the scatterplots the location of the horn and embayment is shown with a text label. A slope of tan(β)=0.079 represents an embayment and a slope of tan(β)=0.109 represents a horn. For each component a scatterplot is shown for a cusp of 452 metres with sandbar if differences are observed compared with a cusp system. In the same scatterplot the trend line of the 452 metres cusp is present for comparison.

6.3.1 Setup

In this section setup is represented in scatterplots with trend lines.

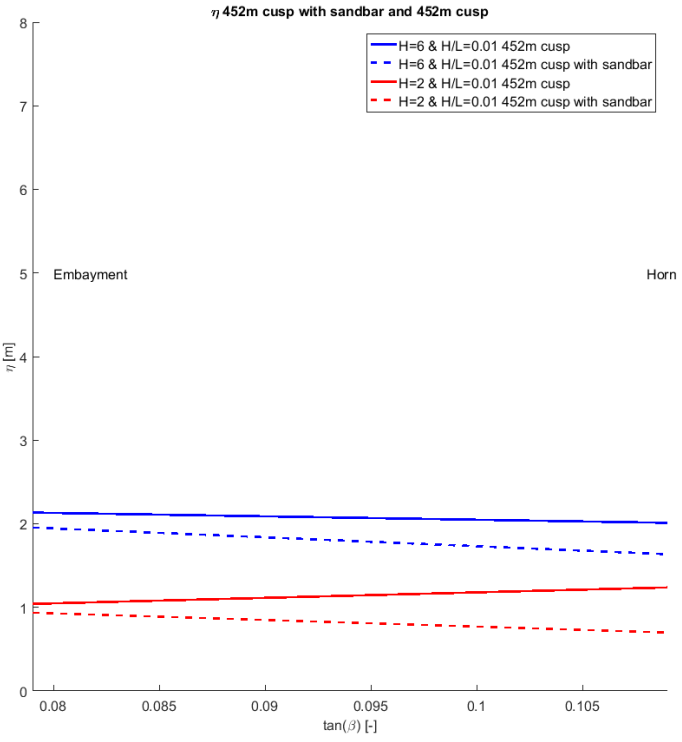

Figure 6-21: trend line for setup along beach slope, solid lines 452 m cusp, dashed lines 452m cusp with sandbar, long waves H_{m0}=6 and H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

When setup is considered the results are slightly different. In the case of a cusp system there is no large difference between the horn and embayment. The trend lines are almost straight lines. However, for a cusp bar system the trend line is decreasing. This can be seen in Figure 6-21 for a wave height of 6 metres and a steepness of 1%. The results are the same for a wave height of 6 metres with a steepness of 3% and a wave height of 4 metres with a steepness of 1% and 3%. However, the magnitude is lower.

A wave height of 2 metres shows an increasing trend line when a cusp system is considered. This is not the case when a cusp bar system is present. A decreasing trend line can be observed when a crescentic sandbar is present. Thus, in this case the same pattern can be observed for a wave height of 4 and 6 metres. Setup is in an embayment larger compared with a horn. Furthermore it can be seen that a cusp bar system contains a smaller magnitude for setup.

6.3.2 Infragravity band swash

In this section infragravity band swash is represented in scatterplots with trend lines.

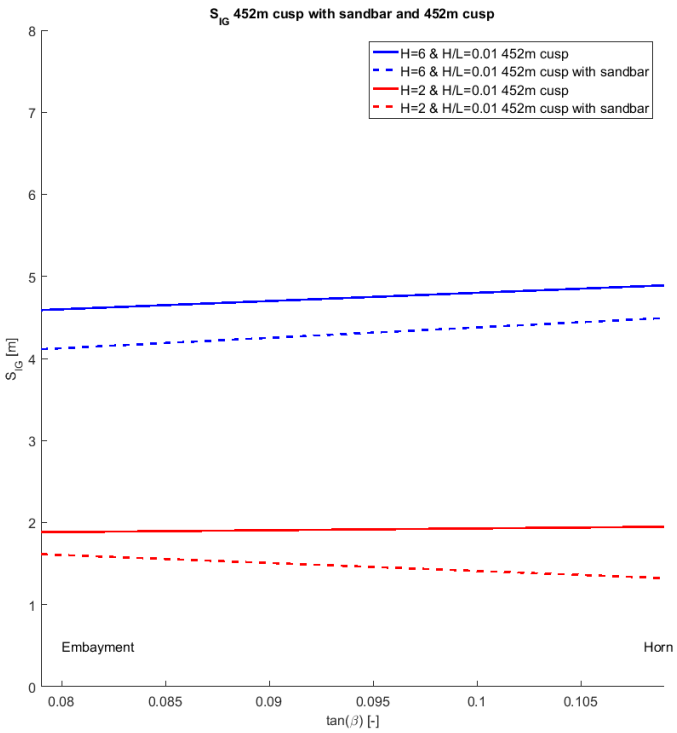

Figure 6-22: trend line for infragravity band swash along beach slope, solid lines 452m cusp, dashed lines 452m cusp with sandbar, short waves H_{m0}=4 and long waves H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

For infragravity band swash similar results are found for a cusp only system in the case of a wave height of 6 metres and a wave height of 4 metres combined with a steepness of 1%. A remark is made that in this case the magnitude is smaller for a cusp bar system. This is shown for a wave height of 6 metres in Figure 6-22.

However, there are differences found for a wave height of 4 metres with a steepness of 3% and a wave height of 2 metres. This is shown for a wave height of 2 metres in Figure 6-22.

A wave height of 2 metres with a steepness of 1% results in a straight trend line for a cusp only system. For a cusp bar system a decreasing trend line can be observed. Thus, at an embayment infragravity band swash is larger compared with a horn. The same holds for a wave height of 4 metres with a steepness of 3%.

6.3.3 Incident band swash

Incident band swash does not show different results compared with a cusp only system. Reference is made to section 5.3.3 where a scatterplot is shown for a cusp only system. In this case there is also no large difference in the magnitude of incident band swash when a cusp only system is compared with a cusp bar system.

6.3.4 Total swash

Total swash does not show different results compared with a system which contains only a cusp. However, there is a difference in magnitude. The cusp bar system contains values for total swash which are lower compared with a cusp system. This was also concluded in section 6.1.1.4. Furthermore it can be concluded that a wave height of 4 metres with a steepness of 3% and a wave height of 2 metres show an increasing trend line, but it is almost flat. Thus, swash does not give large differences between a horn and embayment. The slope which is present is less steep for a cusp bar system. This is explained by the difference in behaviour for the same wave conditions when infragravity band swash is considered, described in section 6.3.2. Reference is made to section 5.3.4 where a scatterplot is shown for a cusp only system with comparable results for the trend lines.

6.3.5 $R_{2\%}$

In this section $R_{2\%}$ is represented in scatterplots with trend lines.

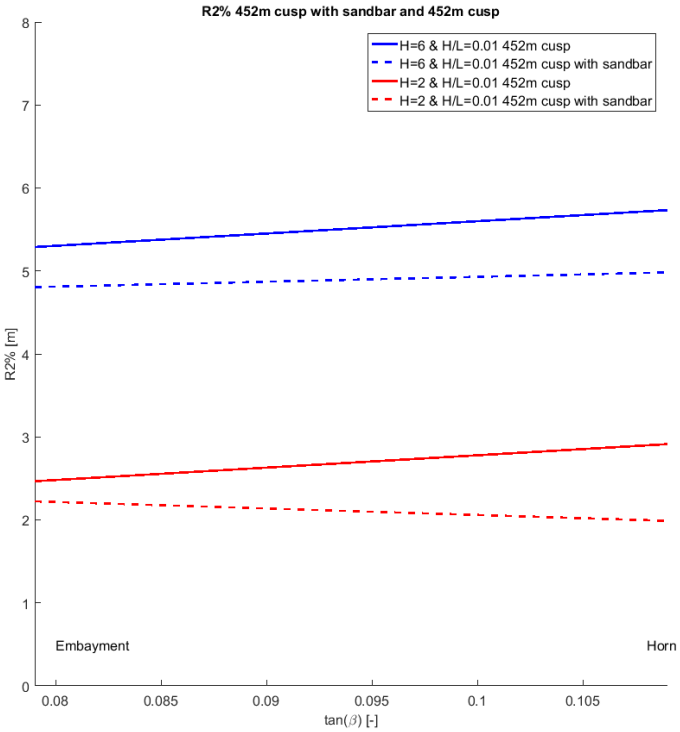

Figure 6-23: trend line for $R_{2\%}$ along beach slope, solid lines 452m cusp, dashed lines 452m cusp with sandbar, long waves H_{m0}=4 and short waves H_{m0}=2, slope 0.079 = embayment and slope 0.109 = horn

$R_{2\%}$ exhibit the same results for a cusp only system and a cusp bar system for wave conditions with a wave height of 4 metres combined with a steepness of 1% and a wave height of 6 metres. In this case the magnitude is lower for a cusp bar system, which was also concluded in section 6.1.1.5. Furthermore the trend lines are less steep. Thus, there is less variation along the cusp between a horn and embayment, this is also shown in Figure 6-23 for a wave height of 6 metres. Total run-up is 3.68% larger at a horn compared to an embayment for a wave height of 6 metres with a steepness of 1%.

Differences are found for a wave height of 4 metres and a steepness of 1% and for a wave height of 2 metres. This is shown for a wave height of 2 metres in Figure 6-23. When a system is considered with only a beach cusp the trend line is increasing. Thus, in the embayment a lower total run-up is observed compared to the horn. However, this behaviour is reversed for a cusp bar system. In this case the trend line is decreasing. Thus, in an embayment the total run-up is larger compared to a horn. A horn contains 10.5% smaller run-up compared with the embayment. Furthermore it can be seen that the magnitude of $R_{2\%}$ for a cusp bar system is lower compared with a system which contains only a beach cusp.

6.3.6 Conclusion alongshore trend total run-up and components for cusp bar system

When setup is considered, a 452 metres cusp shows similar results compared with a 452 metres cusp bar system. However, for a cusp bar system the trend line is decreasing, this holds for all wave conditions. For a 452 metres cusp there is no large difference between the horn and embayment. The trend lines are almost straight lines, but there are still small differences. For large wave heights setup is slightly larger in the embayment compared with the horn, but this is a small difference. For small wave heights setup is slightly smaller in the embayment compared with the horn. Whereas for a cusp bar system it can be concluded that setup is larger at an embayment compared with a horn, this holds for small and large wave height. Furthermore the magnitude is lower compared with a cusp only system.

Infragravity band swash shows similar results for a 452 metres cusp for a wave height of 6 metres and a wave height of 4 metres combined with a steepness of 1%. The trend lines are more or less flat

and slightly increasing for a wave height of 6 metres with a steepness of 1%. Thus, infragravity band swash is smaller in an embayment compared with a horn for this last condition. There are differences compared with a 452 metres cusp system considering a wave height of 4 metres combined with a steepness of 3% and a wave height of 2 metres. In this case infragravity band swash is larger at the embayment compared with the horn, for a cusp bar system. The magnitude is also lower compared with a cusp system only.

The results of incident band swash are the same compared with a system which contains only a beach cusp. In this case it can be seen that incident band swash increases when the slope increases. Thus, in an embayment incident band swash is smaller compared with a horn.

Total swash shows similar results when a cusp bar system is compared with a cusp system. It can be concluded that all wave conditions contain smaller total swash in the embayment compared with the horn. A wave height of 4 metres combined with a steepness of 3% and a wave height of 2 metres contains a trend line which is slightly increasing but almost flat.

When total run-up is considered a main conclusion can be made that the magnitude is lower in the case of a cusp bar system compared with a cusp system. For a cusp only system total run-up is lower at an embayment compared with a horn. However, for a cusp bar system this pattern is not clearly visible. The trend line is slightly increasing for a wave height of 6 metres and a steepness of 1%. And the trend lines are almost flat for a wave height of 4 metres combined with a steepness of 1% and a wave height of 6 metres combined with a steepness of 3%. Furthermore a wave height of 4 metres combined with a steepness of 3% and a wave height of 2 metres shows a decreasing trend line. Thus, the embayment contains larger total run-up compared with a horn.

For large wave height, the horn contains 3.68% larger run-up compared with the embayment in the case of a 452 metres cusp bar system. This number is 8.4% for a cusp system only. The alongshore variance is less when a crescentic bar is present.

For small wave heights, the horn contains 10.5% smaller run-up compared with an embayment for a cusp bar system. Whereas the horn contains 18.1% larger run-up compared with the embayment in the case of a 452 metres cusp system.

7 Alongshore variance and hydrodynamic forcing

In this chapter the normalized standard deviation is described for the uniform bathymetry and the cusp system. In this chapter the normalized standard deviation is analysed with respect to different hydrodynamic forcing components. The components are wave height, steepness, angle of incidence, frequency spreading and directional spreading. First the mean values are considered of the normalized standard deviation for the uniform bathymetry and the cusp (bar) system. After this boxplots are presented in which the normalized standard deviation is shown regarding the different hydrodynamic forcing conditions. The boxplots of the uniform bathymetry and the 452 metres cusp are described, the other results can be found in Appendix XII .

7.1 Mean values normalized standard deviation

In this section the minimum and maximum values of the normalized standard deviation are given for run-up and its components. It is given for a uniform bathymetry in Table 7-1 for a cusp system in Table 7-2 and for a cusp bar system in Table 7-3.

1*std of:	R2%	Setup	swash	Infragravity band swash	Incident band swash
Min [%]	0.171	0.023	0.037	0.055	0.056
Median [%]	1.548	0.478	0.561	0.682	0.854
Max [%]	4.614	2.038	1.891	2.320	3.350

Table 7-1: minima and maxima of normalized standard deviation R2%, setup and swash components uniform bathymetry

1*std of:	R2%	Setup	swash	Infragravity band swash	Incident band swash
Min [%]	1.907	1.128	2.139	1.569	10.592
Median [%]	4.736	3.322	5.225	3.996	14.900
Max [%]	9.061	8.629	8.3076	7.2861	20.085

Table 7-2: minima and maxima of normalized standard deviation R2%, setup and swash components cusp system 452m

1*std of:	R2%	Setup	swash	Infragravity band swash	Incident band swash
Min [%]	2.039	1.631	1.741	1.816	4.571
Median [%]	4.889	7.227	6.124	6.094	14.956
Max [%]	15.299	19.369	11.067	19.026	21.126

Table 7-3: minima and maxima of normalized standard deviation R2%, setup and swash components cusp bar system 452m

The mean value of the normalized standard deviation for total run-up is similar for a cusp system and a cusp bar system. The components of run up give larger values of the normalized standard deviation for a cusp bar system, except for incident band swash. The mean values for total run-up and components are lower for the uniform bathymetry compared with the cusp (bar) system. This indicates that there is more variation along the coast for a cusp (bar) system.

If only long-crested waves are considered the mean values of the normalized standard deviation are much lower for the uniform bathymetry. This is 0.36% for R2% and around 0.11% for setup, swash, infragravity band swash and incident band swash. For a cusp system of 452 metres this is in the order of 3.7% for R2%, setup and swash components. For incident band swash this is 15.9%.

7.2 Normalized standard deviation for uniform bathymetry

Furthermore the standard deviation in alongshore direction of R2%, setup and swash components is described regarding the different parameters which are varied: wave height, steepness, angle of incidence, frequency spreading and directional spreading. The standard deviation is normalized and shown in Appendix IV in Table IV-1.

The results shown in Table IV-1 are presented in boxplots. Each boxplot contains a specific parameter on the x-axis and the normalized standard deviation as shown in Table IV-1 on the y-axis. The mean value of the normalized standard deviation in alongshore direction is represented by a green diamond. The mean value is determined from all the 60 wave conditions. This is shown in Figure 7-1, Figure 7-2, Figure 7-4, Figure 7-7 and Figure 7-8.

Next to the boxplots separate figures are made which represents the normalized standard deviation in alongshore direction on the y-axis and the wave height on the x-axis. With colours the parameters steepness, angle of incidence, frequency spreading and directional spreading are represented. The squares are the mean values for the specified parameter. This is shown in Figure 7-3, Figure 7-5, Figure 7-6 and Figure 7-9.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-1, plotted versus wave height.

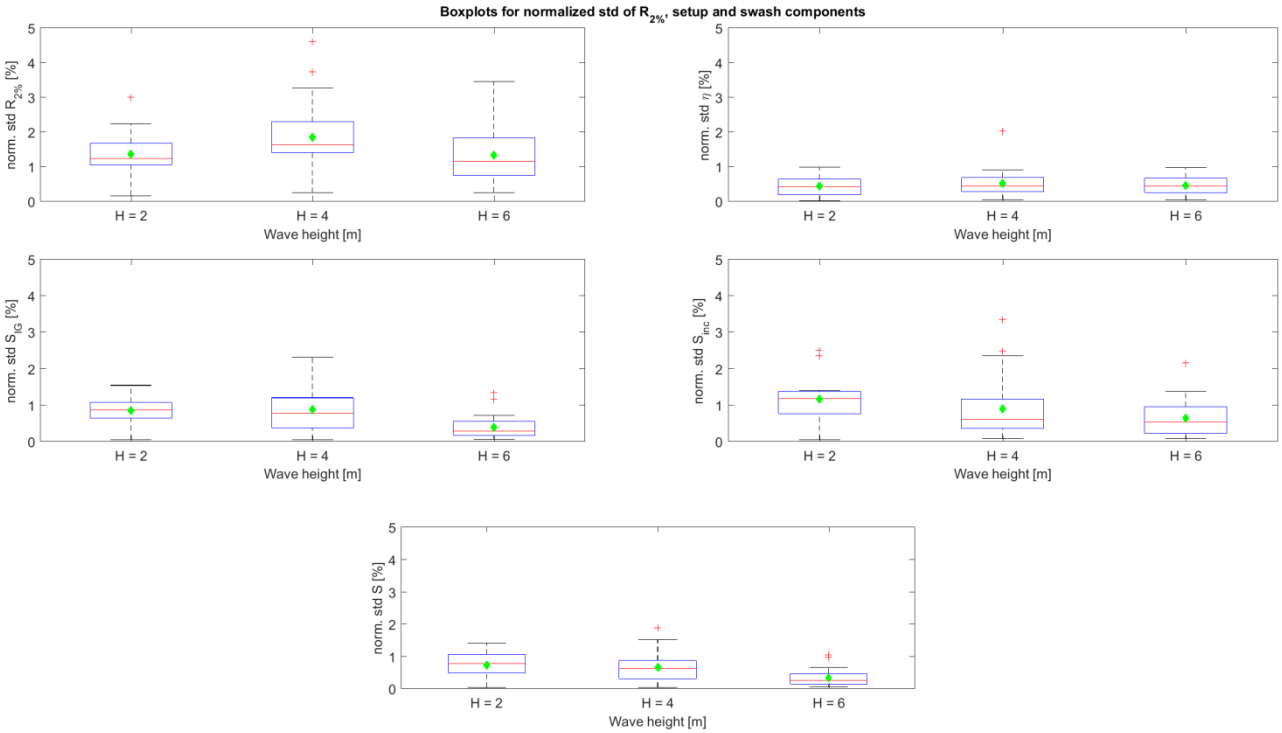

Figure 7-1: boxplots normalized standard deviation in alongshore direction versus wave height, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

From Figure 7-1 a slight decrease can be seen in the mean values of the normalized standard deviation when the wave height rises from 2 to 6 metres. This decrease is within approximately one per cent for all cases, R2%, setup and swash components. An exception holds for total run-up when a wave height of 4 metres is considered, this contains a slightly larger mean value compared with a

wave height of 2 metres. There is some noise present in the calculation, this occurred when 500 waves were selected from the 24 hour model run. This noise level is repeated in Table 7-4, which are the same numbers as in Table 4-1 divided by two. It can be seen that the mean values for the normalized standard deviation in alongshore direction in Figure 7-1 are even lower compared to the noise in the calculations.

	Noise at 500 waves [%]
$R_{2\%}$	3.54
Setup	2.04
Swash	2.75
Infragravity band swash	3.55
Incident band swash	2.89

Table 7-4: noise at 500 waves determined from the 24 hour model run

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-2, plotted versus steepness.

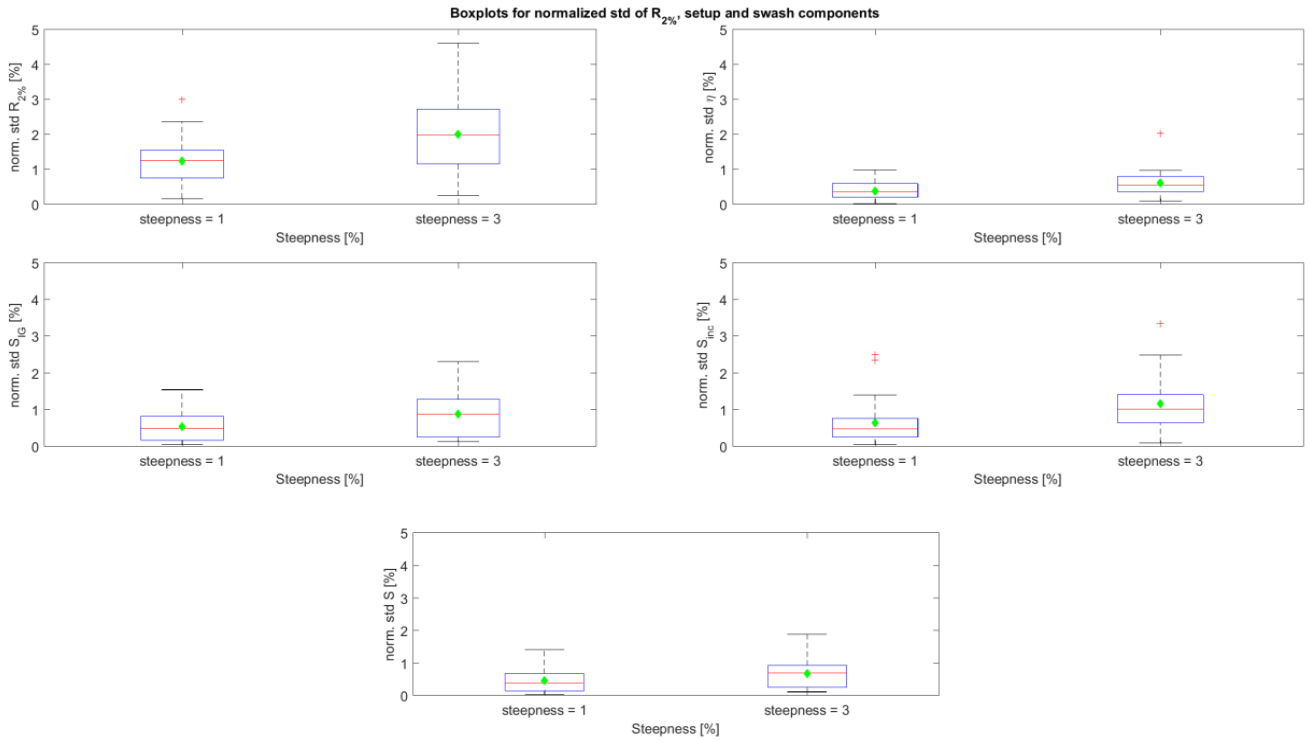

Figure 7-2: boxplots normalized standard deviation in alongshore direction versus steepness, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

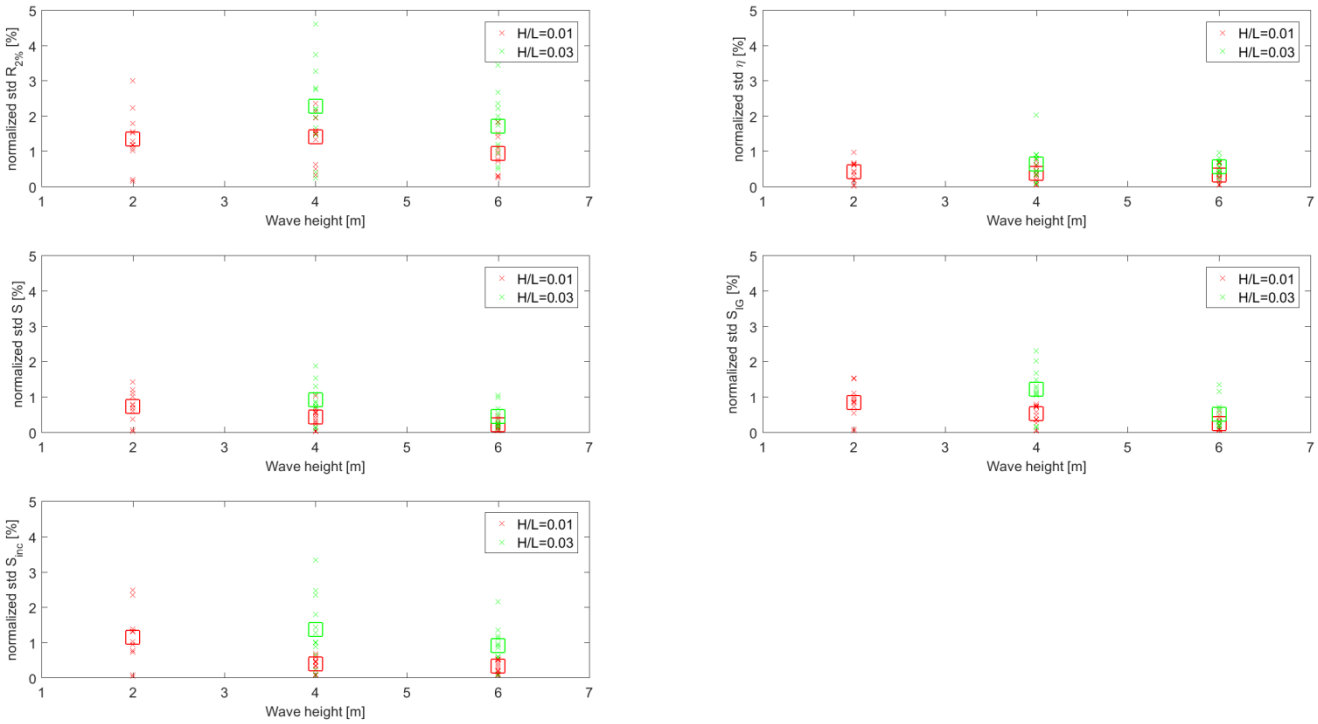

Figure 7-3: normalized standard deviation in alongshore direction versus wave height, red: steepness 1%, green: steepness 3%, squares represents the mean value

From Figure 7-2 a slight increase can be seen in the mean values of the normalized standard deviation when the steepness rises from 1% to 3%. This increase lies within one per cent for all cases, $R_{2\%}$, setup and swash components. This is smaller compared to noise, however, it can be said that waves with a steepness of 3% contain a slightly larger normalized standard deviation for each component. It can be seen that the mean values of the normalized standard deviation in alongshore direction in Figure 7-2 are smaller compared with noise in the calculations which is represented in Table 7-4.

When Figure 7-3 is analysed it can be seen that the mean value of the normalized standard deviation in alongshore direction for a steepness of 3% is larger compared to the mean value belonging to a steepness of 1%. This can be seen for a wave height of 4 and 6 metres. A wave height of 2 metres together with a steepness of 3% is not taken into account, due to a large k*d value which will give errors in the results from XBeach. Thus, waves with a steepness of 3% contain a larger mean value compared to waves with a steepness of 1%. A possible explanation could be that the wave field is more irregular when a steepness of 3% is considered. A steepness of 1% can be seen as swell waves which have a more regular wave field.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-4, plotted versus angle of incidence.

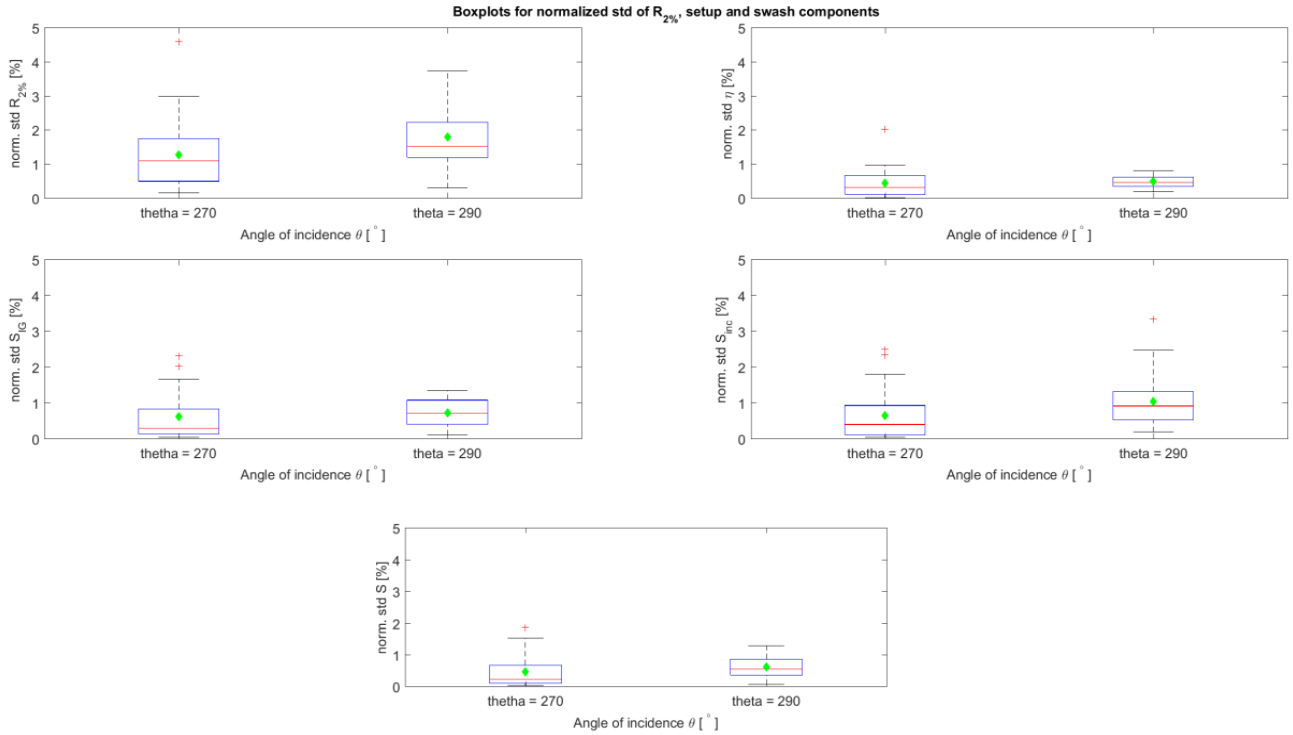

Figure 7-4: boxplots normalized standard deviation in alongshore direction versus angle of incidence, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

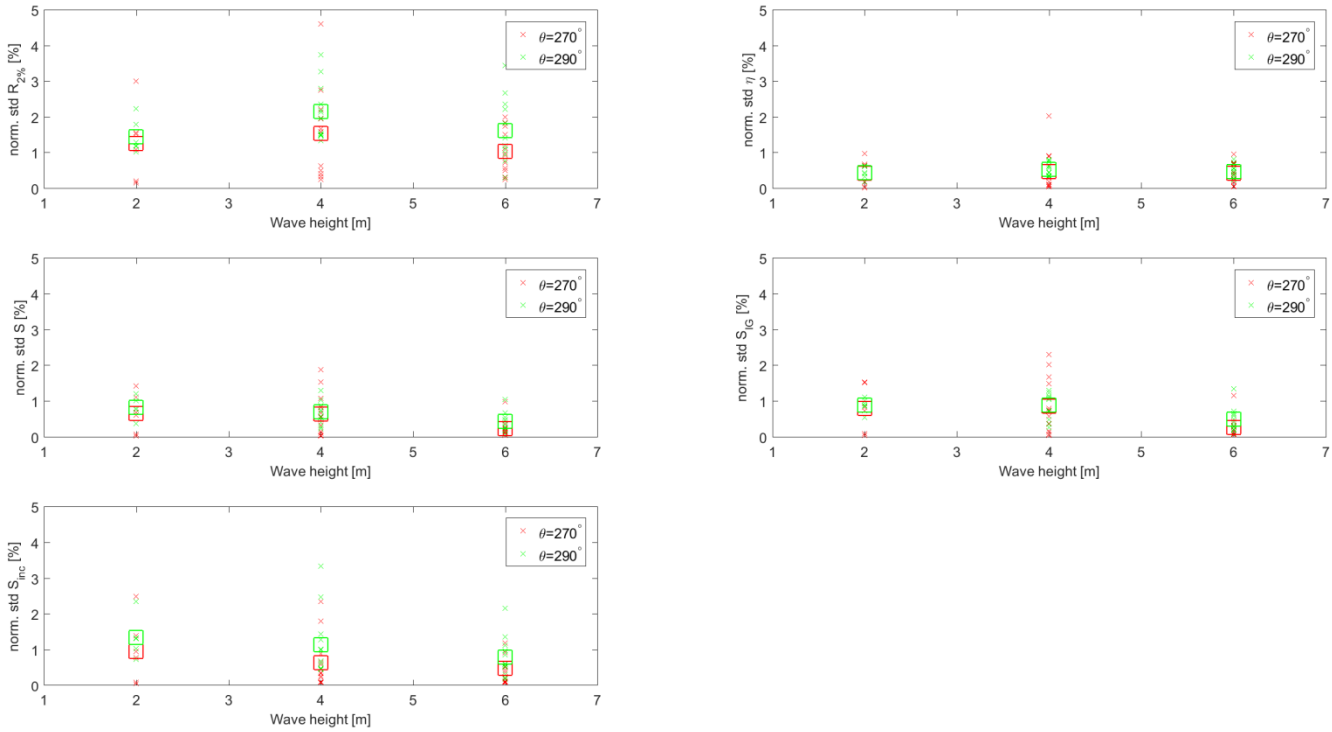

Figure 7-5: normalized standard deviation in alongshore direction versus wave height, red: angle of incidence 270 deg, green: angle of incidence 290 deg, squares represents the mean value

From Figure 7-4 it can be seen that the mean values of the normalized standard deviation increases slightly when the angle of incidence rises from 270 degrees to 290 degrees. The difference lies within 0.6% for all cases, $R_{2\%}$, setup and swash components. This difference is smaller compared to noise. However, an angle of incidence of 290 degrees does contain slightly larger mean values for the normalized standard deviation for each component. It can be seen that the mean values for the normalized standard deviation in alongshore direction in Figure 7-4 is smaller compared to noise in the calculations which is represented in Table 7-4.

When Figure 7-5 is analysed it can be seen that the mean value of the normalized standard deviation in alongshore direction for an angle of incidence of 270 degrees and 290 degrees are almost the same for setup and infragravity band swash. However, for total run-up and incident band swash a larger difference is observed in the mean values of the normalized standard deviation, for total run-up the difference is 0.6%. There is no relation seen between different mean values of the normalized standard deviation with respect to wave heights.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-7, plotted versus frequency spreading.

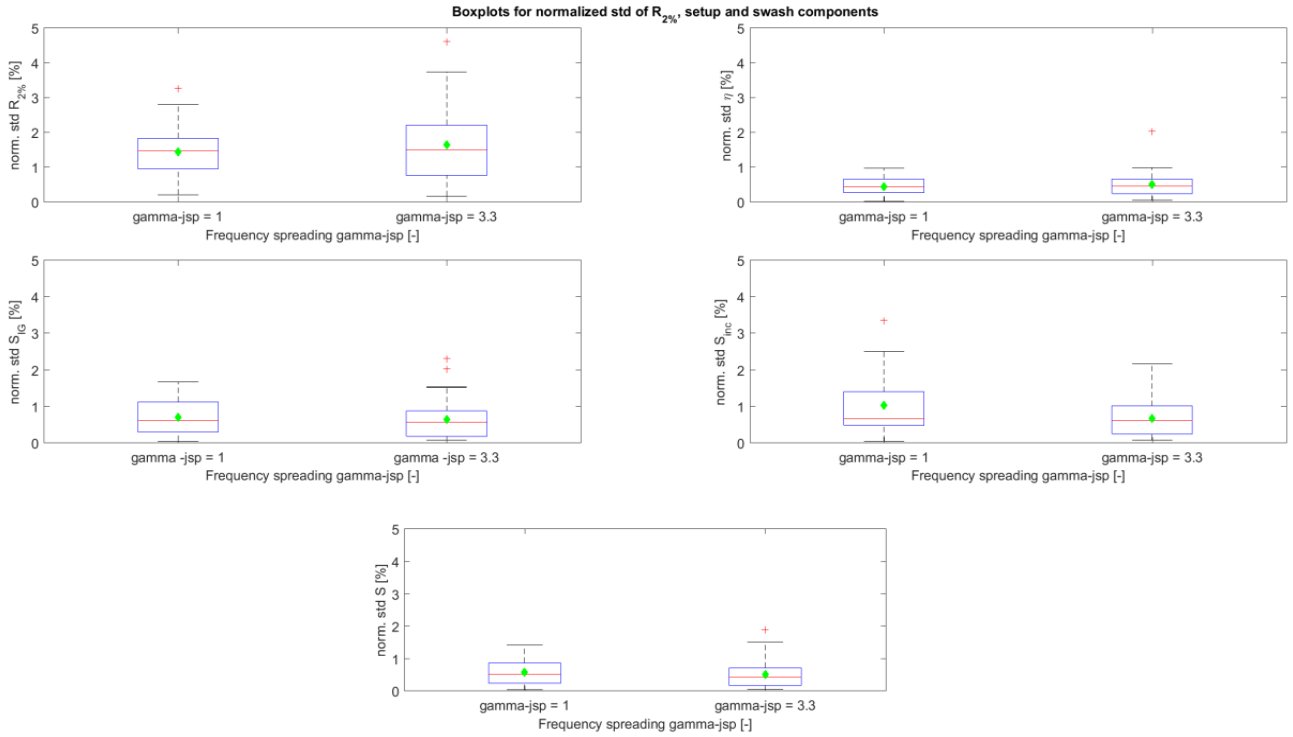

Figure 7-7: boxplots normalized standard deviation in alongshore direction versus frequency spreading, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

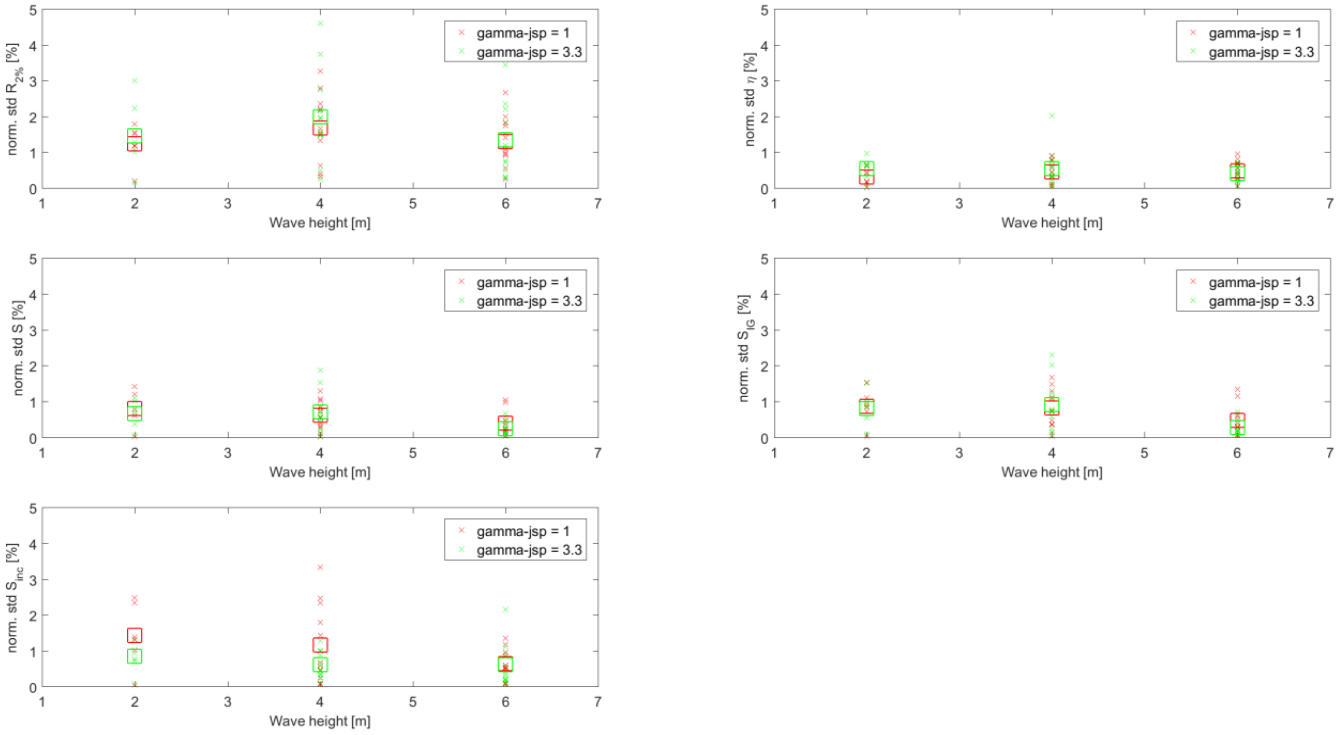

Figure 7-6: normalized standard deviation in alongshore direction versus wave height, red: frequency spreading 1, green: frequency spreading 3.3, squares represents the mean value

In Figure 7-7 there is no large deviation observed for the mean values of the normalized standard deviation when the frequency spreading rises from 1 to 3.3. The mean values stay approximately equal for all cases, $R_{2\%}$, setup and swash components. It can be seen that the mean values for the normalized standard deviation in alongshore direction in Figure 7-7 is smaller compared to noise in the calculations which is represented in Table 7-4.

The same holds when Figure 7-6 is analysed. In this figure there are also no large differences in the mean values of the normalized standard deviation in alongshore direction per wave height. Only incident band swash shows a difference in mean values of the normalized standard deviation when a wave height of 2 and 4 metres is considered. In this case a frequency spread of 3.3 gives a lower normalized standard deviation. This would also be expected, due to less spreading in frequency.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-8, plotted versus directional spreading.

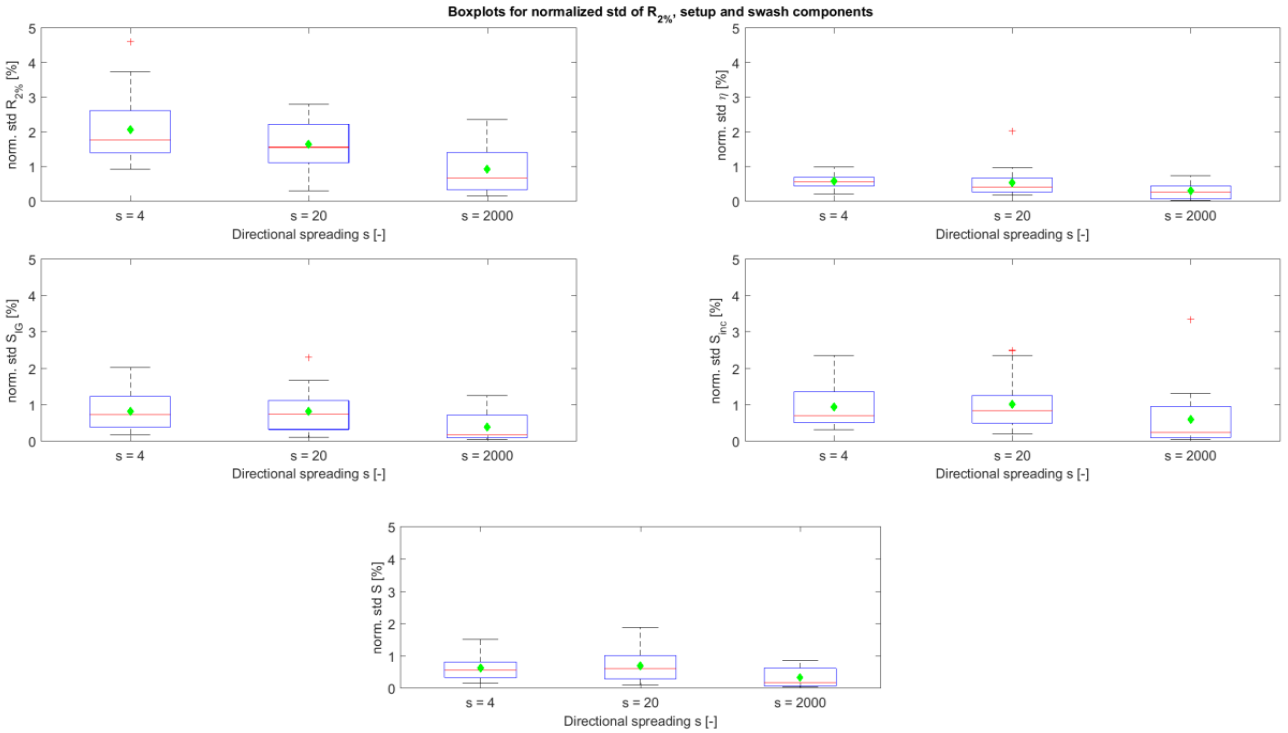

Figure 7-8: boxplots normalized standard deviation in alongshore direction versus directional spreading, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

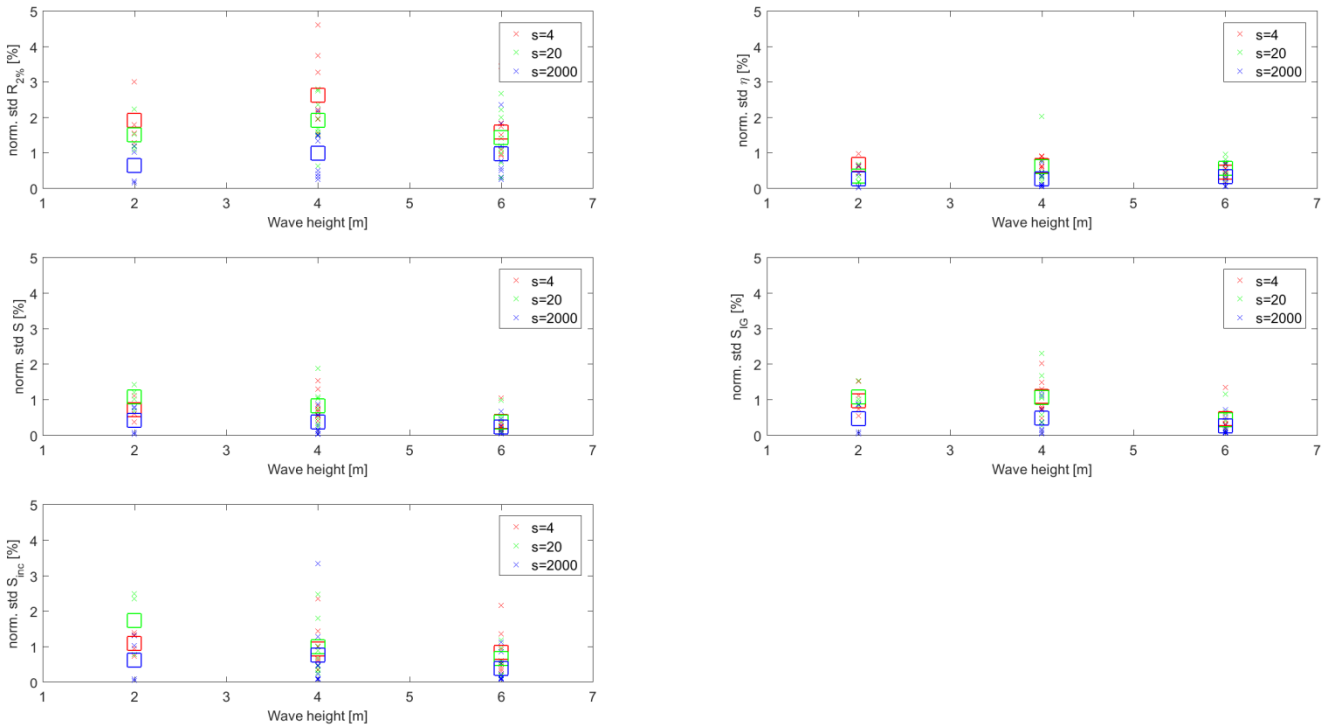

Figure 7-9: normalized standard deviation in alongshore direction versus wave height, red: directional spreading 4, green: directional spreading 20, blue: directional spreading 2000, squares represents the mean value

From Figure 7-8 it can be seen that the mean values of the normalized standard deviation decreases when the directional spreading rises from 4 to 2000 for total run-up. However, the difference is small, within 1.1%. For total swash, infragravity band swash, incident band swash and setup it is observed that the mean values are similar for s=4 and s=20. It can be seen that the mean values for the normalized standard deviation in alongshore direction in Figure 7-8 is lower compared with the noise in the calculations which is represented in Table 7-4.

When Figure 7-9 is analysed it can be seen that the mean value of the normalized standard deviation in alongshore direction for a directional spreading of 2000 is smallest compared to a directional spreading of 4 and 20 for each wave height. A wave height of 2 and 4 metres contains a larger spread in the normalized standard deviation compared with a wave height of 6 metres. The difference lies within 1.6% and is not significant compared to noise.

From the boxplots it is concluded that the normalized standard deviation is even lower compared to the noise obtained from the selection of 500 waves out of a model simulation of 24 hours. However, small differences can be found when a wave height of 2, 4 and 6 metres are compared. The normalized standard deviation decreases when the wave height increases. When the steepness increases the normalized standard deviation increases. The same holds when the angle of incidence increases from 270 degrees to 290 degrees. Frequency spreading does not show differences. Finally the directional spreading does not show large differences when waves contain some directional spreading. The normalized standard deviation is slightly lower if long-crested waves are considered for setup, swash components and total run-up.

7.3 Normalized standard deviation for 452 m cusp system

In this section the normalized standard deviation is shown in boxplots for a cusp with a length of 452 meters. The results for a cusp length of 300 and 100 metres and 452 metres with cusp bar system are shown in Appendix XII . The standard deviation in alongshore direction is calculated for $R_{2\%}$, setup and swash components. The results of the normalized standard deviation are shown in Appendix XI in Table XI-1 and Table XI-2.

The results of the normalized standard deviation shown in the above-mentioned tables in Appendix XI are presented in boxplots. Each boxplot contains a specific parameter on the x-axis and the normalized standard deviation as shown in Table XI-1 and Table XI-2 on the y-axis. The mean value of the normalized standard deviation in alongshore direction is represented by a green diamond. The mean value is determined from all the 60 wave conditions. This is shown in Figure 7-10, Figure 7-11, Figure 7-13, Figure 7-15, and Figure 7-17. The same figures are made for a cusp length of 300 and 100 metres and a cusp bar system of 452 metres located in Appendix XII .

Next to the boxplots separate figures are made which represents the normalized standard deviation in alongshore direction on the y-axis and the wave height on the x-axis. With colours the parameters steepness, angle of incidence, frequency spreading and directional spreading are represented. The squares are the mean values for the specified parameter. This is shown in Figure 7-12, Figure 7-14, Figure 7-16 and Figure 7-18. The same figures are made for a cusp length of 300 and 100 metres and for a cusp bar system of 452 metres, located in Appendix XII .

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-10, plotted versus wave height.

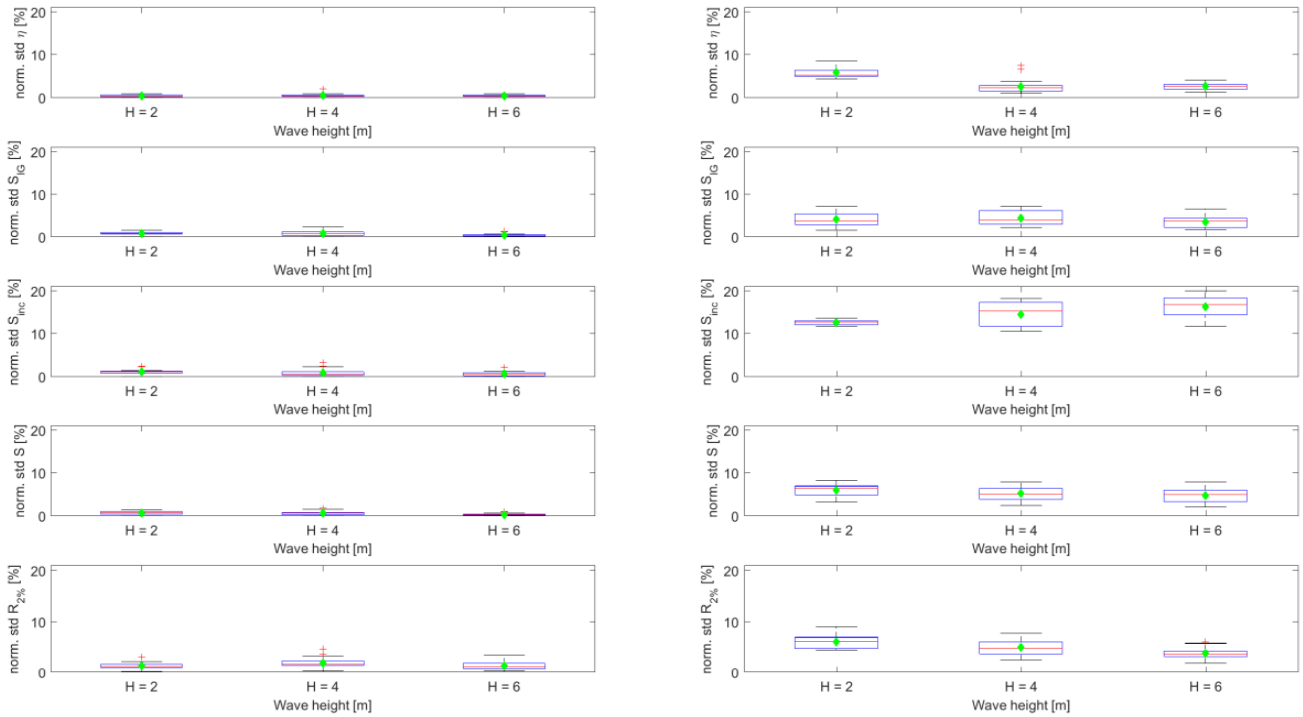

Figure 7-10: boxplots normalized standard deviation in alongshore direction versus wave height for 452 m cusp, from top to bottom: setup, infragravity band swash, incident band swash, total swash and R2%. Left: uniform bathymetry, right: 452 m cusp. The green diamond represents the mean value.

In Figure 7-10 it can be seen that the normalized standard deviation is larger compared to the situation in which an alongshore uniform bathymetry was modelled, written in section 7.2. For R2%, with a wave height of 2 metres, it is around two times as large compared to the noise of 3.54% present in the calculations. Setup also consists of a larger standard deviation compared to noise of 2.04%, especially when a wave height of two metres is taken into account. Furthermore the boxes for the different wave heights do not overlay each other for setup when a wave height of 2 metres is considered. The last also holds for R2% and incident band swash if a wave height of two metres is compared with a wave height of six metres. Infragravity band swash shows a small increase of the standard deviation compared to noise, which equals 3.55%. The boxes for all wave heights do overlay each other for infragravity band swash, thus the normalized standard deviation is more or less equal. Incident band swash shows the largest increase, in which the values range from 12 to 17% when the mean value is considered of the normalized standard deviation. This could be related to a strong correlation with the alongshore varying slope.

A similar pattern can be seen for a cusp length of 300 metres represented in Appendix XII-i . A difference can be found: larger boxes for incident band swash, which can be interpreted as a larger spread in the standard deviation. Another remark is made, the standard deviation rises as the wave height increases for incident band swash, this is not the case for the uniform bathymetry.

The results are different compared with a cusp length of 100 metres. Setup contains in this case a larger standard deviation for all wave heights. It ranges from 7% to 12% when mean values are

considered. Furthermore the infragravity band swash shows a larger standard deviation in the range of 10% to 11% taking into account the mean values. Incident band swash ranges from 16% to 23%. Furthermore it can be seen that the standard deviation rises when the wave height increases for $R_{2\%}$, setup, infragravity band swash and incident band swash, this is a contradiction compared to the results of the uniform bathymetry. These results are shown in Appendix XII-ii .

If the results are compared with a cusp bar system it can be concluded that a cusp bar system contains a larger standard deviation for setup, and also for infragravity band swash. For setup this is almost two times as large compared with a cusp only system. Also total swash gives a larger standard deviation, which is in the order of 5.5 to 6.5 %. However, $R_{2\%}$ gives similar results, with some outliers. These results are shown in Appendix XII-iii .

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-11, plotted versus steepness.

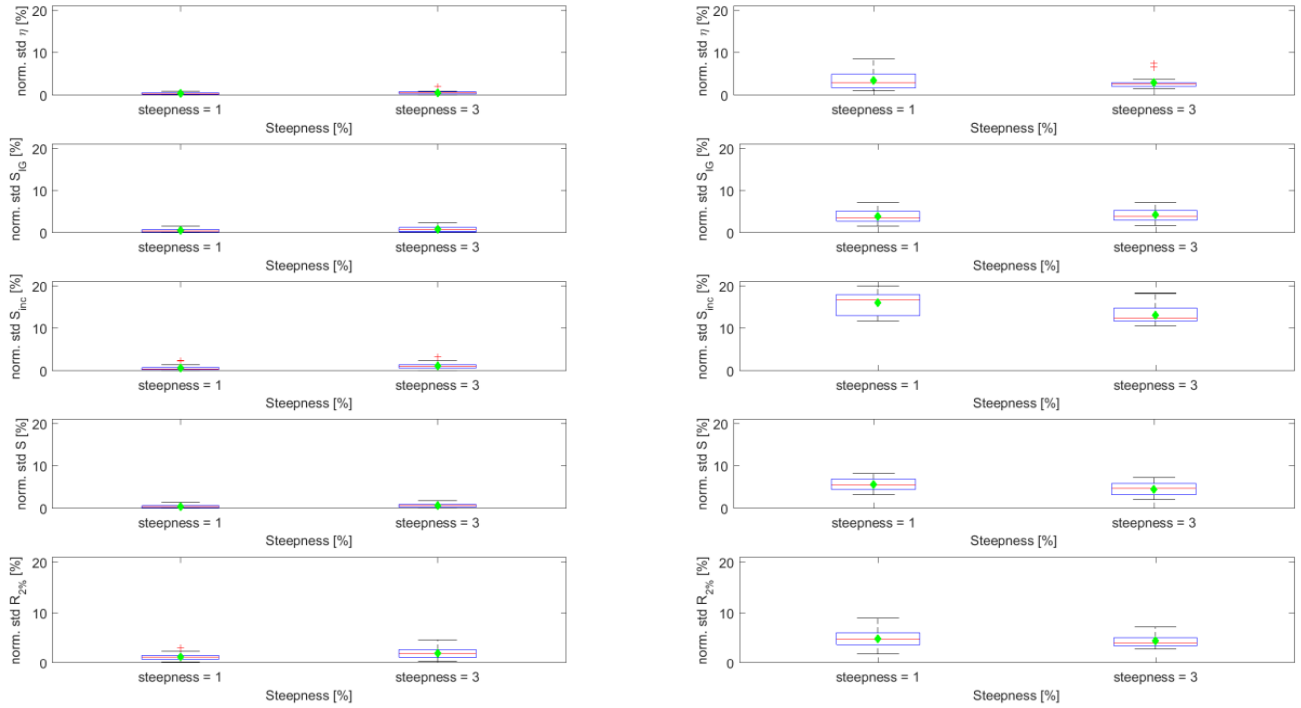

Figure 7-11: boxplots normalized standard deviation in alongshore direction versus steepness for 452 m cusp, from top to bottom: setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$. Left: uniform bathymetry, right: 452 m cusp. The green diamond represents the mean value.

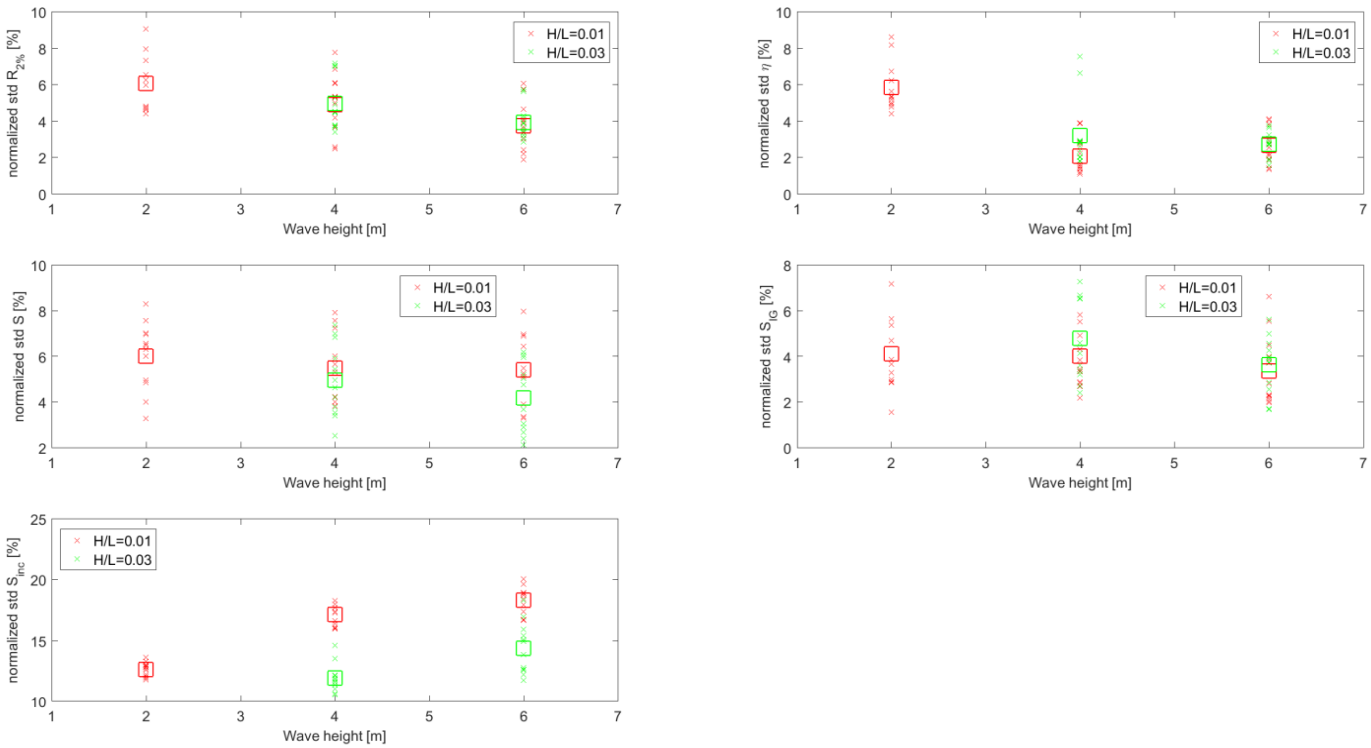

Figure 7-12: normalized standard deviation in alongshore direction versus wave height for 452 m cusp, red: steepness 1%, green: steepness 3%, squares represents the mean value

In Figure 7-11 and Figure 7-12 the results of the normalized standard deviation are shown for the parameter steepness.

When those figures are compared with the uniform bathymetry, it can be seen that the normalized standard deviation in alongshore direction is larger for $R_{2\%}$, setup and swash components compared with noise, especially for incident band swash. Furthermore an increase of steepness from 1% to 3% results in a smaller boxes and a decrease of standard deviation for setup and incident band swash, this does not hold for the uniform bathymetry. Similar results are found for a cusp length of 300 metres.

For a cusp length of 100 metres the standard deviation is larger for $R_{2\%}$, setup and swash components. The boxes do not show an overlay in the case of incident band swash and infragravity band swash. A steepness of 3% contains a larger standard deviation compared with a steepness of 1% for infragravity band swash, the reverse holds for incident band swash.

When the results are compared with a cusp bar system it can be concluded that setup contains a larger standard deviation, which is twice as large. This also holds to a lesser extent for infragravity band swash and for total swash. For total run-up the results are similar, it does contain a few outliers.

When Figure 7-12 is considered, it is noticeable that waves with a steepness of 3% contain a lower standard deviation compared with waves with a steepness of 1%. This holds for swash and incident band swash and this is a contradiction compared to the uniform bathymetry. Furthermore the standard deviation rises when wave height increases for incident band swash, this is also a contradiction compared to the uniform bathymetry. Similar results are found for a cusp length of 300 metres. A cusp length of 100 metres shows the same results. However, swash shows in this case a larger standard deviation for a steepness of 3% compared with a steepness of 1%. And the standard deviation for $R_{2\%}$ and setup rises if the wave height increases from two to six metres, this is not observed at the uniform bathymetry and the cusps lengths of 452 and 300 metres.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-13, plotted versus angle of incidence.

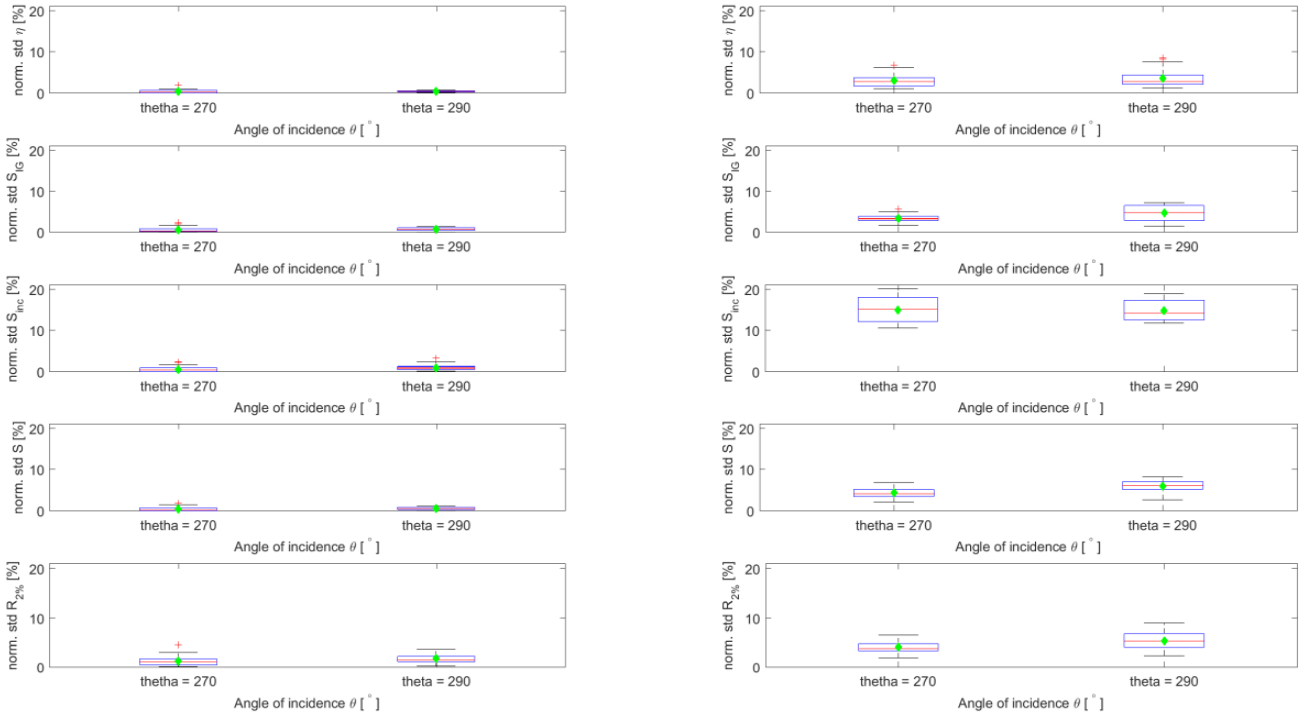

Figure 7-13: boxplots normalized standard deviation in alongshore direction versus angle of incidence for 452 m cusp, from top to bottom: setup, infragravity band swash, incident band swash, total swash and R2%. Left: uniform bathymetry, right: 452 m cusp. The green diamond represents the mean value.

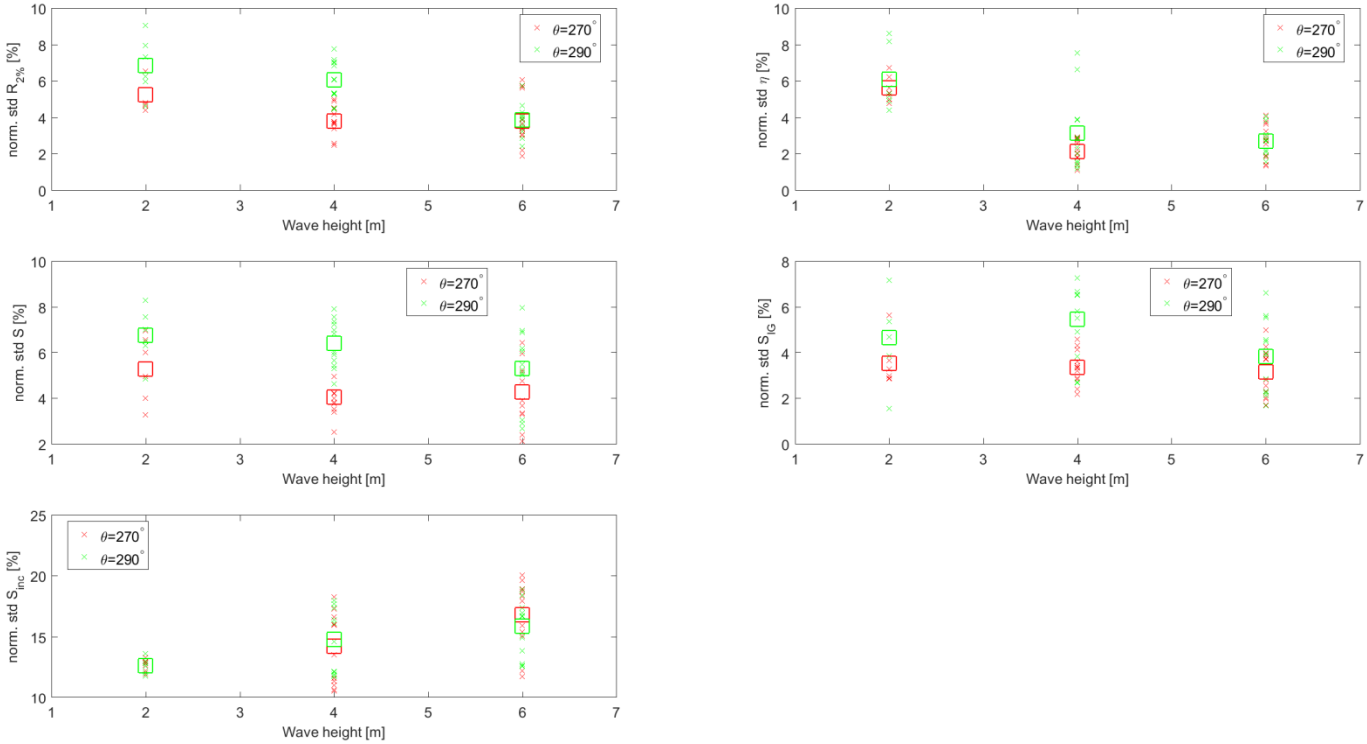

Figure 7-14: normalized standard deviation in alongshore direction versus wave height for 452 m cusp, red: angle of incidence 270 deg, green: angle of incidence 290 deg, squares represents the mean value

In Figure 7-13 and Figure 7-14 the results of the normalized standard deviation are shown for the parameter angle of incidence. The boxes are larger, resulting in a larger spread in standard deviation for $R_{2\%}$, setup and swash components. Furthermore the standard deviation is larger in all cases, especially for incident band swash. Incident band swash is in the order of 15% if the median values are considered.

If a cusp length of 300 metres is considered the same pattern occurs as the 452 metres cusp. However, the standard deviation is larger for a cusp length of 300 metres in the case of setup and infragravity band swash. In both situations of a 300 and 452 meters cusp, the standard deviation for an angle of 290 degrees is larger compared to an angle of 270 degrees except for incident band swash and setup where it is almost the same.

When a cusp of 100 metres is considered it result in a different pattern compared to the cusps of 452 and 300 metres. On average the spread for waves with an angle of 270 degrees is larger compared to waves with an angle of 290 degrees, thus the boxes are larger for 270 degrees. This does not hold for infragravity band swash and total swash, these contain more or less equal sized boxes. Furthermore the standard deviation is larger in the case of $R_{2\%}$ with an angle of 270 degrees. Setup, infragravity band swash and incident band swash contains also a larger standard deviation.

When a comparison is made with a cusp bar system the normalized standard deviation is larger for setup, this is increased by more or less a factor two. Infragravity band swash does also contain a larger standard deviation, incident band swash contain similar results. Total swash increases with approximately 1%. Total run-up gives similar results. However, for waves with an angle of 270 degrees the standard deviation increases with 1.5% and decreases for waves with an angle of 290 degrees with 1%.

If Figure 7-14 is considered it can be clearly seen that waves with an angle of 290 degrees gives a larger standard deviation compared to waves with an angle of 270 degrees. This is not valid for incident band swash, than it is almost the same. The same pattern can be observed when a cusp length of 300 metres is considered, but with a larger standard deviation.

A cusp length of 100 metres gives different results. On average the standard deviation is larger for a wave coming in with an angle of 270 degrees compared with a wave of 290 degrees if the wave height is four or six metres.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-15, plotted versus frequency spreading.

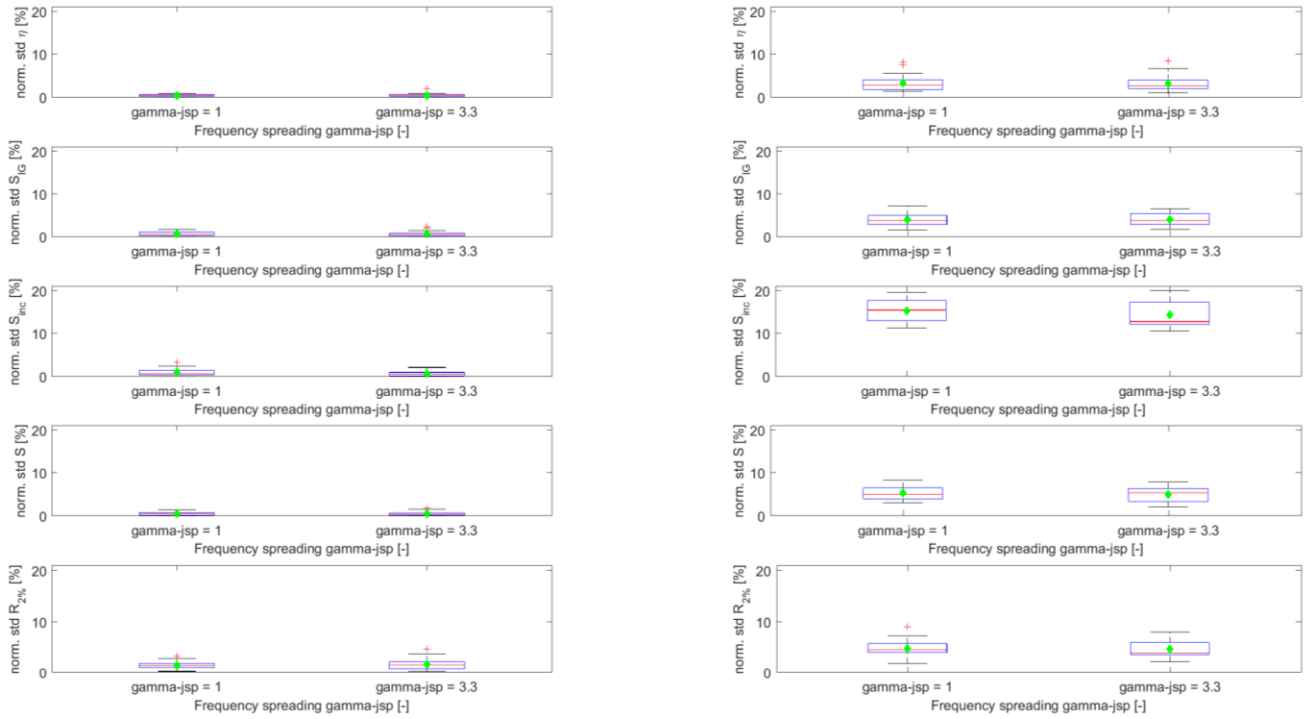

Figure 7-15: boxplots normalized standard deviation in alongshore direction versus frequency spreading for 452 m cusp, from top to bottom: setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$. Left: uniform bathymetry, right: 452 m cusp. The green diamond represents the mean value.

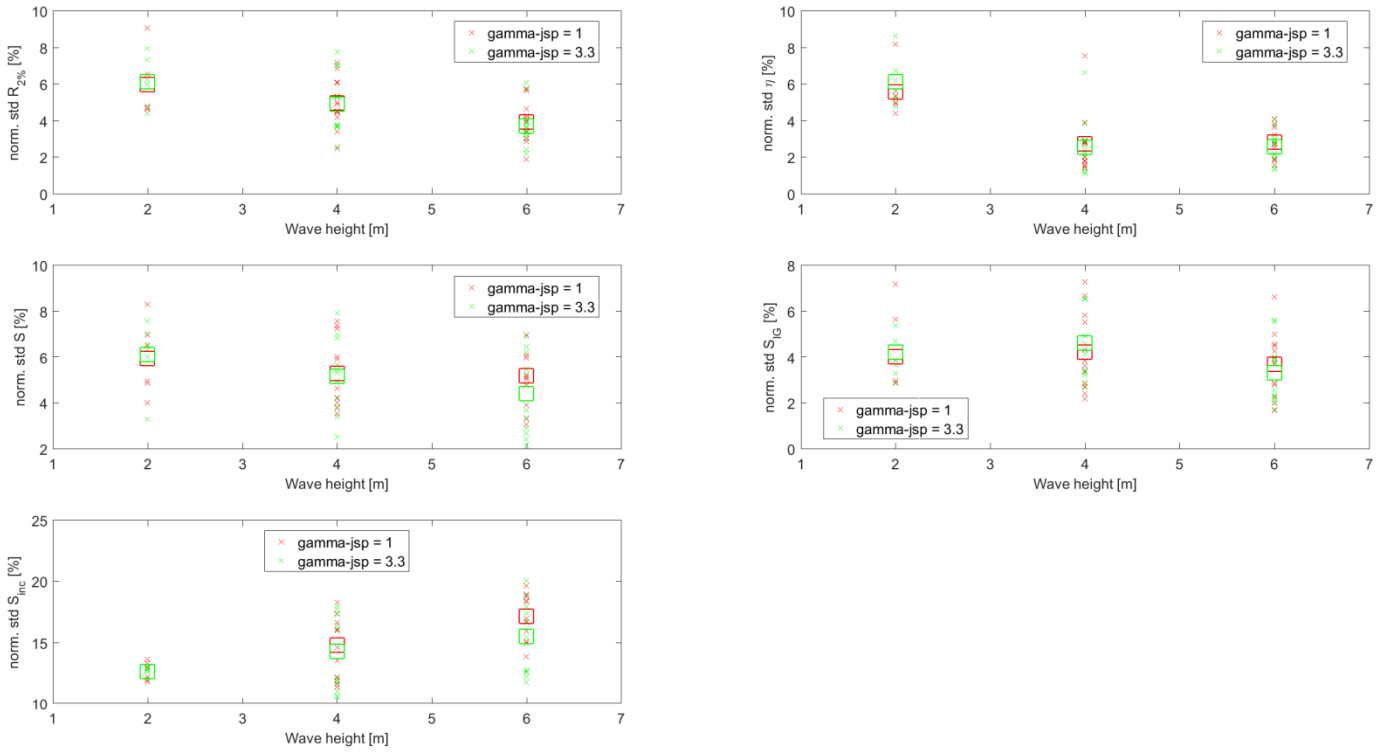

Figure 7-16: normalized standard deviation in alongshore direction versus wave height for 452 m cusp, red: frequency spreading 1, green: frequency spreading 3.3, squares represents the mean value

In Figure 7-15 and Figure 7-16 the results of the normalized standard deviation are shown for the parameter frequency spreading. The boxplots are larger compared to the uniform bathymetry. This means that the spread in standard deviation is larger; this is the case for all boxplots. Furthermore the standard deviation is larger if the mean value is considered, especially for incident band swash, where an increase of 14% is observed. In other cases it is approximately 3% larger compared to noise. Furthermore there is no difference observed between the mean values of a frequency spreading equal to 1 and 3.3.

In the case of a cusp of 300 metres a similar pattern can be observed for $R_{2\%}$, swash and setup. Incident band swash contains contain more spread in standard deviation, what can be seen in a larger whisker.

When a cusp of 100 metres is considered not much variations are visible between a frequency spreading of 1 and 3.3. A larger standard deviation can be observed compared to a cusp length of 452 and 300 metres. Total swash shows a lower magnitude of the normalized standard deviation.

For a cusp bar system it can be seen that setup contains a larger standard deviation. This is doubled compared with a cusp only system. Infragravity band swash increases with approximately 2%, and it contains more outliers. Incident band swash contains similar results. This holds also for total run-up, but more outliers are found for $R_{2\%}$.

When Figure 7-16 is considered similar patterns can be observed for the mean values of a frequency spreading of 1 and 3.3 for the different wave heights. This holds for $R_{2\%}$, swash and setup. Only incident band swash shows some more variations between the different wave heights of 2, 4 and 6 metres. Furthermore the mean values are larger. The standard deviation increases when the wave height increases, this is not the case for a uniform bottom where the standard deviation decreases. A cusp length of 300 metres shows similar results compared with a cusp length of 452 metres, however, the mean values are somewhat larger.

A cusp of 100 metres show a little increase in standard deviation when the wave height increases for $R_{2\%}$ and setup. This is not the case when a cusp of 300 and 452 metres is considered. Furthermore incident band swash shows a similar pattern compared to the 452 and 300 metres cusp. Furthermore the mean values are higher for $R_{2\%}$, setup, infragravity band swash and incident band swash.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure 7-17, plotted versus directional spreading.

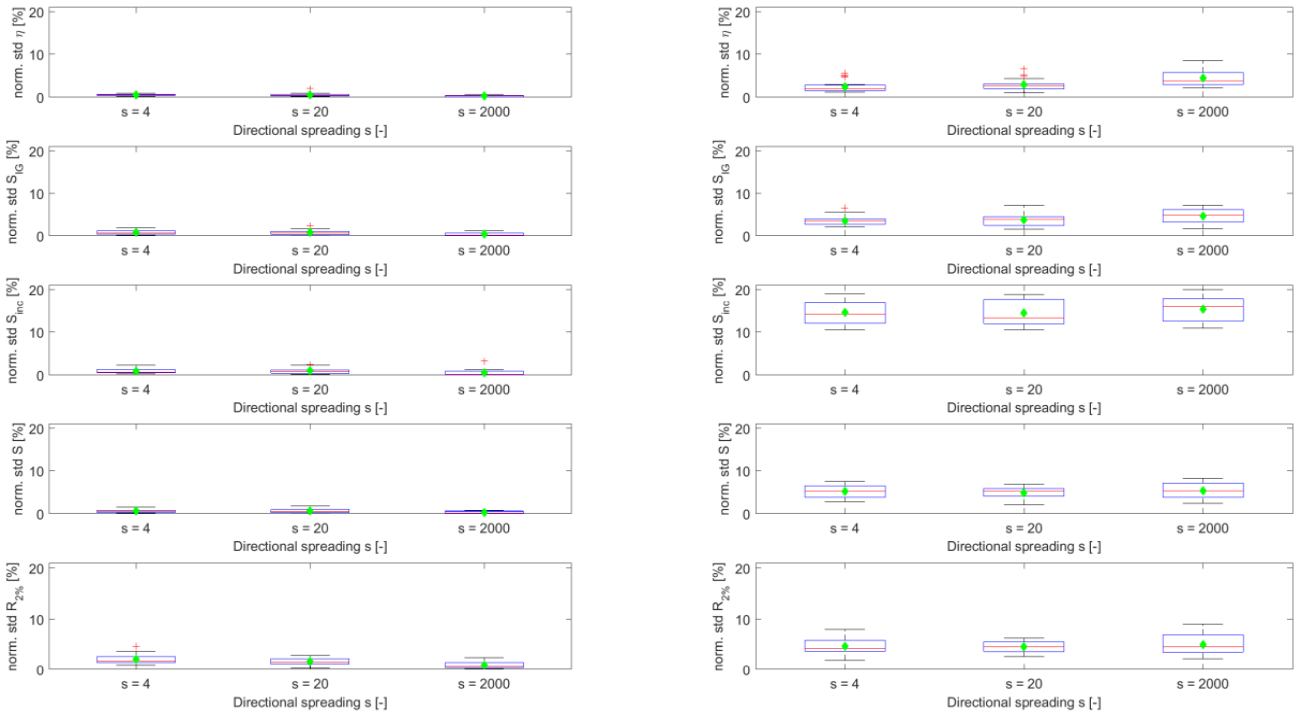

Figure 7-17: boxplots normalized standard deviation in alongshore direction versus directional spreading for 452 m cusp, from top to bottom: setup, infragravity band swash, incident band swash, total swash and $R_{2\%}$. Left: uniform bathymetry, right: 452 m cusp. The green diamond represents the mean value.

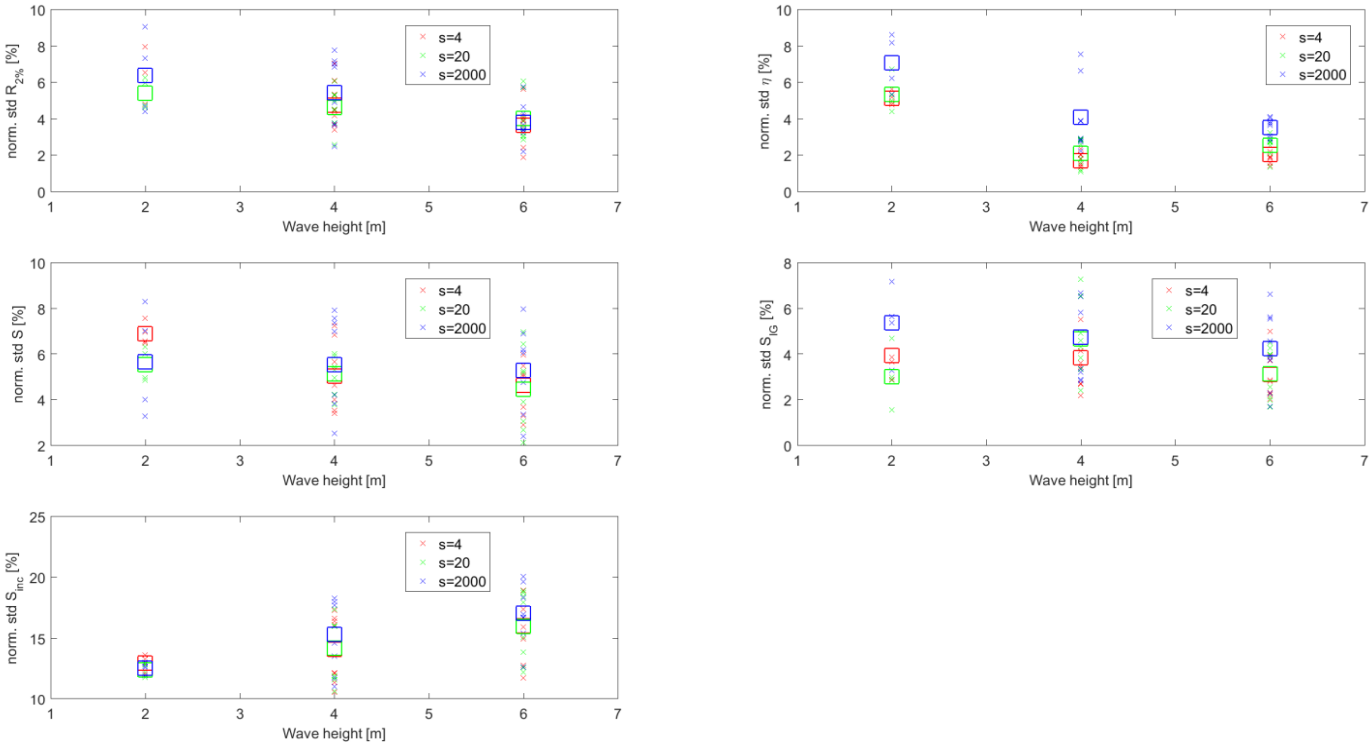

Figure 7-18: normalized standard deviation in alongshore direction versus wave height for 452 m cusp, red: directional spreading 4, green: directional spreading 20, blue: directional spreading 2000, squares represents the mean value

In Figure 7-17 and Figure 7-18 the results of the normalized standard deviation are shown for the parameter directional spreading. The boxplots for a cusp of 452 metres contains larger standard deviation, again this holds especially for incident band swash. The values of the standard deviation are larger compared to noise. In the case of $R_{2\%}$ this is approximately 1.5% larger if the mean value is considered. For setup the increase of the standard deviation is not much for s=4 and s=20. However, for s=2000 the standard deviation increases with 2.5% compared to noise. Infragravity band swash shows a similar pattern compared to setup. Incident band swash shows the largest increase of 12% compared to noise. For total swash the increase compared to noise is approximately 2.75%, doubled compared to noise. A directional spreading of s=2000 gives a boxplot with smaller values for the standard deviation in the case of a uniform bathymetry. This is not the case when a cusp of 452 metres is modelled. In this case the standard deviation is larger compared to a directional spreading of s=4 and s=20. The boxplots are smaller for s=4 and s=20 compared to s=2000 for $R_{2\%}$, setup, infragravity band swash and swash. This means that the spread in standard deviation is smaller. Incident band swash gives boxplots of more or less an equal size.

For a cusp of 300 metres the same patterns can be observed compared to a cusp of 452 metres. The standard deviation is in this case larger for $R_{2\%}$ in the case of s=2000, the same holds for setup, infragravity band swash and swash.

For a cusp of 100 metres a similar pattern can be observed compared to a cusp of 452 metres. However, the standard deviation is larger for all boxplots (thus, for s=4, s=20 and s=2000), for $R_{2\%}$, setup, infragravity band swash, incident band swash and in the case of swash. In this case the boxplots of s=4 and s=20 shows more overlay compared to s=2000. However, still the standard deviation for s=2000 are larger.

If the results are compared with a cusp bar system it can be seen that setup contains a larger standard deviation, it is almost two times as large. The same pattern can be seen, for s=2000 a larger standard deviation is found. Also infragravity band swash contains larger standard deviation and incident band swash shows similar results. Total swash contains a larger standard deviation for s=20 and s=2000, this increases 1% and 2% respectively. For total run-up only an increase in standard deviation is found for s=2000. In this case an increase of 1.7% can be observed.

When Figure 7-18 is considered it can be seen that the mean values of s=2000 are larger compared to s=4 and s=20 in the case of setup, swash, infragravity band swash and incident band swash. This is especially the case for a wave height of 4 and 6 metres. Furthermore it can be seen that the standard deviation rises if the wave height increases from 2 to 6 metres in the case of incident band swash. This does not hold for the uniform bathymetry.

The same holds for a cusp length of 300 and 100 metres. However, the difference between s=2000 and s=4, s=20 is larger. Furthermore the standard deviation is larger as already mentioned above.

8 Physical results

In this chapter the results are interpreted and differences are explained between for instance a cusp bar system and a cusp system. Furthermore the waterline on the beach is given for two wave conditions.

8.1 Uniform bathymetry and cusp (bar) system

The uniform bathymetry contains larger alongshore maxima and mean values for infragravity band swash and total run-up compared with a cusp system and a cusp bar system. This difference can also be seen in the wave height in the model. In Figure 8-1 H_{m0} is shown and this is smaller for a cusp system compared with the uniform bathymetry in the nearshore region. The 2D plots show that waves are dissipated more in the region around a cross shore distance of x=1000 metres. This can also be concluded from Figure 8-2 in which a cross shore profile is given of the alongshore averaged H_{m0}. As closer to shore the wave height is lower than the uniform beach. The difference in dissipation of the waves could be an explanation why total run-up and infragravity band swash is lower in the case of a cusp (bar) system compared with the uniform bathymetry.

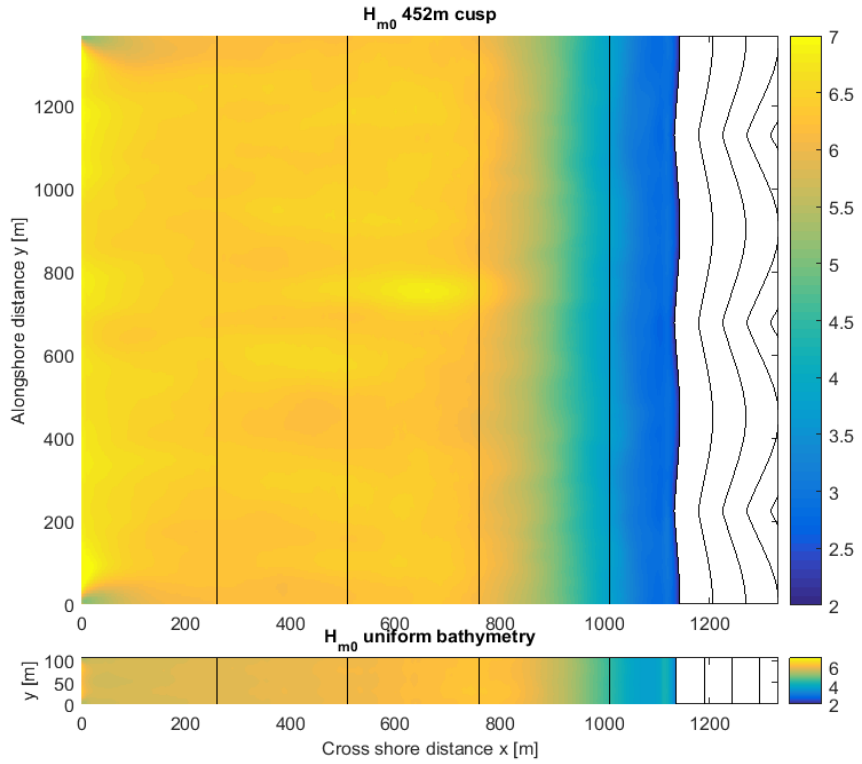

Figure 8-1: H_{m0} for two bathymetries, upper plot: cusp system 452m, lower plot: uniform bathymetry/infinite cusp, for H_{m0}=6m, wave condition 3. The colorbar is equal for both bathymetries.

In Figure 8-2 it becomes clear that a larger wave height at a cross shore location of x=820 metres towards the onshore region is present for the uniform bathymetry. The uniform bathymetry is indicated by the blue line in this graph. At the bottom graph the uniform bathymetry is shown in a cross section. This is also equal to the bathymetry of a cusp system considering a mean slope between the horn and embayment. In the case of the uniform beach it is observed that the foreshore slope of tan(beta)=0.02 changes to a slope of tan(beta)=0.094. The change in slope is located at a cross-shore distance of x=1105 metres. This can also be observed in an increasing wave height. The waves shoal again and eventually the waves break down because the waves are too

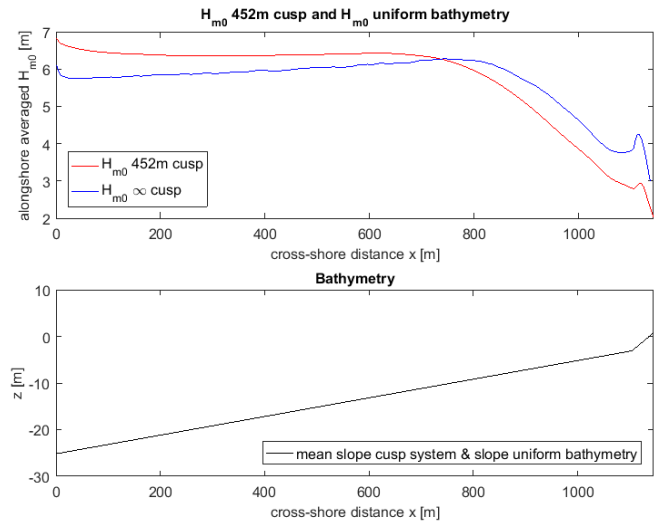

Figure 8-2: alongshore averaged H_{m0} plotted for the uniform bathymetry and a cusp system of 452m, H_{m0}=6m, wave condition 3

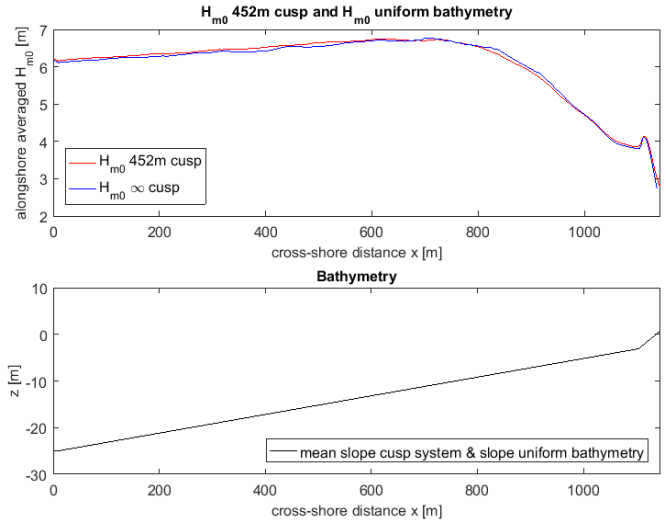

Figure 8-3: alongshore averaged H_{m0} plotted for the uniform bathymetry and a cusp system of 452m, H_{m0}=6m, wave condition 43, long-crested waves

steep. In the case of a cusp bar system a similar pattern can be seen, waves are dissipated more at the same cross shore distance x=1000 metres as the cusp system.

The difference in wave breaking is strange, because the bathymetry does not change between x=0 and x=1105 metres for the uniform bathymetry and the cusp system. Furthermore it is strange why a difference is visible in the wave height at the offshore boundary, this can also be observed in Figure 8-2, while the offshore boundary condition is the same. These differences do not occur if a long-crested wave is considered, shown in Figure 8-3.

Wave breaking occurs at the same location when a long-crested wave is considered; this is a wave with no directional spreading. Thus, for non long-crested waves a different behaviour is observed in wave breaking compared with long-crested waves. There is no analysis made which clarifies this difference. The lateral boundaries of the uniform bathymetry could have an influence on the model. The influence of this aspect is discussed in section 9.1.

8.2 Cusp bar system and cusp system

In this section the differences between the cusp bar system and the cusp system are considered.

8.2.1 Magnitude incident band swash

Smaller alongshore maximum swash and run-up are found for a cusp bar system compared with a cusp system, as described in section 6.2.1. For instance infragravity band swash is 16% smaller for a cusp bar system compared with a cusp system. However, incident band swash does not show a large difference, this is only 3.2%. It was expected that incident band swash would also contain smaller values, due to more breaking waves as a result of the crescentic sandbar. This is not the case because waves are already breaking offshore of the sandbar. This can be seen in Figure 8-4.

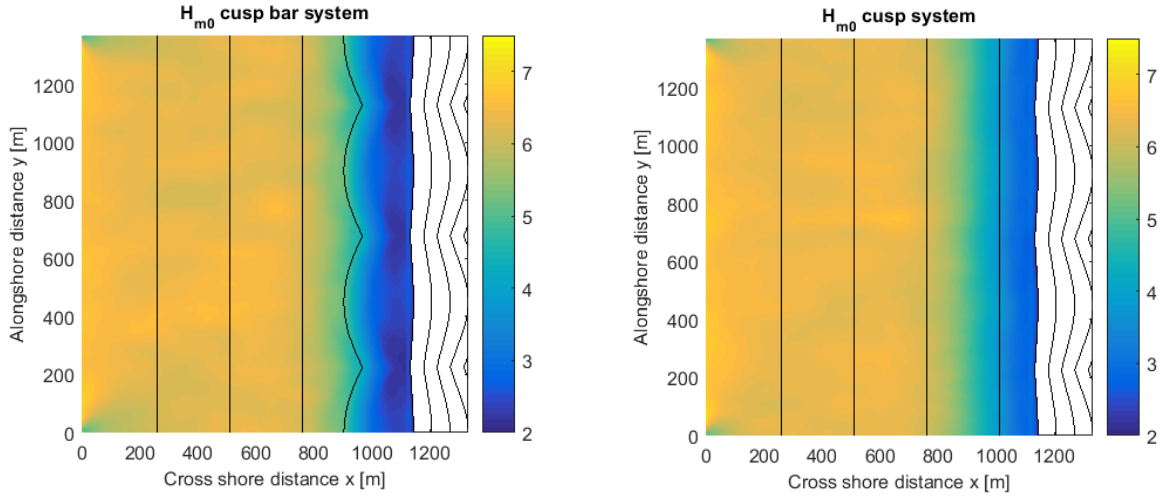

Figure 8-4: H_{m0} for two different bathymetries, left: cusp bar system, right: cusp system, for H_{m0}=6m, wave condition 3

8.2.2 Alongshore pattern infragravity band swash

For small wave heights a different pattern is observed for infragravity band swash when a cusp system is compared with a cusp bar system. For a cusp system it can be seen that, as described in section 6.3.2, there is no large difference between the horn and the embayment in the cusp. For a cusp bar system a decreasing trend line is shown, thus the embayment contains larger infragravity band swash compared with the horn. This is also observed in wave height shown in Figure 8-5. It can be seen that a cusp bar system contains a larger wave height in the embayment and smaller wave height at the horns. This indicates that swash is larger at the embayment compared with the horn, which is in agreement with the result of the trend line.

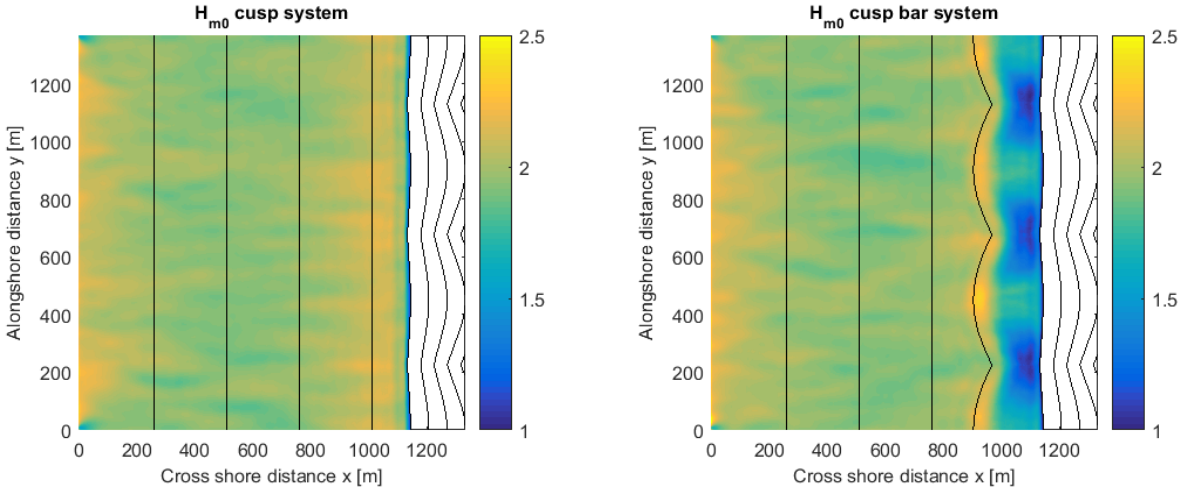

Figure 8-5: H_{m0} for two different bathymetries, left: cusp system, right: cusp bar system, for H_{m0}=2m, wave condition 1

This can also be observed if the wave height is plotted in a cross shore transect for an embayment and a horn. This is shown in Figure 8-6.

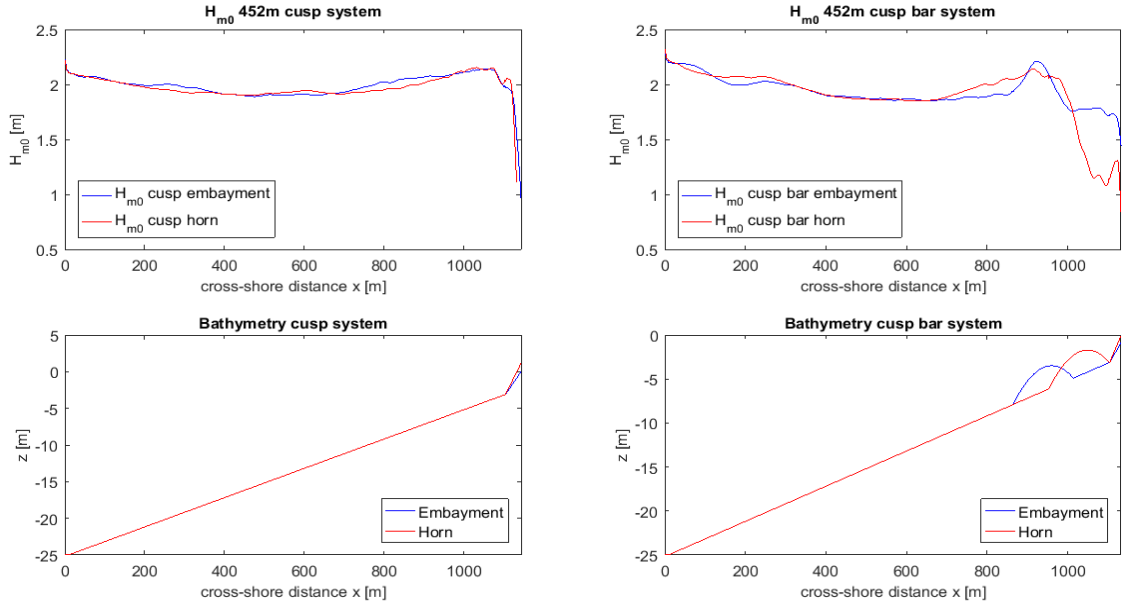

Figure 8-6: H_{m0} and bathymetry, left: cusp system 452m, right: cusp bar system 452m, H_{m0}=2m, wave condition 1

Waves are shoaling in front of the sandbar as can be seen in Figure 8-6 around a cross shore distance of x=820. At a certain moment the waves tend to be too steep and break down. However, the waves are breaking more at a horn, this can be explained by a local higher sandbar. The height of the sandbar is constant relative to a bed without sandbar. Thus, the sandbar is locally higher at a horn compared with an embayment due to the influence of the foreshore slope. At a horn waves are breaking more, which would result in lower waves and thus a lower total swash. Infragravity band swash could be smaller due to this influence compared with a cusp system where waves are breaking with more or less the same degree.

8.3 Waterline at beach

In this section the waterline is shown on the idealized bathymetry. This gives an indication where the waterline is present for certain wave conditions. Furthermore bar plots are shown in which the magnitude of different components of total run-up is represented. The bar plots are given at six location along the central cusp. This does also show the alongshore variation in the magnitude of the components.

8.3.1 Formulation of Stockdon

Formula (2.8) was given in section 2.3, this formula describes the $R_{2\%}$ and is given by Stockdon[2]. Setup and significant swash are two input parameters for this formulation. In Figure 8-7 an overview is given of the waterline at the beach, in which $R_{2\%}$ is plotted and also $R_{2\%}$ given in formula (2.8) based on Stockdon with the parameters setup and significant swash. The top figure shows the waterline, this is plotted versus the alongshore normalized distance of the cusp system. Thus, at 0.5 a horn is present and an embayment is present at 0 and 1.

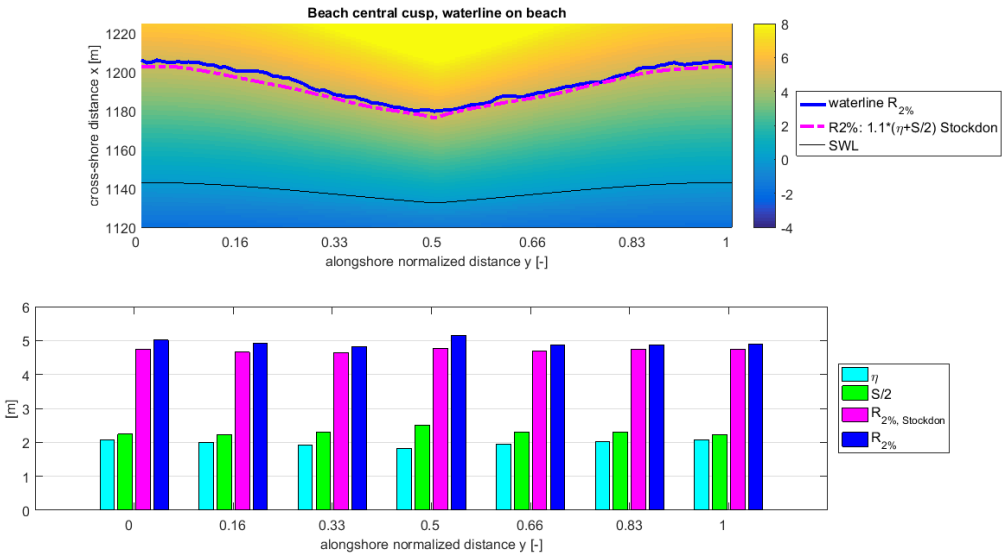

Figure 8-7: overview waterline along beach, $R_{2\%}$ and $R_{2\%}$ formulated by Stockdon. The Alongshore distance is normalized by cusp length of 452m. Bottom figure: total run-up and components, H_{m0}=6m, wave condition 3

The top view shows comparable results for the total run-up calculated from the time series of XBeach and the total run-up calculated by the formulation of Stockdon. A small underestimation is visible for the total run-up formulated by Stockdon, this is also observed in the bar plot. Similar results are obtained if different wave conditions are considered.

8.3.2 Cusp system and cusp bar system

In this section a comparison is made for the cusp system and the cusp bar system considering the waterline on the beach. Furthermore the different components are represented in bar plots along the beach. This is done for a wave height of 2 and 6 metres. Furthermore the offshore crescentic sandbar is not present at the top view, because this is located further offshore.

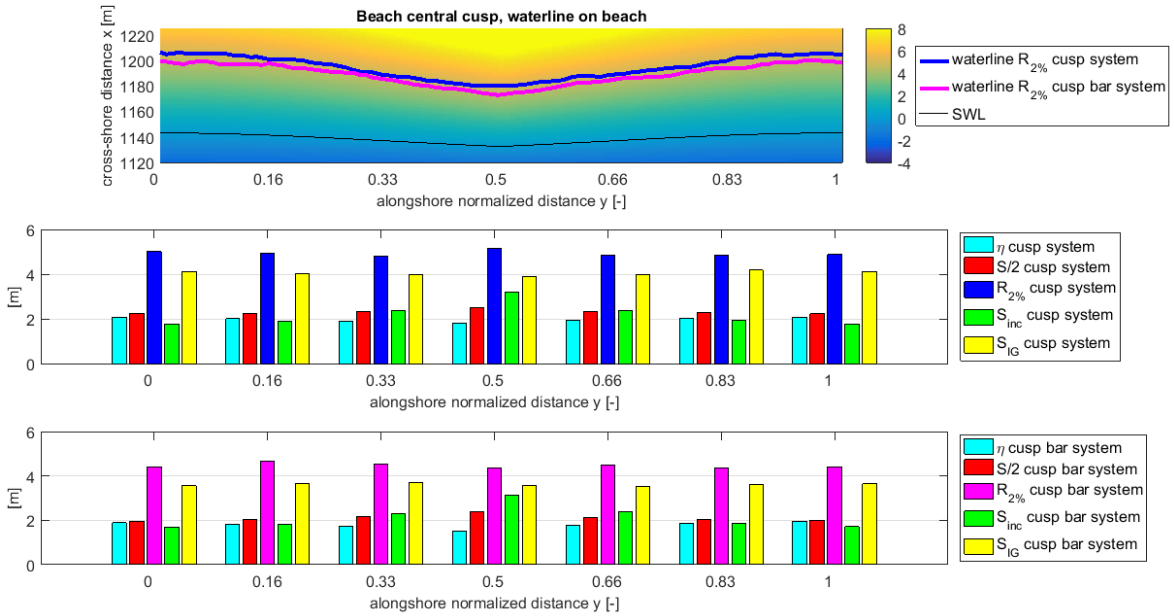

Figure 8-8: top: overview waterline on beach, centre: bar plot of components and total run-up for a cusp system, bottom: bar plot of components and total run-up for a cusp bar system, for H_{m0}=6m, wave condition 3

The waterline on the beach is represented in Figure 8-8 for a wave height of 6 metres. The differences between a cusp system and a cusp bar system can be seen. The waterline is more onshore located for a cusp system compared with a cusp bar system. The cross-shore difference between the waterlines is around 5 to 10 metres. The still water line is also plotted. The cross-shore difference between the total run-up and the still water line is in the range of 44 metres at a horn and 60 metres at an embayment. Furthermore the components of run-up are presented in bar plots. It can be seen that $R_{2\%}$ and incident band swash are larger at a horn compared with the embayment, which was also concluded in section 5.3 and 6.3.

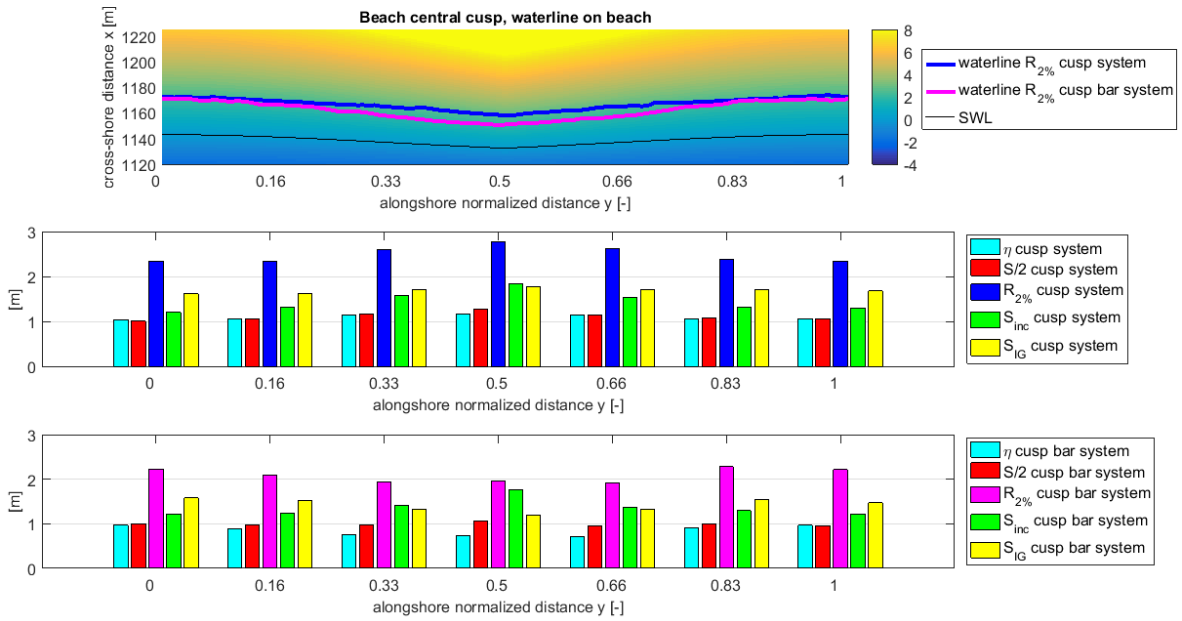

Figure 8-9: top: overview waterline on beach, centre: bar plot of components and total run-up for a cusp system, bottom: bar plot of components and total run-up for a cusp bar system, for H_{m0}=2m, wave condition 1

In Figure 8-9 the waterline is plotted along the beach for a wave height of 2 metres. The waterline shows similar results at an embayment when a cusp system and cusp bar system is compared. However, for a cusp bar system total run-up is smaller at the horn compared with the cusp system. The difference at the embayment and horn is in the range of 2 and 9 metres respectively. The difference with the still water line is in the range of 22 to 30 metres. In the bar plots it can be observed that total run-up behaves different for a cusp system compared with a cusp bar system, which was also concluded in section 5.3 and 6.3. A cusp system shows larger run-up at a horn and lower run-up at an embayment, this is opposite when a cusp bar system is considered. This is also the reason why the difference between the waterlines are larger at a horn compared with the embayment. For large wave height infragravity band swash is dominant compared with incident band swash, which can also be seen in the bar plots in Figure 8-8. However, when small wave heights are considered incident band swash is dominant at a horn. Infragravity band swash is still dominant at an embayment.

9 Discussion

In this chapter the results are discussed in which uncertainties occur or in which not a full analysis is made which results in open questions. First, the uniform bathymetry is discussed. Secondly the cusp systems are discussed and at last a discussion is given of numerical modelling in general.

9.1 Difference in wave breaking, uniform bathymetry and cusp (bar) system

A difference is observed in wave breaking when long-crested waves and non long-crested waves are considered. This was shown in section 8.1. In Figure 8-3 it was concluded that long-crested waves break at the same location in the case of a uniform bathymetry and a cusp system. However, non long-crested waves do not break at the same location when those two bathymetries are considered, this was shown in Figure 8-2. Furthermore a difference in wave height was observed in Figure 8-2 on the offshore boundary while the boundary condition is the same for both bathymetries. There is no analysis made to clarify this difference based on all wave conditions.

For a few wave conditions an analysis is made to check whether reflected waves could have an influence. The wave height was split into an incoming and outgoing wave. However, this did not resolve the problem, because the incoming wave height was more or less equal to the total wave height.

The difference in wave height at the offshore boundary only occurs for waves which contain directional spreading. The uniform bathymetry is modelled with an alongshore width of 100 metres. It could be possible that the model domain is too small and, despite of the cyclic boundary conditions which are used, the model results are influenced by the lateral boundaries. A model simulation is made of the uniform bathymetry of 3x452 metres. This model contains the same alongshore width as the cusp system for a cusp length of 452 metres. In this case also the alongshore averaged H_{m0} is plotted in a cross shore transect, this is shown in Figure 9-1.

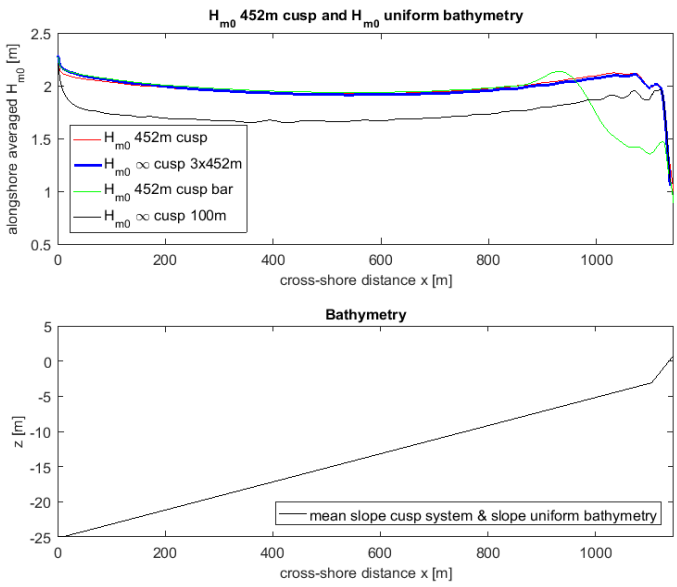

Figure 9-1: alongshore averaged H_{m0} plotted for a cusp system of 452m and for the uniform bathymetry of 100m and 3*452m, H_{m0}=2m, wave condition 1

In this case a wave height of 2 metres is modelled. Alongshore averaged H_{m0} is shown for the uniform bathymetry of 100 metres and 3x452 metres. It is observed that a bathymetry of 100 metres contains a smaller wave height, indicated by the black line. While a bathymetry of 3*452 metres contains a wave height which is similar for the cusp (bar) system, indicated by the blue line. Furthermore wave breaking occurs at the same moment for the uniform bathymetry with a domain of 3x452 metres and the cusp system. This would suggest that the model domain of the uniform bathymetry should be enlarged for non long-crested waves. The same results are obtained if a

wave height of 6 metres is applied.

It was concluded that the uniform bathymetry contains larger alongshore averaged total run-up and also larger alongshore maxima values compared with a cusp (bar) system. This conclusion still holds, because the wave height of the non long-crested waves will be larger for the uniform bathymetry if the model domain is enlarged. This will result in higher values for run-up. However, it is not known how large the difference is between total run-up for a cusp(bar) system and the uniform bathymetry.

9.2 452m and 100m cusp

In the results it can be observed that a cusp of 452 metres gives comparable results with a cusp of 300 metres. These are the cusps which are most common at Anmok Beach. However, the results of a 100 metres cusp contain different results. For instance the alongshore maximum values are larger compared with a 452 metres cusp for different components, described in section 5.2.1. The alongshore averaged values are larger for a 452 metres cusp compared with a 100 metres cusp except for incident band swash. However, the most clear differences are found in the alongshore trend. When trend lines are considered of the behaviour of the different components within a cusp it can be concluded that a 100 metres cusp gives different results as described in section 5.3. For instance a negative trend is shown for a cusp length of 100 metres for total run-up, while a positive trend was observed if a 452 metres cusp is considered. The same hold for infragravity band swash.

The differences could be explained by the formation of edge waves. In section 2.2.1 formula (2.1) is given where the alongshore wave length of edge wave can be calculated depending on the period of edge waves, mode number and the slope of the bed. When sub harmonic waves are considered, waves with twice the wave period of incident waves, it results in length scales in the order of 100 metres. This check is performed for the wave conditions which are applied in this thesis. Thus, when a cusp length of 100 metres is considered it could be that zero mode edge waves are excited. A remark is made that a cusp length of 100 metres is not present at Anmok beach. This could explain the difference between a 452 metres cusp and a 100 metres cusp and the similarities between a 452 metres cusp and a 300 metres cusp. An analysis if edge waves are excited is not made.

9.3 Long-crested waves

In the results long-crested waves are taken into account. Long-crested waves do not contain directional spreading and contain an angle of incidence of 270 degrees. Those waves give some larger values for $R_{2\%}$, setup and swash, this can also be seen in section 5.2.2. However, in practise these waves are not present, wave do contain some directional spreading. The long-crested waves are taken into account to see what kind of patterns occurred.

9.4 Model

All the model simulations are performed in XBeach in which a non-hydrostatic mode is used. In this case all the waves are resolved in the model. An idealized bathymetry is used in the model. However, in practise this bathymetry is not present at Anmok Beach. An idealized bathymetry is used to make conclusion about the relation between cusp characteristics and run-up on the beach, in this way influences from for instance irregular cusps formation are excluded.

In this thesis a sensitivity analysis is made on two different cusp systems, a constant sloped cusp system and a varying sloped cusp system. This is described in Appendix VI . From this analysis it was decided to use a varying sloped cusp system, based on the comparison of the measured bathymetry

in the survey of 2008. When a varying sloped cusp system is used a sharp gradient is present in the bathymetry at the location of the horn. This is also visible in Figure VI-2. In nature this sharp gradient is not present at a horn.

The sharp gradient in the bathymetry can be avoided by adding extra harmonics; in this case a smooth transition is present at the horn instead of a sharp gradient. An analysis is made to get insight in the influence of this sharp gradient. This is described in Appendix IX . It was concluded that the influence on total run-up is negligible. However, for setup a local downward peak was seen at the location of the horn. If extra harmonics are added this downward peak is not present.

It is mentioned that a cusp length of 100 metres is more sensitive to this sharp gradient compared with a cusp length of 452 metres. The reason is that the slope has to change on a smaller alongshore length compared with a cusp length of 452 metres. Though it does not have a major influence on total run-up, thus the results are useful when a bathymetry is used with a sharp gradient.

Furthermore the model is not updated with bed morphology. Contrarily in nature the waves will have an impact on bed morphology. Conclusions about cusp characteristics and total run-up cannot be made if the cusp characteristics are changing due to for instance a varying bed. It is for this reason why only hydrodynamic conditions are analysed in this MSc thesis without a bed update.

10 Conclusion

In this chapter an answer is given on the research questions which are described in section 1.1.2. Each sub question will be repeated following with an answer; finally the main research question will be answered.

What is a useful definition of significant alongshore variance in wave run-up?

It can be concluded that wave height and steepness are the two dominant parameters which influence the results of the $R_{2\%}$, setup and swash components. A wave height of 2 meters gives lower values for run-up compared to a wave height of 6 metres. Furthermore when waves with a steepness of 1% are considered the magnitude is larger compared with waves which contain a steepness of 3%. A change in the angle of incidence, from 270 to 290 degrees, gives slightly larger values for an angle of 270 degrees. This holds for long crested waves without directional spreading. No clear pattern can be observed when a difference is applied in frequency spreading and directional spreading.

From the $R_{2\%}$, setup and swash the standard deviation in alongshore direction is calculated. This resulted in 60 definitions of the variance in alongshore direction for $R_{2\%}$, setup, swash, infragravity band swash and incident band swash. These numbers are the reference situation, used for comparison when the same calculations are made for other bathymetries, for instance a bathymetry with beach cusps or a cusp bar system. The normalized standard deviation ranges between 0.17% and 4.61% for $R_{2\%}$, between 0.02% and 2.04% for setup, between 0.037% and 1.89% for swash, between 0.05% and 2.32% for infragravity band swash and between 0.06% and 3.35% for incident band swash.

When the boxplots are analysed it can be seen that the normalized standard deviation is even lower compared to the noise obtained from the selection of 500 waves out of a model simulation of 24 hours. However, small differences can be found when a wave height of 2, 4 and 6 metres are compared. The normalized standard deviation decreases when the wave height increases. When the steepness increases from 1% to 3% the normalized standard deviation increases. The same holds when the angle of incidence increases from 270 degrees to 290 degrees. Frequency spreading did not show differences. Finally the parameter directional spreading did not show large differences when waves contain some directional spreading. The normalized standard deviation is slightly lower if long-crested waves are considered for setup, swash components and total run-up.

How does the magnitude and the alongshore variance in wave run-up vary relative to cusp characteristics and are there any dependencies visible?

Similar alongshore mean values are found for total run-up and the components of run-up when a cusp length of 452 metres and a cusp length of 300 metres are considered. Infragravity band swash is one of the largest components of total run-up. The same holds for the alongshore maximum values of a cusp system. Small differences can be found for a cusp of 100 metres, which could be present due to edge waves. Furthermore, it can be concluded that a uniform bathymetry contains similar values for total run-up. This holds for the alongshore averaged run-up and for the alongshore maximum of total run-up considering long-crested waves. For non long-crested waves alongshore maximum total run-up is 11.3% lower for a cusp system compared with the uniform bathymetry.

This percentage could be different due to the influence of the lateral boundaries on the model results of the uniform bathymetry.

The magnitude of total run-up is lower for waves which contain a steepness of 3% and the magnitude is larger for waves with a steepness of 1%. Furthermore if the wave height increases also the magnitude increases. The uniform bathymetry contains larger values for non long-crested waves, which is especially the case for large wave heights compared with small wave heights. However, the results of the uniform bathymetry can be influenced by the lateral boundaries for non long-crested waves. Moreover, it is concluded that long-crested waves give comparable results for the magnitude in total run-up. This does not depend on cusp characteristics but on the wave conditions.

When different components of run-up are considered the alongshore variance gives different results when small waves and large waves are compared. However, for total run-up it is concluded that this will be larger at a horn compared with the embayment for a cusp length of 452 metres. A cusp length of 300 metres shows similar results. This holds for small wave heights and large wave heights, the difference is 18% and 8.4% respectively. Less variation along the cusp can be seen when waves are considered with a steepness of 3%.

The pattern is different for a cusp of 100 metres. Large waves show opposite behaviour, thus at a horn total run-up is 15.5% smaller compared with the embayment. This behaviour reverses for small wave heights, in this case the horn contains 2.22% larger run-up compared with the embayment. Furthermore it is observed that the alongshore variance remains equal for both wave steepnesses, which is not the case when a 452 metres cusp is considered. It can be said that a larger wave height contains a larger alongshore variance compared with smaller wave heights; this is not valid for a 452 metres cusp.

For the beach cusps system it can be seen that the normalized standard deviation is larger compared with the normalized standard deviation of a uniform bathymetry. This results in a larger alongshore variance for run-up at a beach cusp system.

How does the magnitude and the alongshore variance in wave run-up vary on bar characteristics in combination with cusp characteristics and is this different from that found for question 2?

It is concluded that the magnitude of the alongshore mean values of total run-up are smaller for a cusp bar system compared with a cusp system of 452 metres. This holds also for the components of run-up. The same conclusion is drawn when alongshore maximum values of total run-up are taken into account. On average the alongshore maximum of total run-up is 15.8% smaller for a cusp bar system compared with a cusp system. Furthermore, it is concluded that the magnitude of total run-up is smaller for a cusp bar system compared with the uniform bathymetry. This holds for both the alongshore mean values and the alongshore maximum values of run-up. The alongshore maximum of total run-up is 25.7% smaller compared to the uniform bathymetry. A remark is made that this percentage could be different due to the influence of the lateral boundary conditions on the uniform bathymetry.

The same conclusion is drawn for a cusp system. The magnitude of total run-up is lower for waves which contain a steepness of 3% and the magnitude is larger for waves with a steepness of 1%. Furthermore as the wave height increases also the magnitude increases. The uniform bathymetry

contains larger magnitude for run-up, which is especially the case for large wave heights compared with small wave heights. This holds for non long-crested waves. Moreover, it can be concluded that the magnitude for total run-up from long-crested waves is smaller for a cusp bar system compared with the uniform bathymetry. This is a difference with the cusp system which gave comparable results. However, the magnitude of total run-up from non long-crested waves is even lower for a cusp bar system compared with the uniform bathymetry. This does not depend on cusp characteristics but on the wave conditions. A remark is made that the non long-crested waves are influenced by the lateral boundary conditions on the uniform bathymetry.

For a cusp system it can be seen that total run-up is lower in the embayment and larger at the horn, this holds for small wave heights and large wave heights. However, this pattern is different for a cusp bar system. A lower run-up in the embayment is only observed for large wave heights. A difference of 3.68% is seen when the horn is compared with the embayment. When the wave height decreases the pattern gives an opposite behaviour. Therefor 10.5% smaller run-up is observed at a horn compared with an embayment for small wave heights. For large wave heights the variance along a cusp decreases if the steepness increases. Whereas it can be seen that for smaller wave heights the variance along a cusp increases if the steepness increases. This pattern is not observed for a cusp system, it was shown that the variance along a cusp decreases for large and smaller wave heights. Moreover, the variance between a horn and embayment is less for a cusp bar system compared with a cusp system.

Also a cusp bar system consist larger normalized standard deviation compared with the uniform bathymetry. This indicates a larger alongshore variance in run-up and components for a cusp bar system.

The sub research questions have been answered. The main research question is answered below.

Do cusps and bar morphology significantly affect alongshore variation in wave run-up on intermediate, rhythmic bar and beach state, beaches?

First of all, the magnitude of run-up is similar when a comparison is made between a cusp system and the uniform bathymetry if long crested waves are considered. A cusp bar system result in lower values compared with the uniform bathymetry for long-crested waves. Non long-crested waves give lower values for run-up at a cusp (bar) system compared with the uniform bathymetry. When a cusp system is considered, it can be seen that the magnitude of run-up is different in a horn and in an embayment. Thus, alongshore variation is present due to an alongshore varying slope. At a horn run-up is larger compared with an embayment. If each component of run-up is analysed it contains alongshore variation when a cusp bar system is considered. However, if all the components are combined for total run-up it is shown that there is less variation along a cusp compared with a cusp system. The normalized standard deviation contains similar values for a cusp bar system compared with a cusp system. Thus, a cusp bar system and cusp system do affect the alongshore variation in wave run-up on intermediate, rhythmic bar and beach state, beaches.

11 Recommendations

In this chapter further recommendation are mentioned for this research in bullet points.

- To give more accurate results it is recommended to model more than 500 waves. For this thesis 500 waves are chosen from a model run of 24 hours which include an error of 7.5% with a 95% confidence interval. However, this can be improved by modelling more than 500 waves. The downside of this is a longer computational time.
- The results contain differences between a 452 metres cusp and a 100 metres cusp. Edge waves could be excited for a cusp length of 100 metres. It is not known whether edge waves are present in the model. Further analysis is needed to determine if the results are influenced by the presence of edge waves.
- The uniform bathymetry is generated with an alongshore distance of 100 metres using cyclic boundary conditions. With an alongshore grid resolution of dy = 2 metres. In the case of a cusp system, in total three cusps are modelled next to each other and the central cusp is analysed. For the cusps an alongshore resolution of dy = 4 metres is used which reduced the computational time. This results in only 25 data points available for a 100 metres cusp. When dy = 2 metres is taken it result in 50 data points for a 100 metres cusp, which gives a more accurate analysis of the data.
- Furthermore it is recommended to use the same alongshore distance for the uniform bathymetry compared with the cusp systems. Thus, when the 452 metres cusp is compared with the uniform bathymetry, a uniform bathymetry of 3*452 metres should be used. More space is created to generate edge waves when the alongshore length is increased of the model domain.
- Moreover, influences of lateral boundaries are excluded from the model results if the central part of the model domain is analysed when the model domain is large enough. The results of the uniform bathymetry are based on a model with an alongshore width of 100 metres. Most likely the results are influenced by the lateral boundary which is described in the discussion. It is recommended to model the wave conditions again with an alongshore width of 3*452 metres.
- In this thesis only one cusp bar system is modelled for a cusp length of 452 metres. It is recommended to model also crescentic sandbars in the case of a cusp length of 300 and 100 metres. Furthermore multiple bar characteristics can be varied to get insight in the influence of the crescentic sandbar on total run-up.

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13 Appendix

Appendix I Run-up points

The water level time series at the waterline is analysed, a filter is applied on this data. Certain points are selected as run-up points and other points are ignored. How this works is explained in this appendix.

A representative wave period is given as input, which is equal to $T_{m-1,0}$ in XBeach, a spectral wave period. Furthermore the water level time series at the waterline is given as input. From this data the extreme values are selected. These are the local maxima in the time series. The local maxima are stored together with the index number of those values.

From this moment all the local maxima are analysed in the time series. The question is whether the local maximum is a run-up candidate and whether it will be saved as a run-up candidate. The goal of this question is to filter all the local maxima. The following requirements hold:

The first point of the data, named: point A, is a possible run-up candidate. Thereafter the next local maximum is analysed. This is point B. A first condition will be applied on point B:

1. Is point B larger than still water level (SWL)?

If yes, than the next two conditions are applied:

2. Is the time value which belongs to point B larger or equal to the time value belonging to the previous run-up candidate (in this case point A) plus half the representative wave period?
3. OR is the minimum value from the data of the water level elevation smaller than SWL in the interval from the previous run-up candidate (point A) until and including with the present point B?

If requirement 2 or 3 holds than the previous run-up candidate (in this case point A) is stored as a first run-up point.

Subsequently the next local maximum is analysed, which is point C. the requirements starts again at rule number one. So is this point larger than 0? If yes an analysis is performed whether this point is located outside half the representative wave period in comparison with the previous point OR if the minimum value from the data of the water level elevation (with the interval: the previous run-up candidate until and including with point C) is smaller than 0. The previous run-up candidate will be stored as a run-up point if this is the case. If not: an analysis is performed whether point C is larger compared with the previous run-up point. If yes: point C will be seen as a new run-up candidate.

Thereafter the analysis starts over again for an analysis of the next local maxima, point D will be analysed etc.

For example a figure is included which gives the run-up points of the first 200 seconds from a water level elevation time series measured at the waterline. This can be seen in Figure I-1. The run-up points are marked with a green + and surrounded with a red circle. The local maxima which are deleted are only marked with a green +. The horizontal magenta line is the mean water level. The

SWL is located at 0 metres. It can be seen that no run-up points are marked below SWL, which is in agreement with the conditions described above.

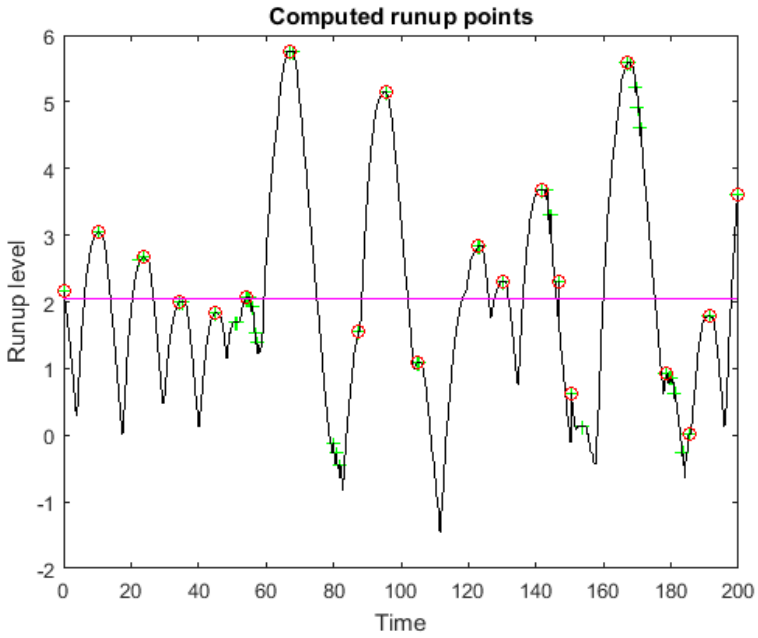

Figure I-1: run-up points are marked with a green + surrounded by a red circle and local maxima which are erased are marked with a green +

With those rules all local maxima are analysed, resulting in run-up points and points which are erased due to filtering. The run-up points will be stored, ready for a new statistical analysis.

Appendix II Wave conditions

An overview is given of all modelled wave conditions, generated by varying five parameters, which are: wave height, steepness, angle of incidence, frequency spreading and directional spreading. This is shown in Table II-1.

Model simulation	Waveheight [m]	Steepness [-]	Period [sec]	Mainangle [deg]	gamma_jsp [-]	s [-]	Duration [sec]	dbtc
1	2	0,01	11,32	270	1	4	6159	1
2	4	0,01	16,01	270	1	4	8503	1
3	6	0,01	19,60	270	1	4	10302	1
4	4	0,03	9,24	270	1	4	5121	1
5	6	0,03	11,32	270	1	4	6159	1
6	2	0,01	11,32	290	1	4	6159	1
7	4	0,01	16,01	290	1	4	8503	1
8	6	0,01	19,60	290	1	4	10302	1
9	4	0,03	9,24	290	1	4	5121	1
10	6	0,03	11,32	290	1	4	6159	1
11	2	0,01	11,32	270	3,3	4	6159	1
12	4	0,01	16,01	270	3,3	4	8503	1
13	6	0,01	19,60	270	3,3	4	10302	1
14	4	0,03	9,24	270	3,3	4	5121	1
15	6	0,03	11,32	270	3,3	4	6159	1
16	2	0,01	11,32	290	3,3	4	6159	1
17	4	0,01	16,01	290	3,3	4	8503	1
18	6	0,01	19,60	290	3,3	4	10302	1
19	4	0,03	9,24	290	3,3	4	5121	1
20	6	0,03	11,32	290	3,3	4	6159	1
21	2	0,01	11,32	270	1	20	6159	1
22	4	0,01	16,01	270	1	20	8503	1
23	6	0,01	19,60	270	1	20	10302	1
24	4	0,03	9,24	270	1	20	5121	1
25	6	0,03	11,32	270	1	20	6159	1
26	2	0,01	11,32	290	1	20	6159	1
27	4	0,01	16,01	290	1	20	8503	1
28	6	0,01	19,60	290	1	20	10302	1
29	4	0,03	9,24	290	1	20	5121	1
30	6	0,03	11,32	290	1	20	6159	1
31	2	0,01	11,32	270	3,3	20	6159	1
32	4	0,01	16,01	270	3,3	20	8503	1
33	6	0,01	19,60	270	3,3	20	10302	1
34	4	0,03	9,24	270	3,3	20	5121	1
35	6	0,03	11,32	270	3,3	20	6159	1
36	2	0,01	11,32	290	3,3	20	6159	1
37	4	0,01	16,01	290	3,3	20	8503	1
38	6	0,01	19,60	290	3,3	20	10302	1
39	4	0,03	9,24	290	3,3	20	5121	1

40	6	0,03	11,32	290	3,3	20	6159	1
41	2	0,01	11,32	270	1	2000	6159	1
42	4	0,01	16,01	270	1	2000	8503	1
43	6	0,01	19,60	270	1	2000	10302	1
44	4	0,03	9,24	270	1	2000	5121	1
45	6	0,03	11,32	270	1	2000	6159	1
46	2	0,01	11,32	290	1	2000	6159	1
47	4	0,01	16,01	290	1	2000	8503	1
48	6	0,01	19,60	290	1	2000	10302	1
49	4	0,03	9,24	290	1	2000	5121	1
50	6	0,03	11,32	290	1	2000	6159	1
51	2	0,01	11,32	270	3,3	2000	6159	1
52	4	0,01	16,01	270	3,3	2000	8503	1
53	6	0,01	19,60	270	3,3	2000	10302	1
54	4	0,03	9,24	270	3,3	2000	5121	1
55	6	0,03	11,32	270	3,3	2000	6159	1
56	2	0,01	11,32	290	3,3	2000	6159	1
57	4	0,01	16,01	290	3,3	2000	8503	1
58	6	0,01	19,60	290	3,3	2000	10302	1
59	4	0,03	9,24	290	3,3	2000	5121	1
60	6	0,03	11,32	290	3,3	2000	6159	1

Table II-1: overview modelled wave conditions, generated by varying five parameters

Appendix III Mean values run-up and components uniform bathymetry

The mean of $R_{2\%}$, setup and swash components in alongshore direction is shown in Table III-1 for the uniform bathymetry considering 60 model simulations.

Model simulation	Mean $R_{2\%}$ [m]	Mean setup [m]	Mean swash [m]	Mean infragravity band swash [m]	Mean incident band swash [m]
1	2,95	1,11	0,66	0,54	0,38
2	5,23	1,91	1,29	1,19	0,48
3	7,15	2,46	1,73	1,64	0,56
4	3,19	1,13	0,78	0,66	0,41
5	4,94	1,61	1,27	1,18	0,45
6	2,69	1,06	0,61	0,48	0,38
7	5,91	1,89	1,36	1,27	0,48
8	7,50	2,52	1,75	1,67	0,54
9	3,02	1,17	0,74	0,62	0,40
10	4,91	1,61	1,24	1,15	0,45
11	2,66	1,11	0,61	0,49	0,37
12	5,23	1,86	1,22	1,11	0,49
13	7,19	2,50	1,67	1,58	0,55
14	3,31	1,16	0,81	0,71	0,38
15	5,03	1,61	1,31	1,24	0,41
16	2,62	1,08	0,59	0,47	0,36
17	5,13	1,84	1,21	1,11	0,48
18	7,10	2,46	1,68	1,59	0,54
19	3,11	1,15	0,77	0,67	0,38
20	5,06	1,57	1,29	1,22	0,42
21	3,04	1,19	0,69	0,57	0,40
22	5,93	1,97	1,38	1,29	0,49
23	7,31	2,52	1,75	1,66	0,54
24	3,87	1,31	0,97	0,86	0,44
25	5,28	1,70	1,33	1,23	0,50
26	2,86	1,15	0,66	0,53	0,38
27	5,35	1,88	1,26	1,16	0,50
28	7,21	2,54	1,77	1,69	0,53
29	3,24	1,18	0,83	0,72	0,42
30	5,45	1,68	1,29	1,21	0,45
31	3,10	1,18	0,70	0,60	0,36
32	5,67	1,94	1,33	1,25	0,47
33	7,39	2,50	1,71	1,62	0,54
34	3,63	1,25	0,92	0,81	0,42
35	5,84	1,81	1,42	1,34	0,47
36	2,89	1,18	0,62	0,52	0,35
37	5,35	1,87	1,26	1,16	0,47
38	6,82	2,43	1,61	1,51	0,56

39	3,21	1,15	0,82	0,72	0,38
40	5,22	1,66	1,36	1,27	0,47
41	3,25	1,26	0,74	0,62	0,41
42	5,49	2,03	1,28	1,17	0,52
43	6,97	2,55	1,68	1,58	0,57
44	4,10	1,44	0,99	0,89	0,44
45	5,81	1,95	1,47	1,39	0,47
46	3,08	1,17	0,71	0,60	0,39
47	5,02	1,88	1,23	1,12	0,50
48	7,20	2,58	1,77	1,68	0,55
49	3,24	1,24	0,84	0,73	0,42
50	4,83	1,66	1,23	1,15	0,45
51	3,18	1,22	0,70	0,59	0,38
52	5,34	1,92	1,22	1,13	0,48
53	6,92	2,51	1,76	1,68	0,55
54	3,76	1,38	0,94	0,85	0,41
55	5,32	1,80	1,38	1,31	0,43
56	2,97	1,17	0,66	0,55	0,37
57	4,97	1,85	1,19	1,09	0,49
58	6,56	2,45	1,68	1,59	0,56
59	3,35	1,17	0,84	0,74	0,39
60	5,23	1,67	1,30	1,22	0,44

Table III-1: results of the 60 model simulations, mean of $R_{2\%}$, setup and swash components for uniform bathymetry

Appendix IV Normalized standard deviation uniform bathymetry

In Table IV-1 the normalized values of the standard deviation in alongshore direction for $R_{2\%}$, setup and swash components is shown.

Calculation number	$R_{2\%}$	Setup	Swash	Infragravity swash	Incident swash
1	1,57	0,66	0,62	0,74	1,41
2	1,51	0,47	0,58	0,76	0,60
3	0,93	0,46	0,23	0,30	0,44
4	2,23	0,92	0,84	1,50	2,36
5	1,75	0,72	0,24	0,30	0,61
6	1,81	0,45	0,80	1,13	1,34
7	1,54	0,57	0,42	0,49	0,48
8	1,09	0,41	0,55	0,63	0,55
9	3,27	0,81	1,31	1,32	1,46
10	0,97	0,57	1,06	1,35	1,38
11	3,01	0,99	1,12	1,53	0,96
12	1,95	0,29	0,68	0,81	0,38
13	1,52	0,22	0,16	0,19	0,38
14	4,61	0,90	1,54	2,03	0,67
15	1,85	0,45	0,35	0,45	0,94
16	1,30	0,62	0,39	0,55	0,74
17	2,15	0,62	0,56	0,75	0,63
18	1,21	0,35	0,28	0,33	0,32
19	3,74	0,63	0,74	1,16	1,02
20	3,45	0,55	0,30	0,22	2,16
21	1,53	0,18	1,43	1,55	2,50
22	0,64	0,29	0,34	0,39	0,27
23	0,99	0,68	0,11	0,11	0,54
24	1,67	0,37	1,09	1,68	1,82
25	2,01	0,97	0,99	1,16	1,21
26	1,18	0,20	1,22	0,95	2,35
27	2,37	0,45	1,04	1,15	0,70
28	1,43	0,25	0,40	0,41	0,62
29	2,81	0,80	0,76	1,09	2,49
30	2,68	0,83	0,49	0,61	0,98
31	1,09	0,68	0,69	0,84	0,80
32	1,60	0,20	0,49	0,58	0,35
33	0,73	0,39	0,14	0,15	0,21
34	2,76	2,04	1,89	2,32	0,90
35	1,14	0,69	0,20	0,20	1,13
36	2,24	0,34	1,03	1,02	1,32
37	1,52	0,35	0,25	0,27	0,47
38	0,31	0,25	0,19	0,21	0,20
39	1,97	0,47	0,89	1,06	1,03
40	2,22	0,50	0,56	0,67	0,61

41	0,21	0,02	0,04	0,06	0,06
42	0,34	0,06	0,04	0,05	0,09
43	0,26	0,07	0,06	0,07	0,11
44	0,41	0,12	0,12	0,15	0,10
45	0,58	0,29	0,18	0,20	0,11
46	1,20	0,42	0,81	0,87	1,04
47	1,35	0,44	0,29	0,37	0,49
48	1,84	0,27	0,47	0,52	0,53
49	2,19	0,34	0,88	1,12	3,35
50	1,20	0,46	0,28	0,29	0,87
51	0,17	0,05	0,09	0,10	0,10
52	0,51	0,07	0,06	0,08	0,12
53	0,32	0,05	0,08	0,08	0,09
54	0,25	0,11	0,17	0,18	0,25
55	0,51	0,18	0,12	0,14	0,13
56	1,03	0,64	0,77	0,88	1,32
57	1,51	0,75	0,60	0,72	0,48
58	0,77	0,67	0,08	0,11	0,25
59	1,48	0,36	0,89	1,25	1,30
60	2,36	0,74	0,68	0,73	1,14

Table IV-1: normalized values of the standard deviation in alongshore direction for $R_{2\%}$, setup and swash components

Appendix V Plots mean values uniform bathymetry

Mean values of $R_{2\%}$ are shown in scatterplots for all possible wave conditions in Figure V-1.

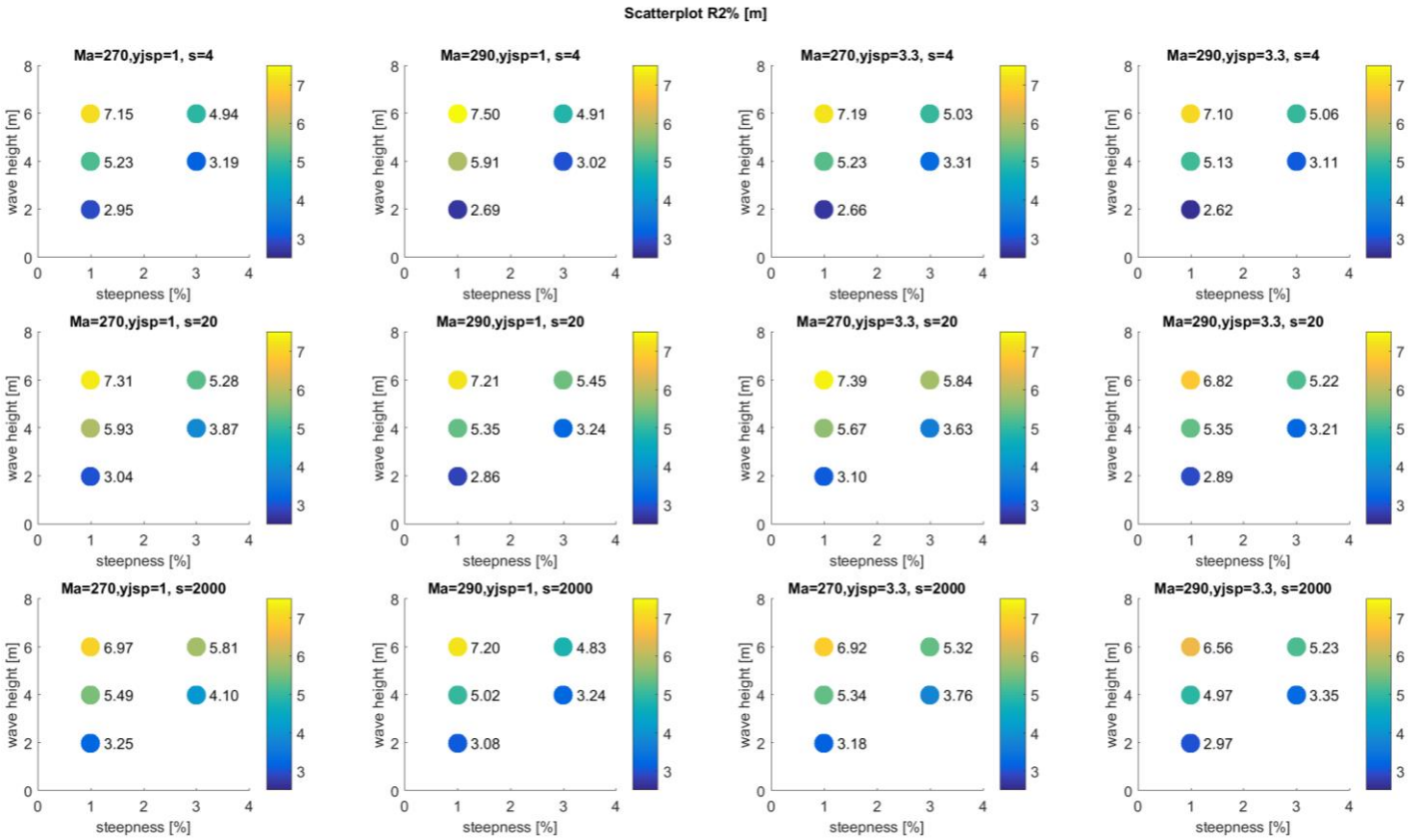

Figure V-1: mean values $R_{2\%}$ for all wave conditions, uniform bathymetry

Mean values of setup are shown in scatterplots for all possible wave conditions in Figure V-2.

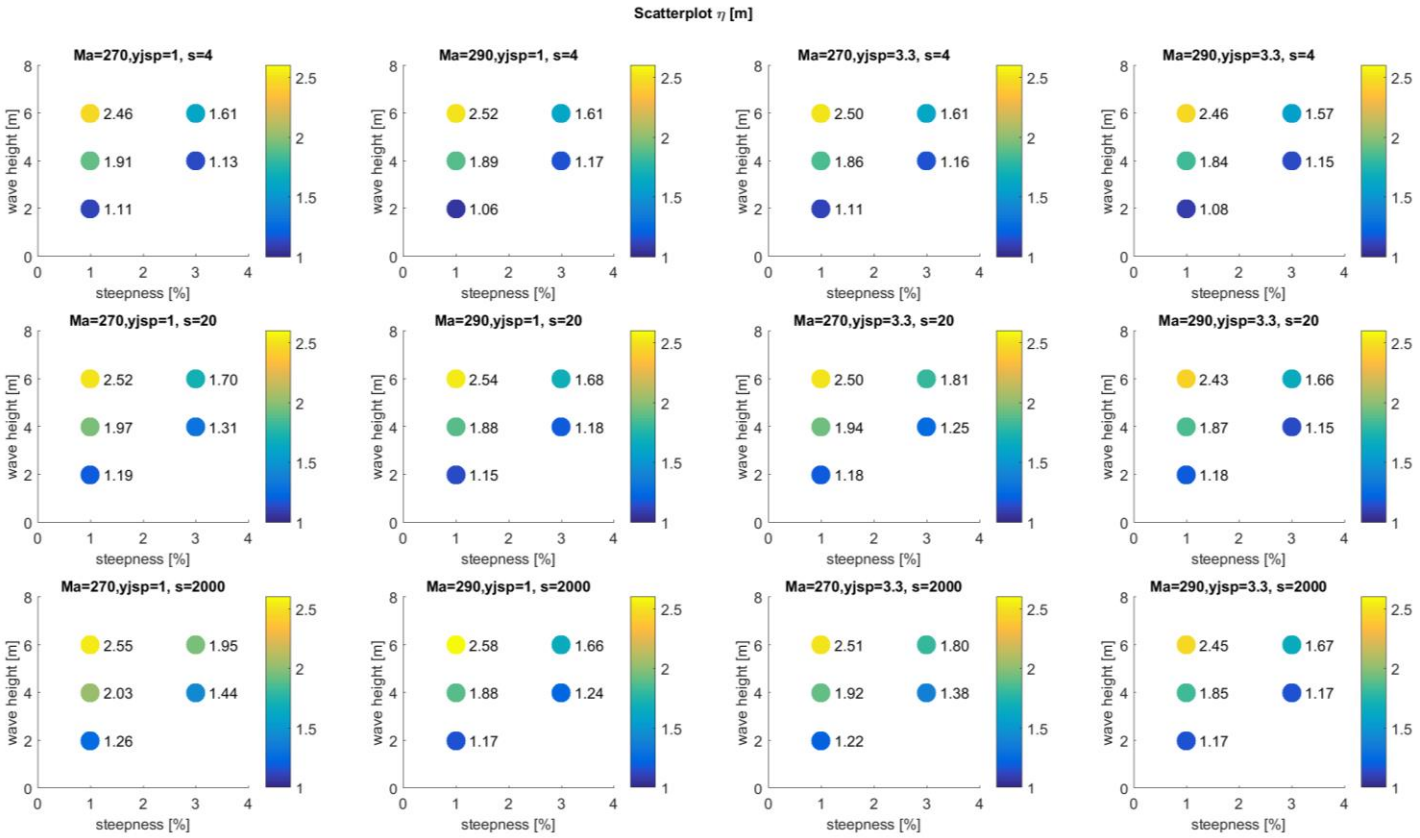

Figure V-2: mean values setup for all wave conditions, uniform bathymetry

Mean values of swash are shown in scatterplots for all possible wave conditions in Figure V-3.

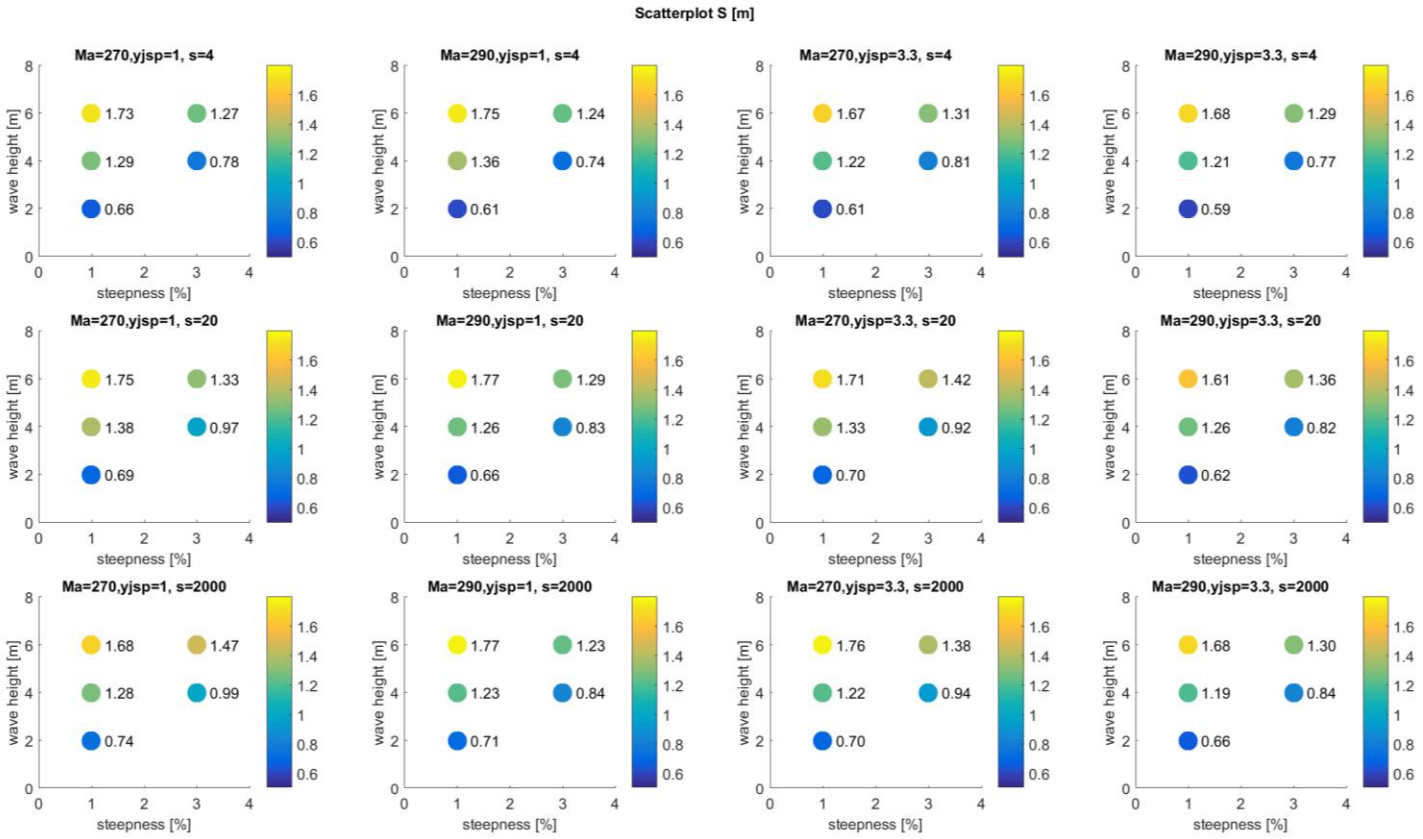

Figure V-3: mean values swash for all wave conditions, uniform bathymetry

Mean values of infragravity band swash are shown in scatterplots for all possible wave conditions in Figure V-4.

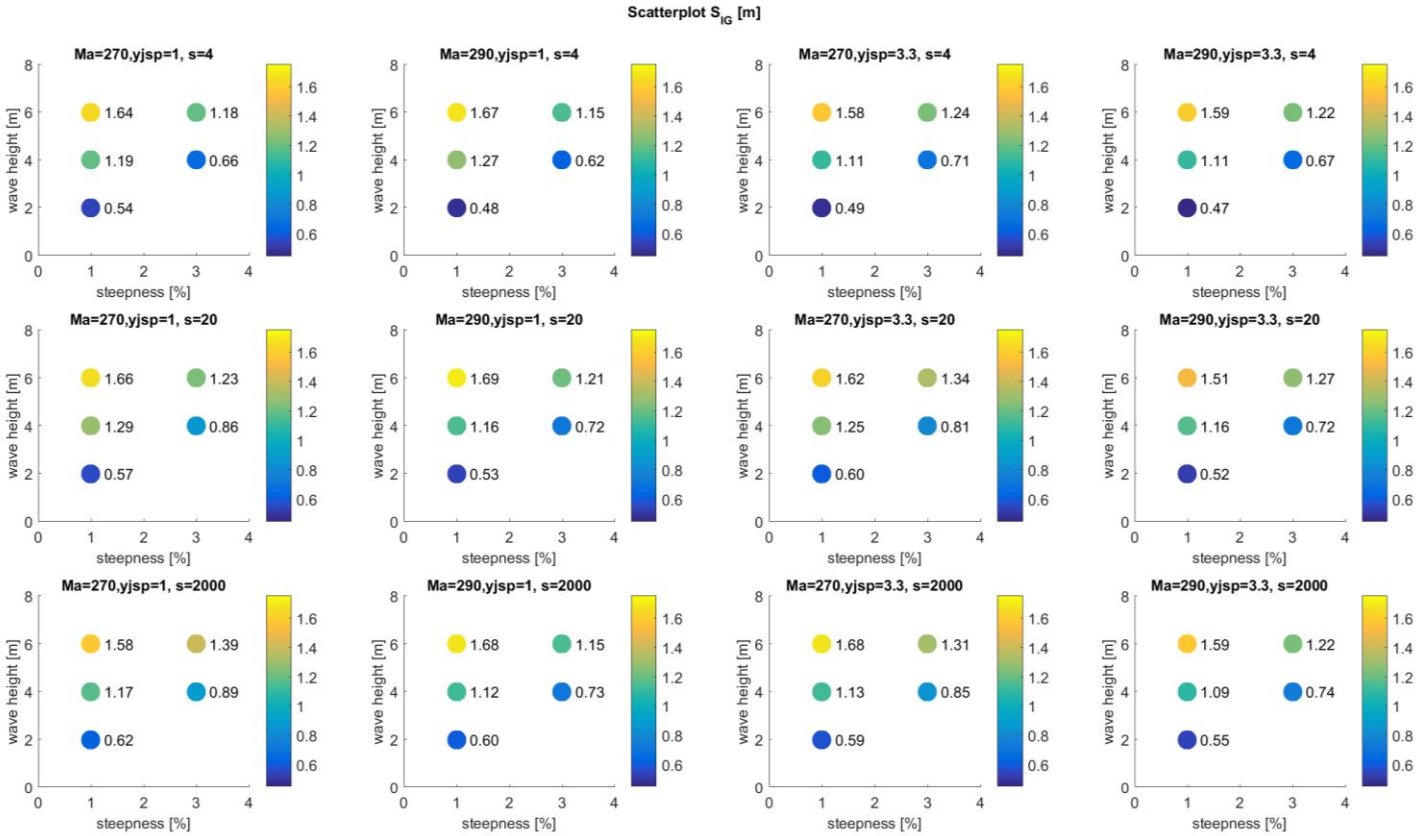

Figure V-4: mean values infragravity band swash for all wave conditions, uniform bathymetry

Mean values of incident band swash are shown in scatterplots for all possible wave conditions in Figure V-5.

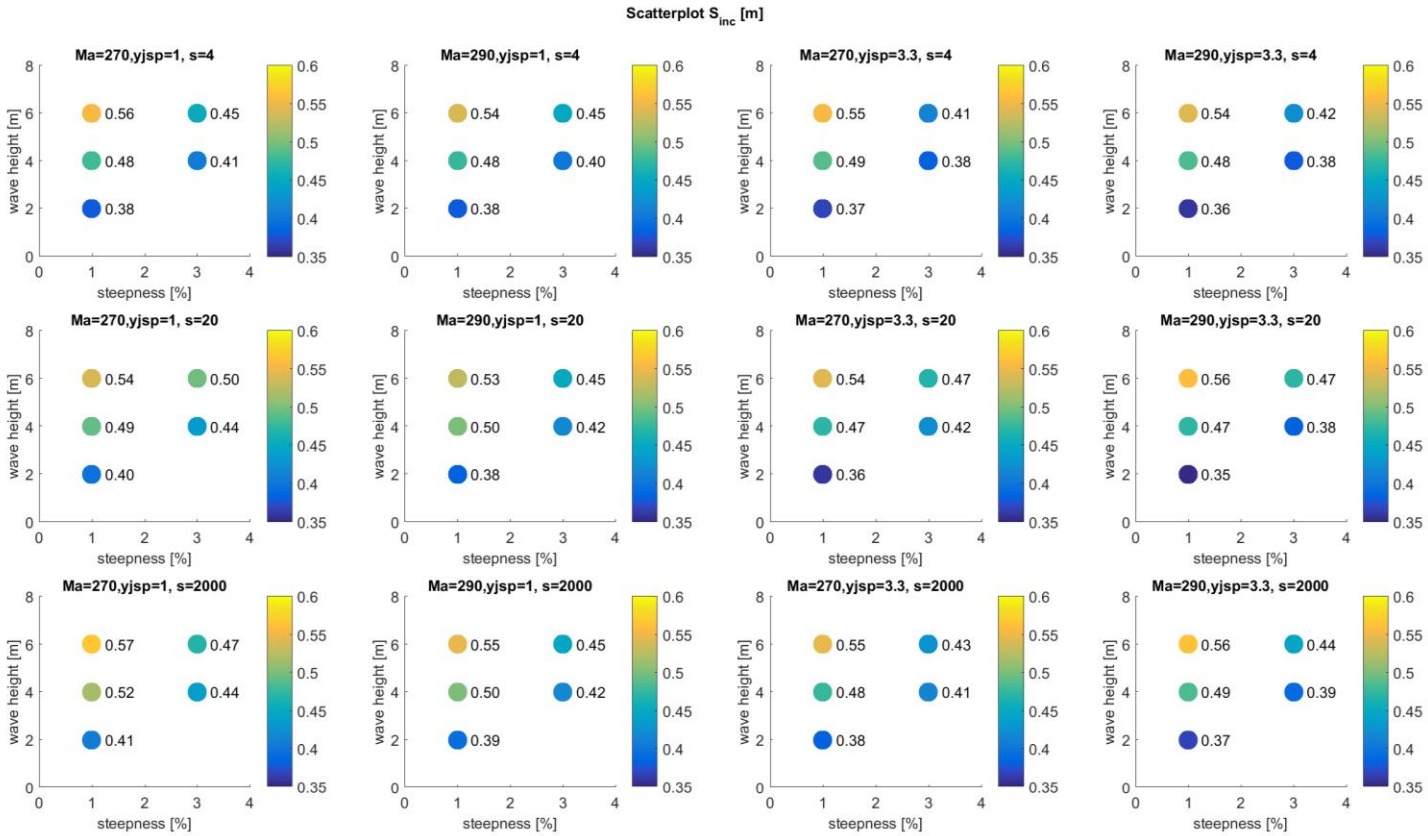

Figure V-5: mean values incident band swash for all wave conditions, uniform bathymetry

Appendix VI Idealized bathymetry

The idealised bathymetry is generated with formulas in Matlab. This can be done with two different methods. The two methods are described in this section and both methods are compared with the survey of the bathymetry which was made in 2008.

Appendix VI-i Method 1: constant sloped cusps

In this method the constant sloped cusps are described (CS cusps). With this method the point where the beach cusps start in cross shore direction varies with an absolute cosine function in alongshore direction. The slope of the beach cusps will be kept constant. The disadvantage of this method is the constant slope of the beach cusps. The horn and embayment contains the same slope in this case. To illustrate how the beach cusps are generated with this method a plot of the cusps is shown in Figure VI-1.

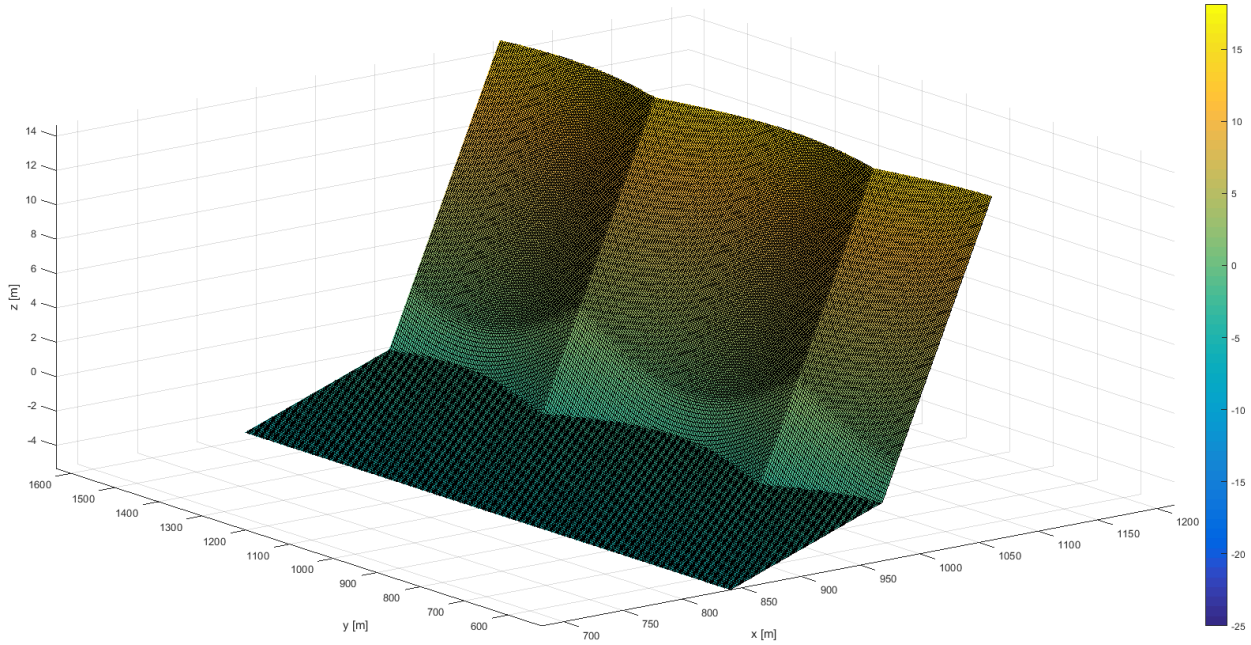

Figure VI-1: constant sloped cusps, starting point of beach cusps varies with an absolute cosine function in alongshore direction

Appendix VI-ii Method 2: varying sloped cusps (VS cusps)

In this method the varying sloped cusps are described (VS cusps). With this method the beach cusps start at the same point in cross shore direction, while the slope of the beach cusps varies with an absolute cosine function in alongshore direction. Thus, in this case the starting point of the cusps in a cross shore transect will be kept constant in alongshore direction. The slope varies for an embayment and horn, which is an advantage. To illustrate how the beach cusps are generated with this method a plot of the cusps is shown in Figure VI-2.

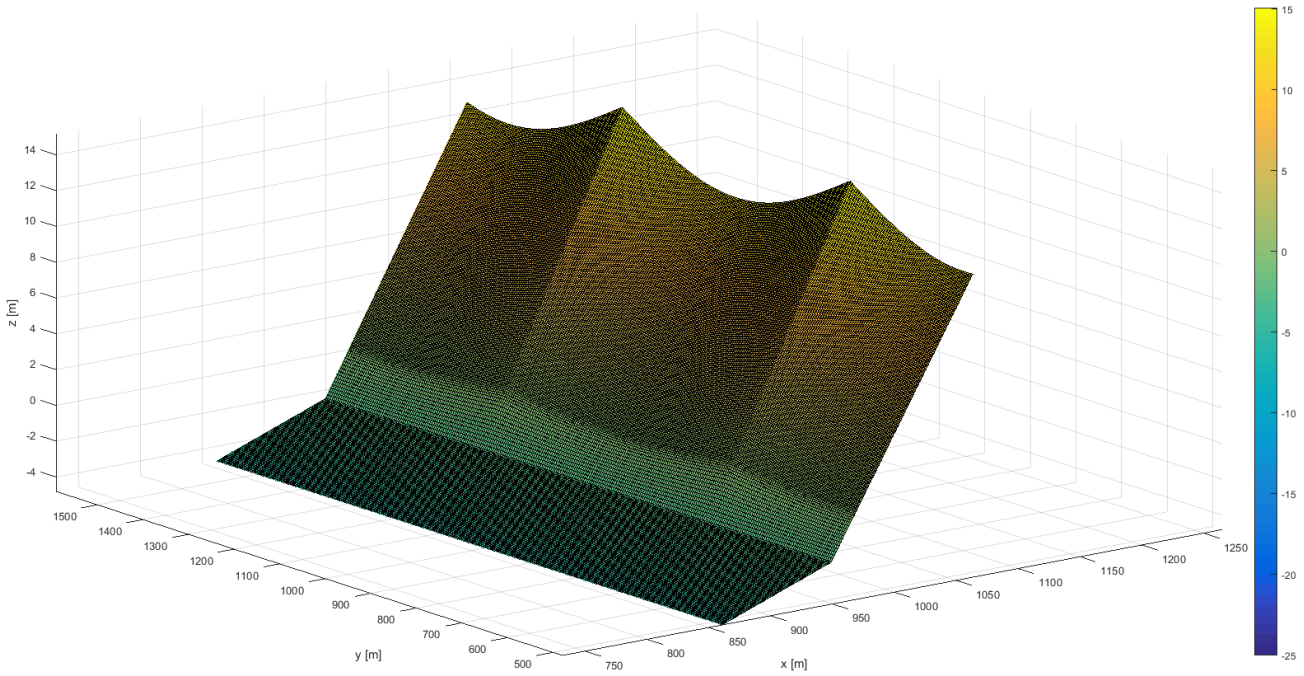

Figure VI-2: varying sloped cusps, slope of beach cusps varies with an absolute cosine function in alongshore direction

The method, which resembles the bathymetry from the survey in 2008 well, will be chosen to model the beach cusps.

Appendix VI-iii Comparison method 1 & 2 with survey

The survey contains four subsequent cusps from which the horn and embayment is analysed. A comparison is made with the idealized bathymetry generated with Matlab. This is shown in Figure VI-3 and Figure VI-4 for method 1 and in Figure VI-5 and Figure VI-6 for method 2.

The choice which method fits the survey from 2008 the best is made with an assessment model, with an indication of +, +/– and – sign. The horn and embayment is compared at four locations. These four locations are indicated in Figure VI-3 – VI-6 by green, black, red and blue lines. In which solid lines represent the horns and the dashed lines represent the embayments. If the horn and embayment resembles both the survey well a + sign is assigned to the specified method. If either a horn or an embayment fits the survey well a +/– sign is assigned to the specified method. If both the horn and embayment resembles the survey poorly a – sign is assigned to the specified method. In Table VI-1 an overview is given of the results of the assessment model.

	Green transect	Black transect	Red transect	Blue transect
Constant sloped cusps	–	+	–	–
Varying sloped cusps	+/–	+/–	+	+

Table VI-1: overview results assessment model

For each situation an explanation is given why a certain sign is chosen as described below.

Method 1

In Figure VI-3 the constant sloped cusps are shown together with the green transect and black transect. It can be seen that the black transect, for both the horn and embayment is represented well by the idealized bathymetry. Only a small deviation occurs at the profile above still water level

(SWL) in the case of an embayment. In this case a + sign is given for the constant sloped cusps. The green transect, which is shown in the same figure, is represented poorly by the constant sloped cusps. For the embayment a deviation occurs at the underwater profile from x=-80 to x=-30, where x is the cross shore distance. A second deviation is visible when the transition from the underwater profile to the beach occurs. The horn is represented well above SWL. However, a large deviation is visible in the underwater profile, from x=-80 to x=-40. This also occurs due to the presence of a crescentic offshore sandbar. A – sign is given for the constant sloped cusps regarding the green transect.

In Figure VI-4 the blue and red transect is shown together with the constant sloped cusps. In this case it can be seen that the horn of the constant sloped cusps resembles the survey well considering the beach profile. A closer look to the underwater profile shows deviations for both the horns of the blue and red transects. For the embayment the same pattern is observed as with the green transect. There is a deviation visible at the underwater profile from x=-60 to x=-25m for the red transect and from x=-50 to -35m for the blue transect. In both cases (red and blue transect) a deviation is observed in the transition from the underwater profile to the beach profile. This is the reason that both the blue and red transect contains a – sign for the constant sloped cusps.

Method 2

In Figure VI-5 the varying sloped cusps are shown together with the green and black transects. The varying sloped cusps resembles the black transect well in the case of a horn. However, in the case of an embayment a deviation is visible in the underwater profile and the beach profile. In this case a +/– sign is given for the varying sloped cusps regarding the black transect. There are also deviations visible in the case of the green transect. The horn is not represented well in the underwater profile. The embayment shows also a deviation, the real bathymetry is located 0.3 m lower compared to the varying sloped cusps. The slope is more or less the same. This is the reason why a +/– sign is given for the varying sloped cusps considering the green transect.

In Figure VI-6 the blue and red transects are shown together with the varying sloped cusps. The varying sloped cusps resemble both the horn and embayment well in the case of the blue and red transects. A small deviation is visible considering the horns at x=-30 and at x=-10 considering the embayments. Overall the varying sloped cusps resembles the survey from 2008 well at the location of the blue and red transects, this is the reason why in both cases a + sign is assigned.

From Table VI-1 it can be concluded that the varying sloped cusps contains the best results in comparison with the survey of 2008. Thus, the beach cusps will be modelled with the varying sloped cusps as shown in Figure VI-2.

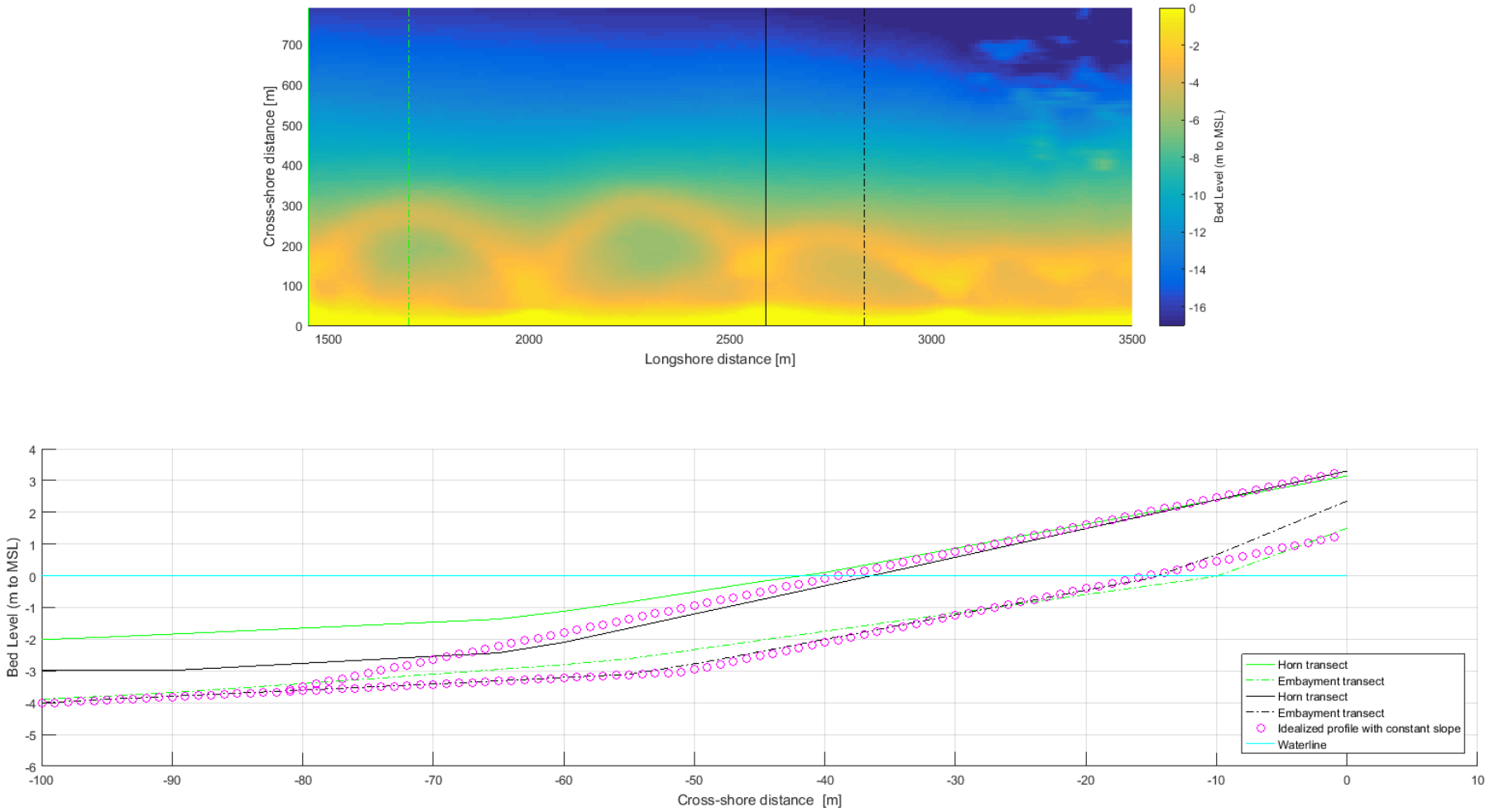

Figure VI-3: constant sloped cusp (idealized bathymetry, magenta lines) compared with survey (black and green transects), upper plot: survey 2008, lower plot: cross shore transects

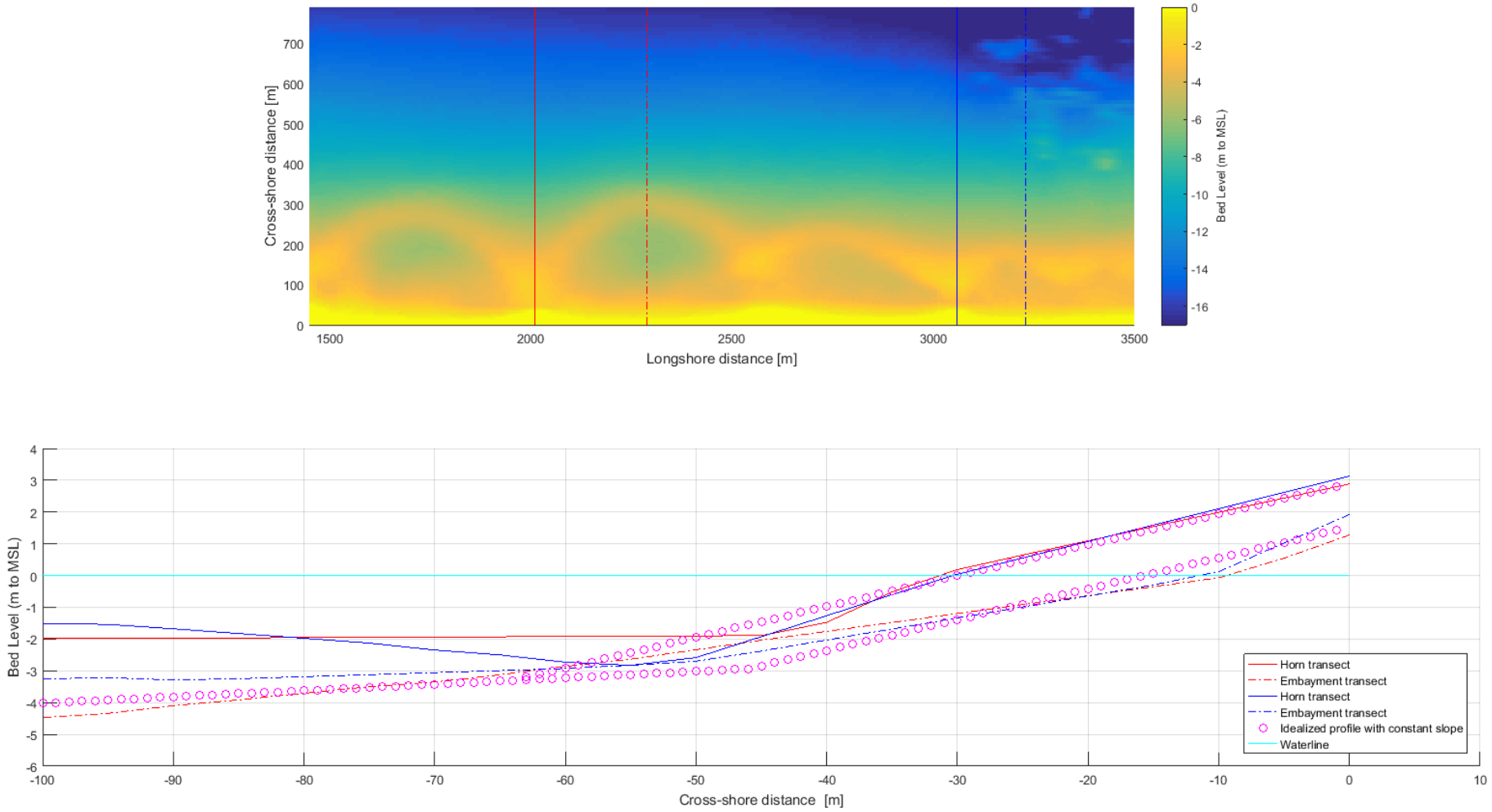

Figure VI-4: constant sloped cusp (idealized bathymetry, magenta lines) compared with survey (red and blue transects), upper plot: survey 2008, lower plot: cross shore transects

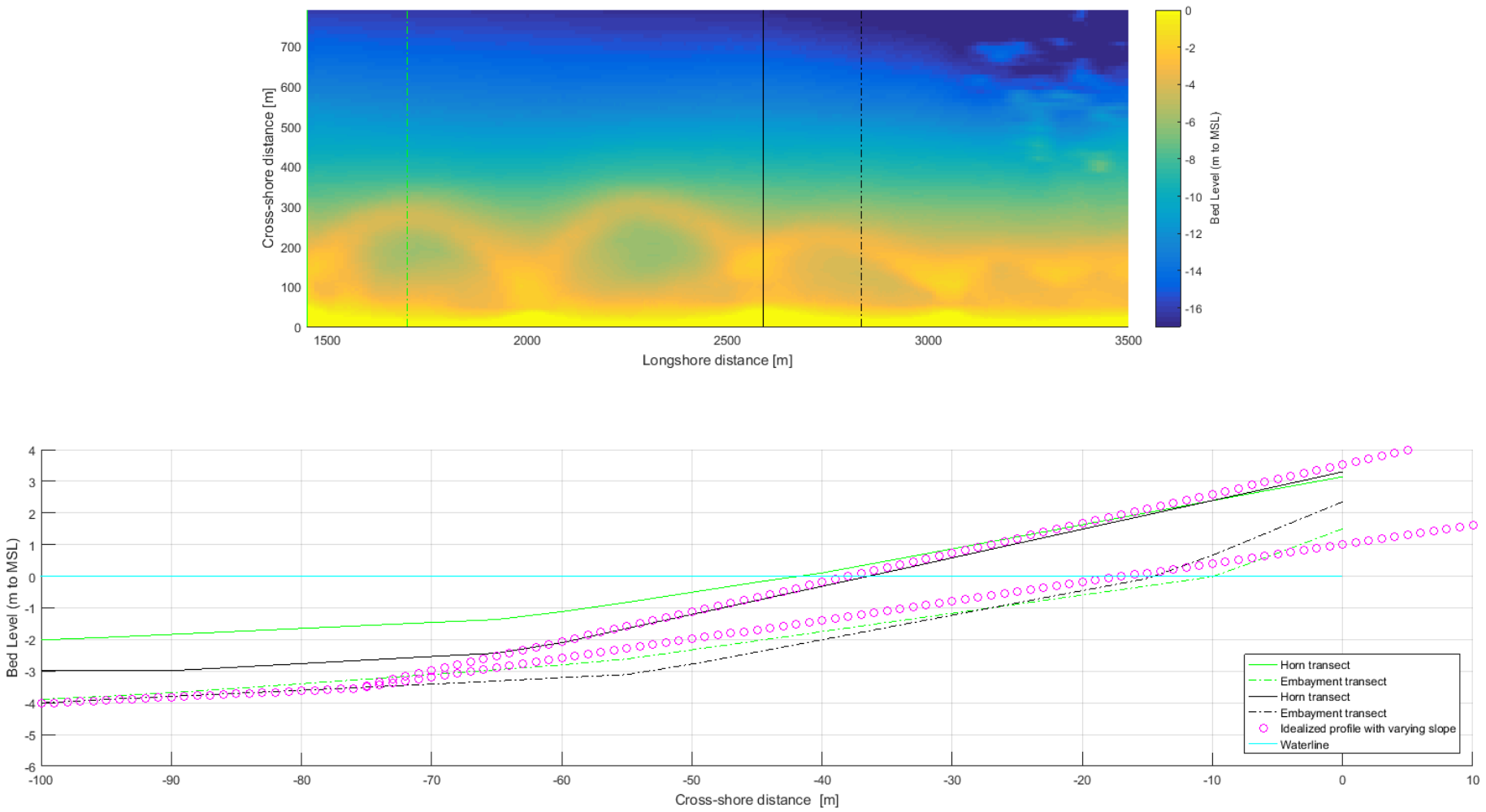

Figure VI-5: varying sloped cusp (idealized bathymetry, magenta lines) compared with survey (black and green transects), upper plot: survey 2008, lower plot: cross shore transects

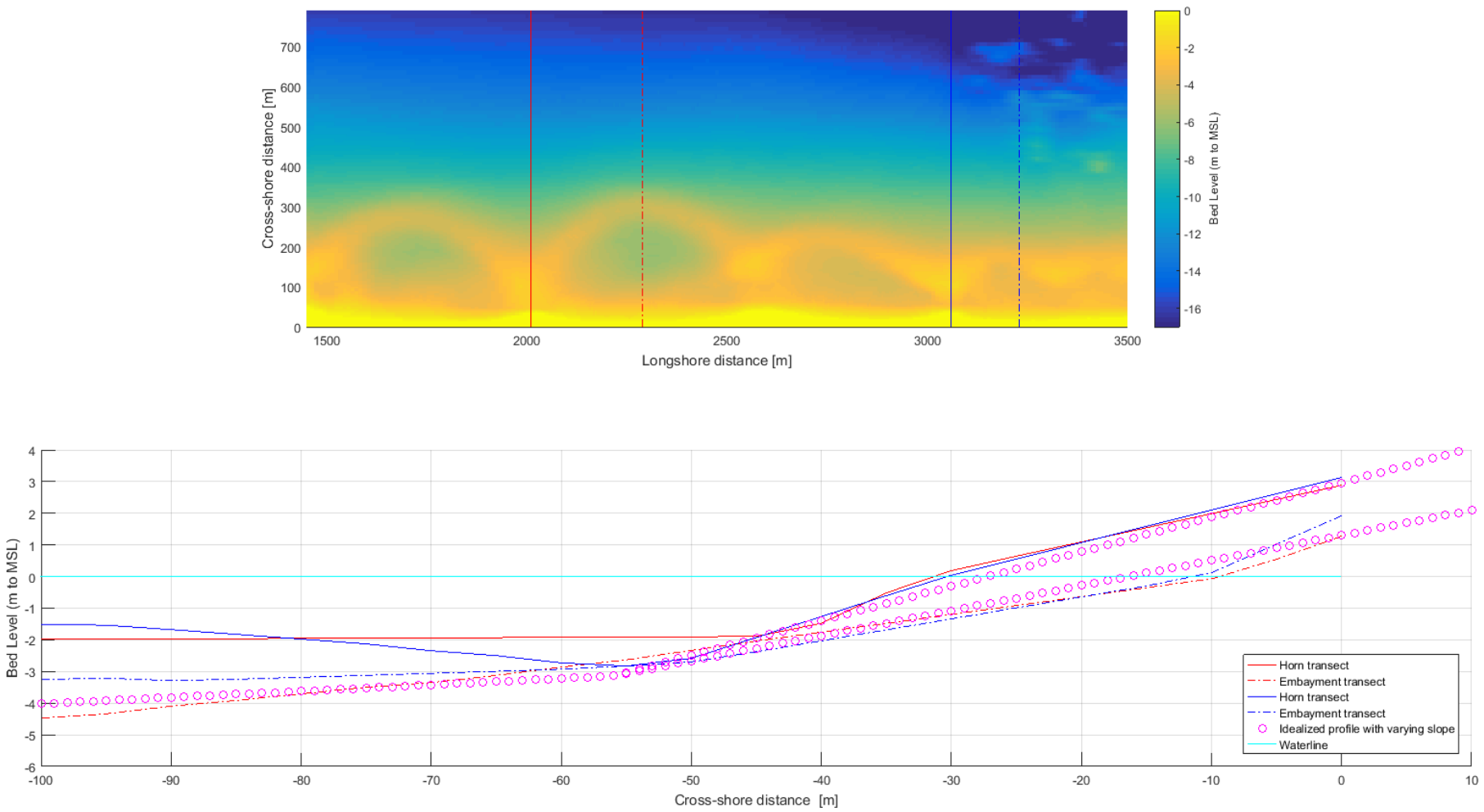

Figure VI-6: varying sloped cusp (idealized bathymetry, magenta lines) compared with survey (red and blue transects), upper plot: survey 2008, lower plot: cross shore transects

Appendix VII Number of cusps

In this section the number of cusps which should be modelled is determined. In total five calculations are made, consisting of nine, seven, five or three cusps next to each other and one calculation consisting of one cusp. For these calculations the central cusp is analysed. Thus, this means the cusp which is located in the middle of the domain. For this central cusp the $R_{2\%}$, setup, swash, infragravity band swash and incident band swash is calculated. The wave conditions which is used for this analysis is the same as described in section 3.3.1.2.

To check whether the same pattern could be observed in $R_{2\%}$, setup and swash components the $R_{2\%}$, setup and swash values are plotted versus the distance from the edge of the central cusp. The results are shown in Figure VII-2, Figure VII-4, Figure VII-6, Figure VII-8 and Figure VII-10. From these figures it can be clearly seen that incident band swash, in Figure VII-10, contains a strong correlation together with the beach cusps. In the same figures the bathymetry is shown of one cusp. The incident band swash increases at the horns and decreases at the embayment. Contrary, for the infragravity band swash, Figure VII-8, there is no clear pattern visible relating to the beach cusps. The location of the horn can be observed in a local decrease of the setup, this is shown in Figure VII-4. At the horns an increase of $R_{2\%}$ can be observed, however, this pattern is not clearly visible when only one cusp is plotted. This pattern can be observed when nine cusps next to each other are plotted this is shown in Appendix VIII . In this appendix the $R_{2\%}$, setup and swash components are plotted versus the alongshore slope, together with a subplot of the bathymetry. For this reason it is better to model more than one cusp. The ideal situation is to model one cusp, this will reduce the computational time.

Correlation plots are made from $R_{2\%}$, setup and swash components, relating each of these aspects to the alongshore varying slope due to the beach cusps. The correlations plots are shown in Figure VII-1, Figure VII-3, Figure VII-5, Figure VII-7 and Figure VII-9. The horns contains a slope of $\tan(\beta)=0.109$ and the embayment contains a slope of $\tan(\beta)=0.079$. In these figures the different model runs are indicated with different coloured scatters. The 'nine model run' which consist of nine subsequent cusps shows the scatter of the central cusp, this holds also for the seven, five, three and one model run. From all of these figures it is visible that the 'nine model run' shows the same patterns as the 'three model run'. The regression line fitted through the scatter results in more or less the same slope. A deviation is visible, because the regression line of the 'three model run' lies below the regression line of the 'nine model run'. However, this deviation is small and can be considered as noise as shown in Table 7-4. It can be seen that the deviation becomes larger when $\tan(\beta)$ increases. This holds for $R_{2\%}$ and infragravity band swash. This is not valid for setup, as shown in Figure VII-3. Setup does not show a strong correlation at all. The deviation visible for setup is considered as noise. As described in the previous paragraph the incident band swash shows a strong correlation with the beach cusps, this is also visible in the correlation plot in Figure VII-9.

It is chosen to model three cusps next to each other. This reduces the computational time compared to for instance nine cusps. Moreover, the deviations visible in the correlation plots are not significantly large and can be considered as noise, from which the values are represented in Table 7-4. Within three cusps the patterns are visible between for instance $R_{2\%}$ and the beach cusps which is less visible for one cusp.

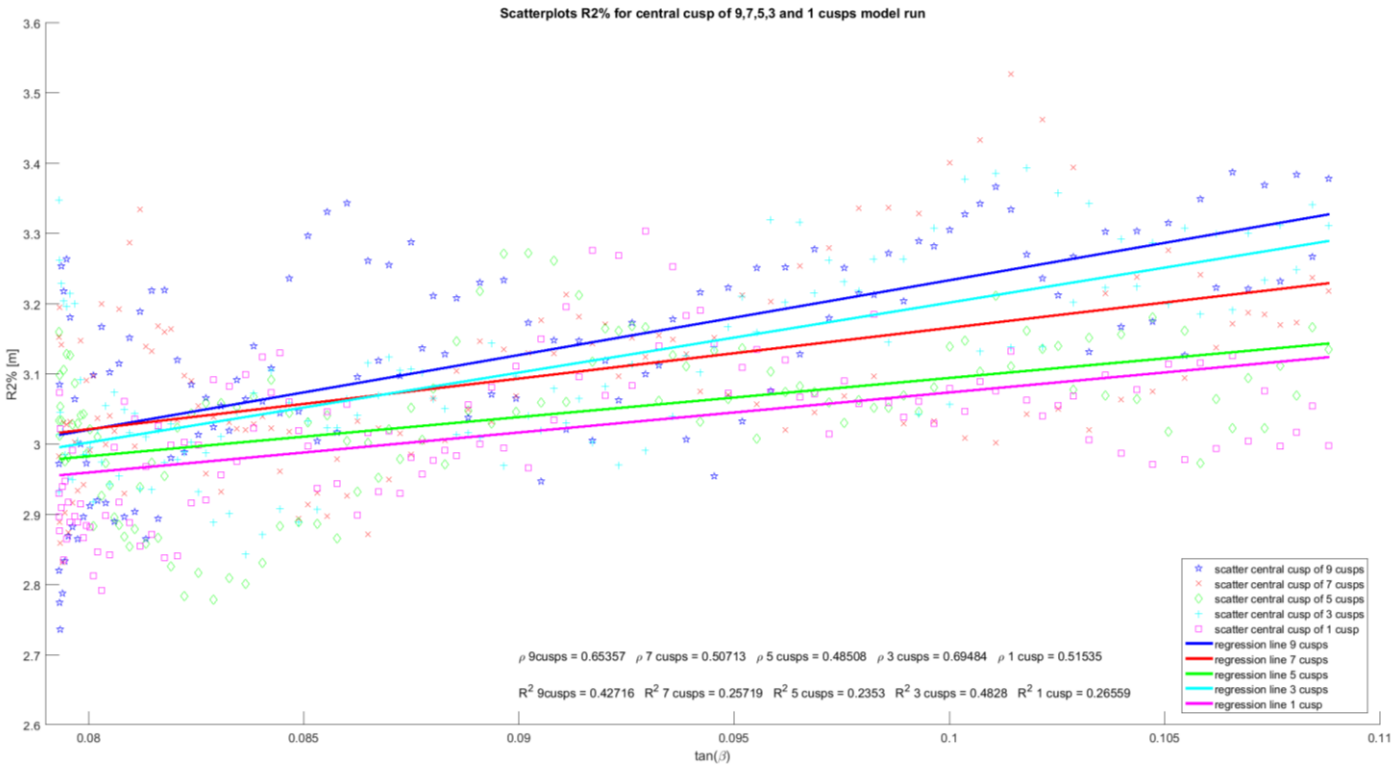

Figure VII-1: correlation plot $R_{2\%}$ versus alongshore slope, each central cusp is analysed for 9, 8, 7, 5, 3 and 1 cusp model run

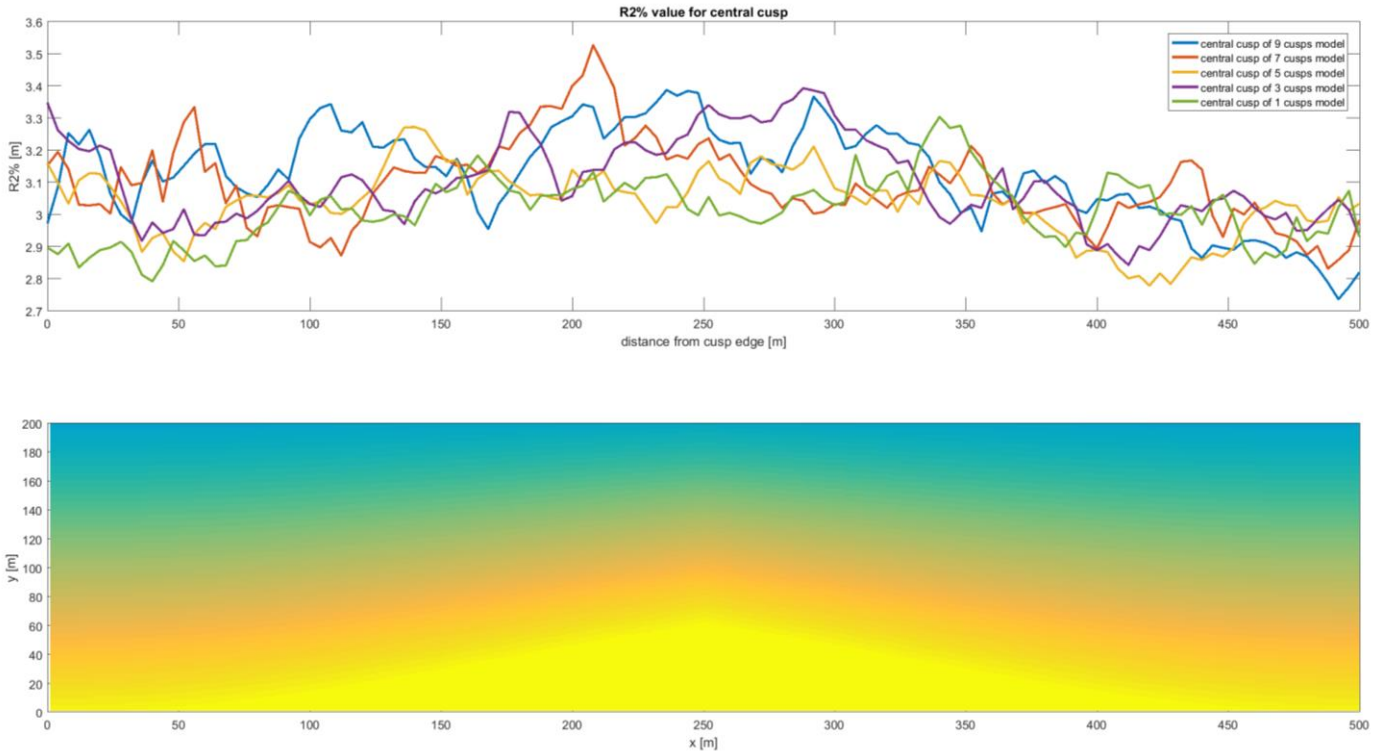

Figure VII-2: upper plot: $R_{2\%}$ versus distance from cusp edge, lower plot: bathymetry consisting of 1 cusp

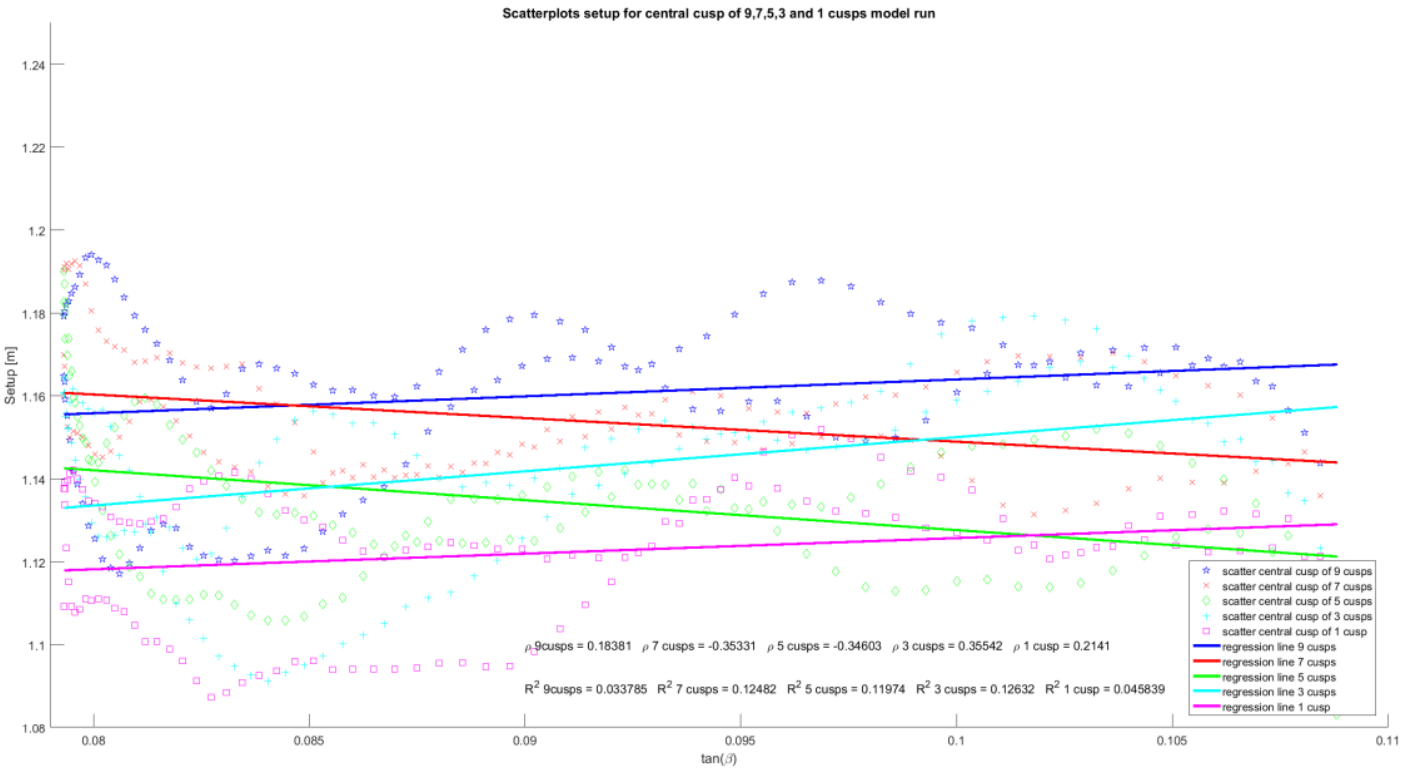

Figure VII-3: correlation plot setup versus alongshore slope, each central cusp is analysed for 9, 8, 7, 5, 3 and 1 cusp model run

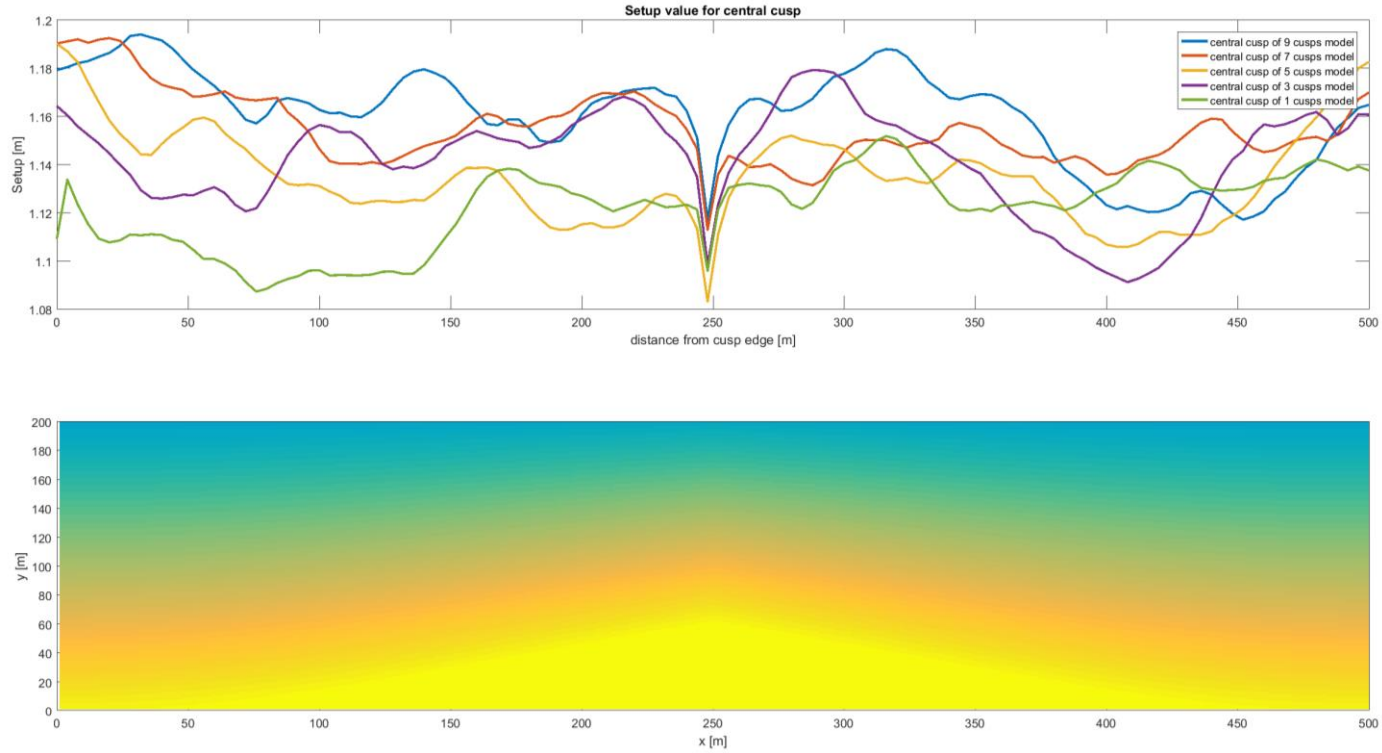

Figure VII-4: upper plot: setup versus distance from cusp edge, lower plot: bathymetry consisting of 1 cusp

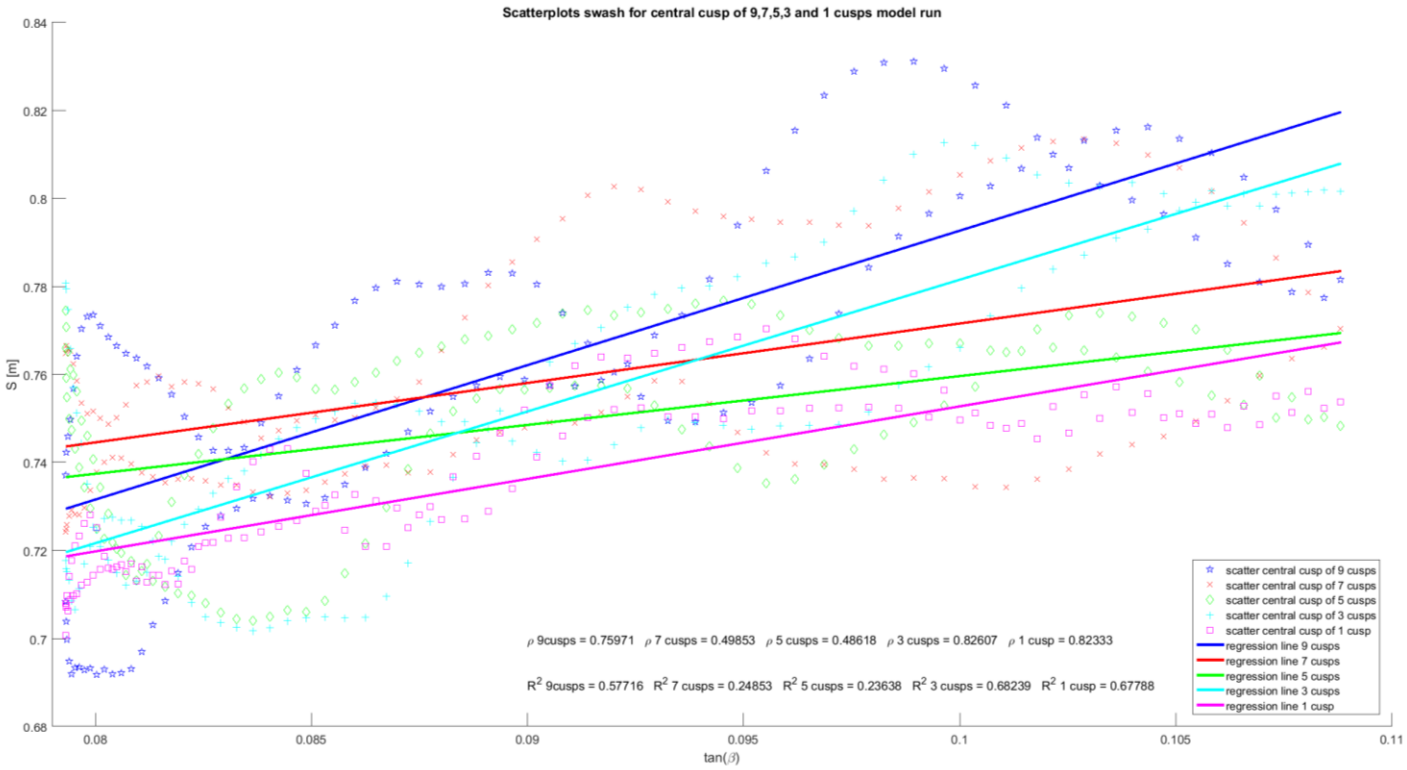

Figure VII-5: correlation plot swash versus alongshore slope, each central cusp is analysed for 9, 8, 7, 5, 3 and 1 cusp model run

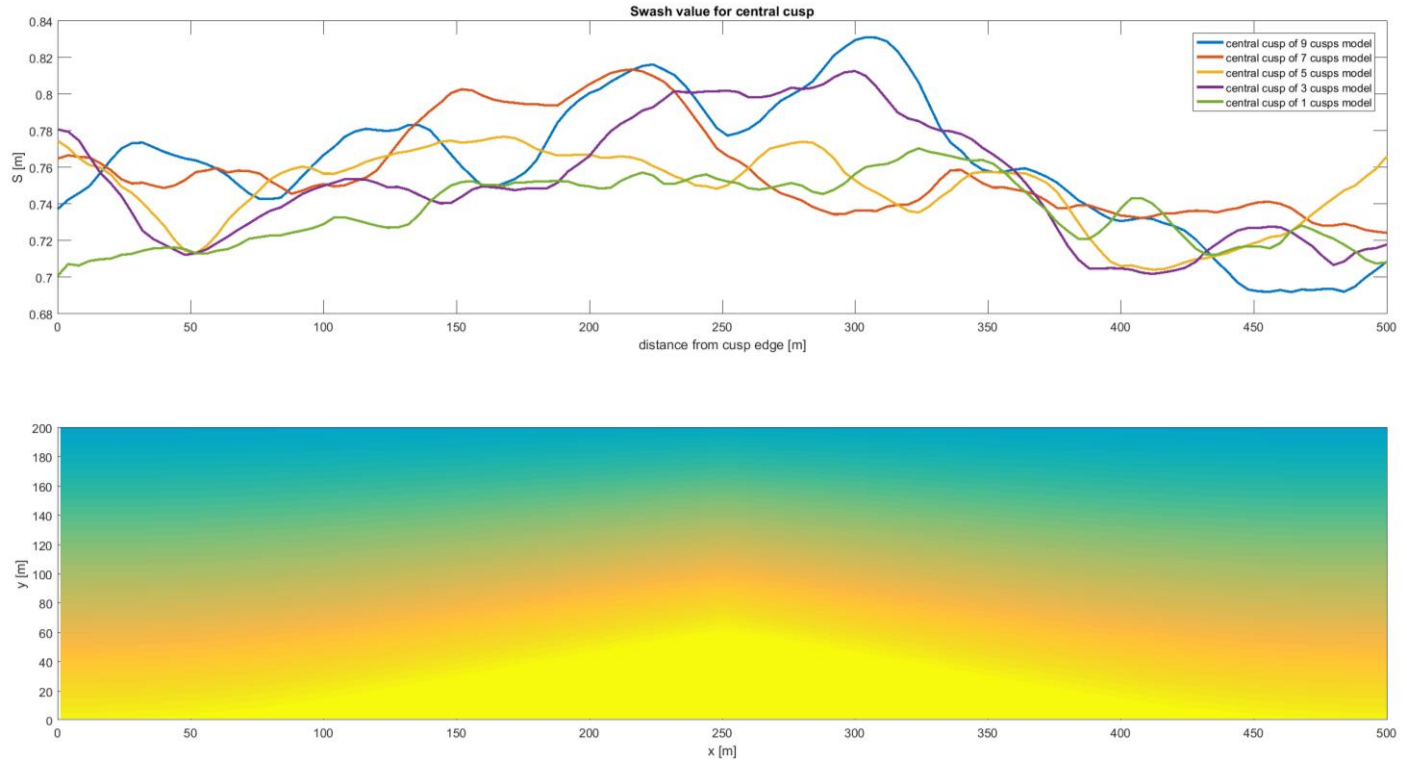

Figure VII-6: upper plot: swash versus distance from cusp edge, lower plot: bathymetry consisting of 1 cusp

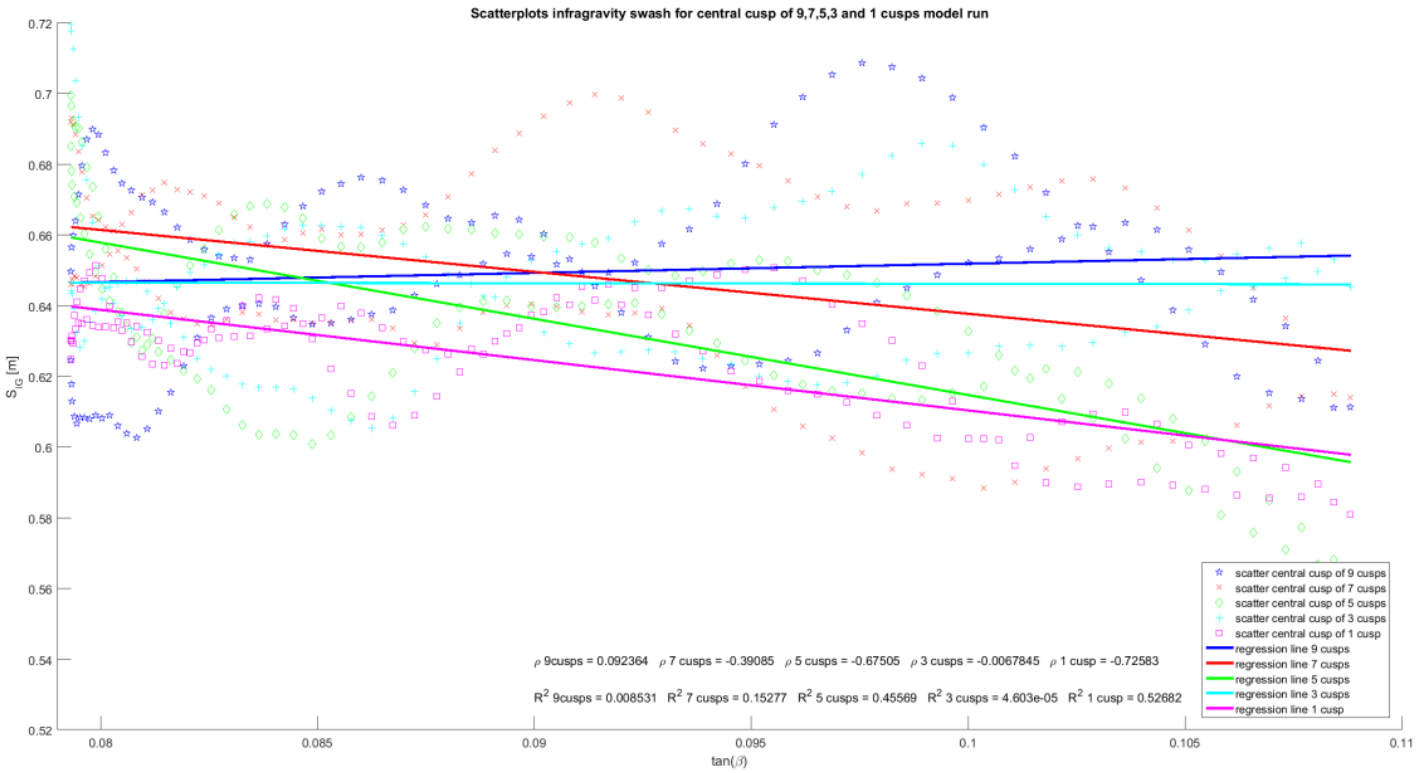

Figure VII-7: correlation plot infragravity band swash versus alongshore slope, each central cusp is analysed for 9, 8, 7, 5, 3 and 1 cusp model run

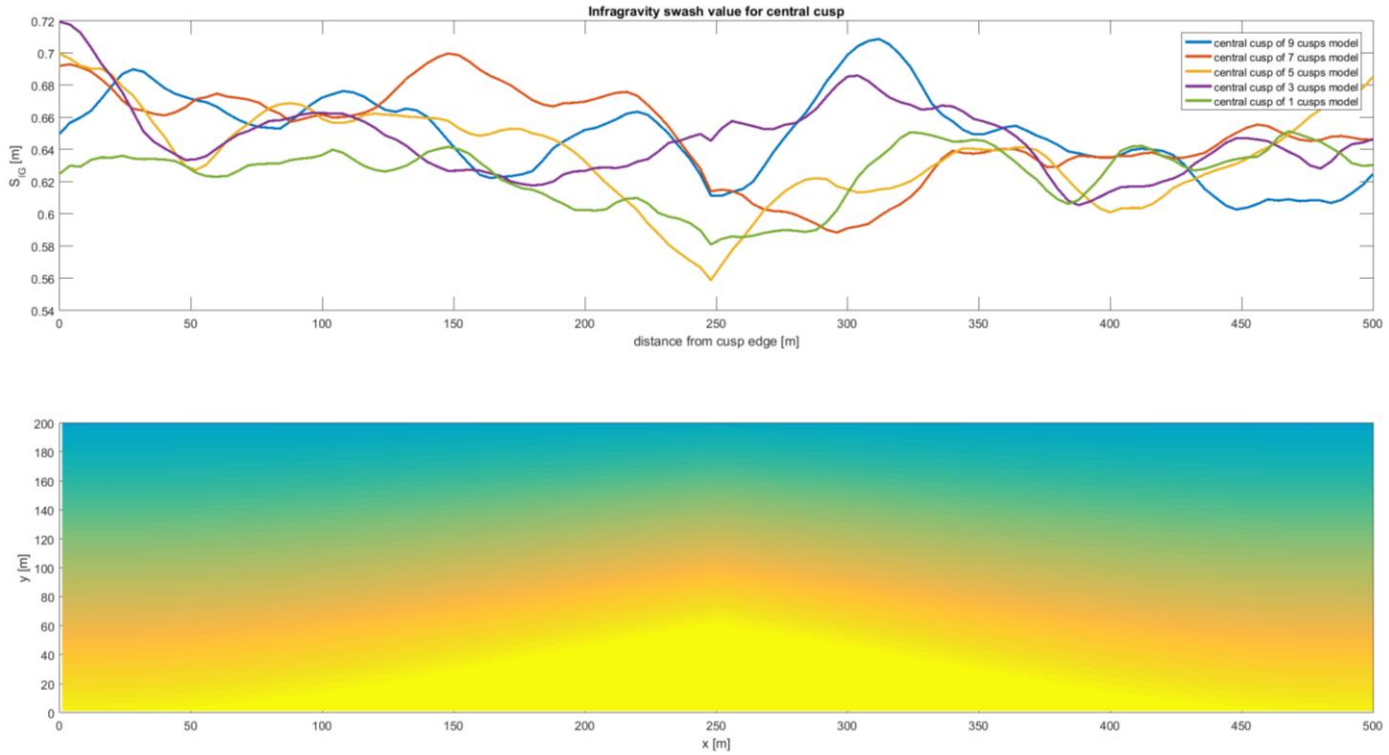

Figure VII-8: upper plot: infragravity band swash versus distance from cusp edge, lower plot: bathymetry consisting of 1 cusp

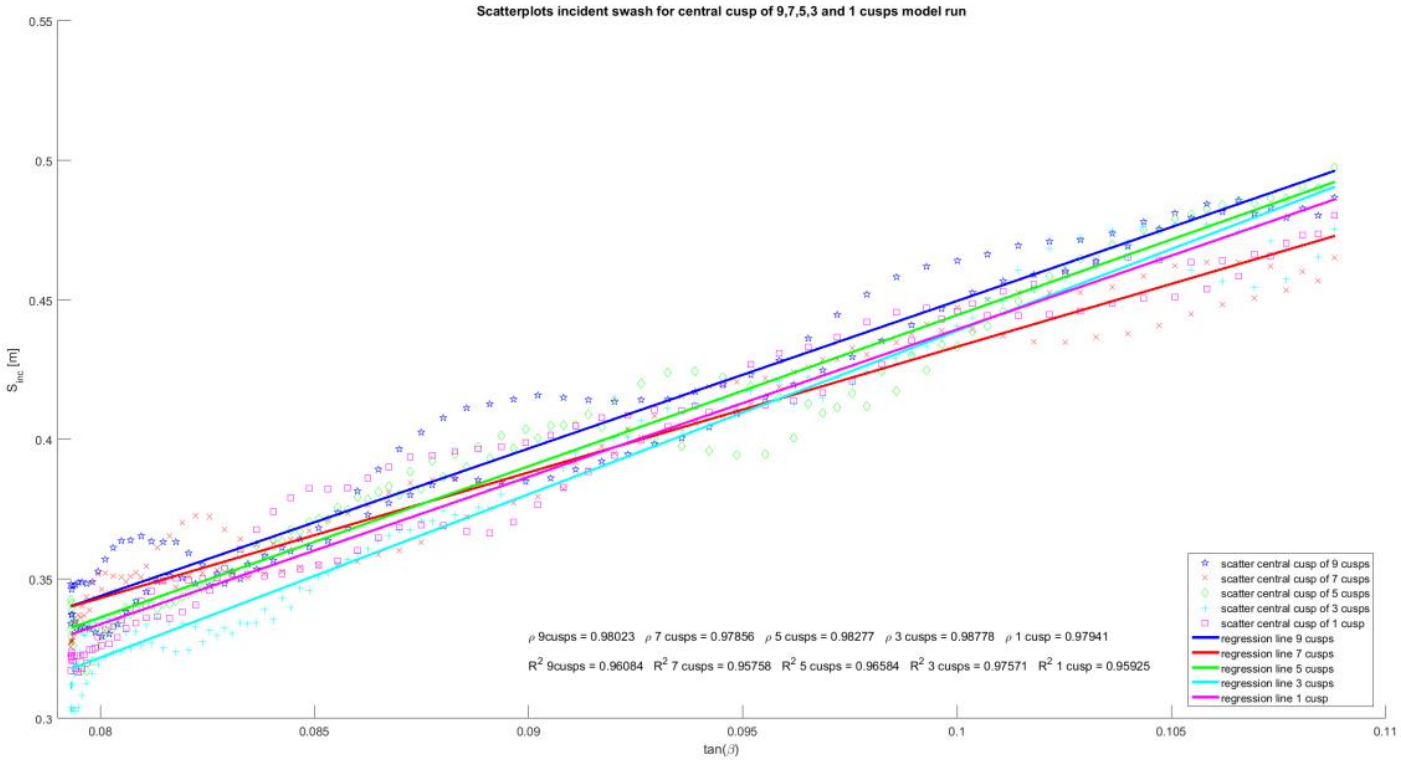

Figure VII-9: correlation plot incident band swash versus alongshore slope, each central cusp is analysed for 9, 8, 7, 5, 3 and 1 cusp model run

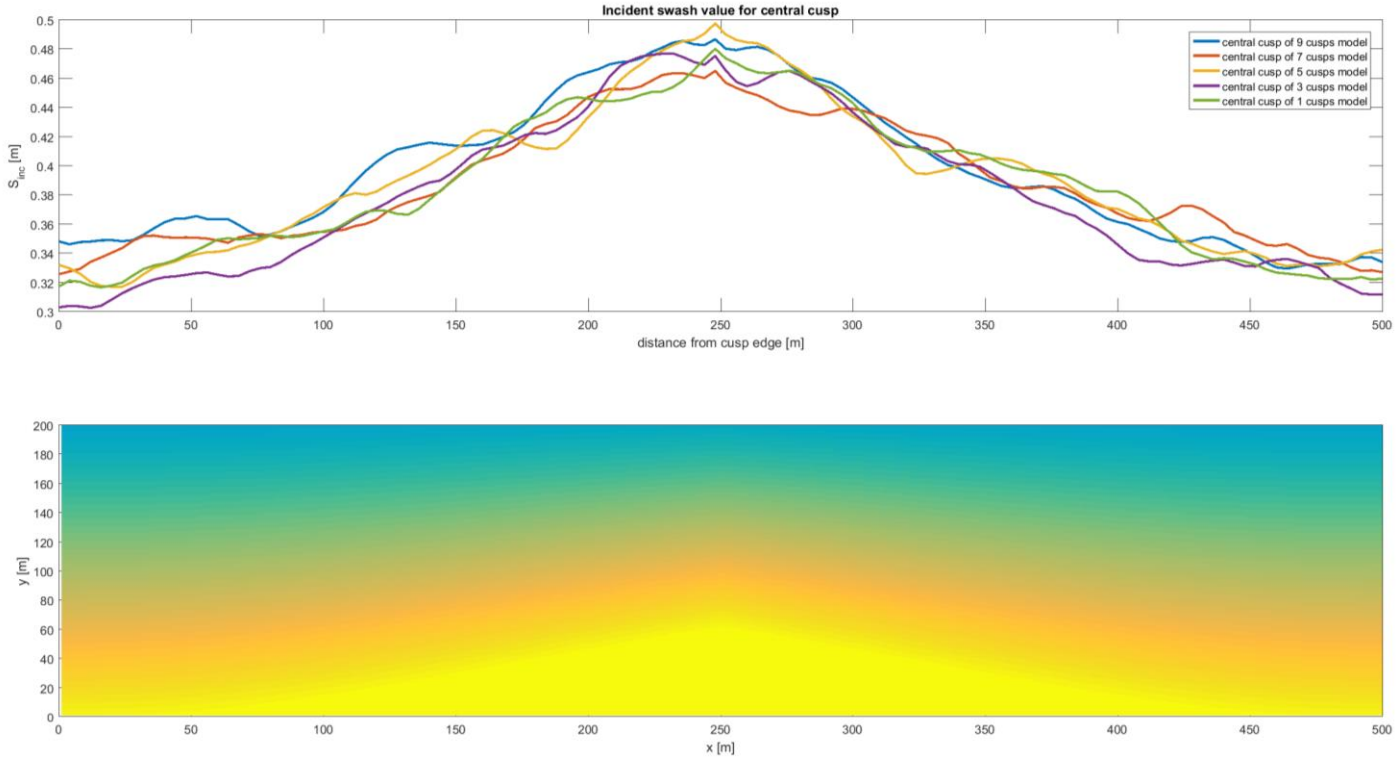

Figure VII-10: upper plot: incident band swash versus distance from cusp edge, lower plot: bathymetry consisting of 1 cusp

Appendix VIII Alongshore results nine cusps model

In this appendix R2%, setup, swash, infragravity band swash and incident band swash is shown along 9 cusps.

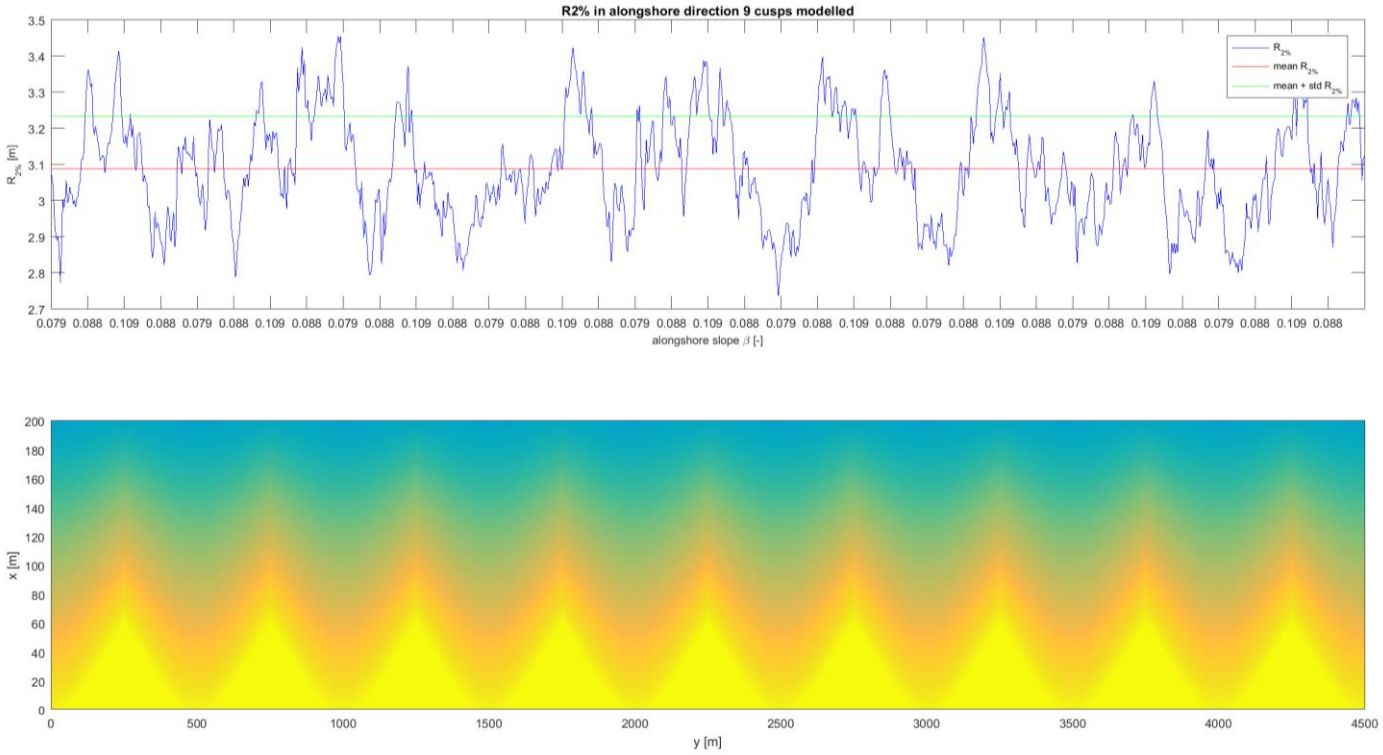

Figure VIII-1: R2% along 9 cusps

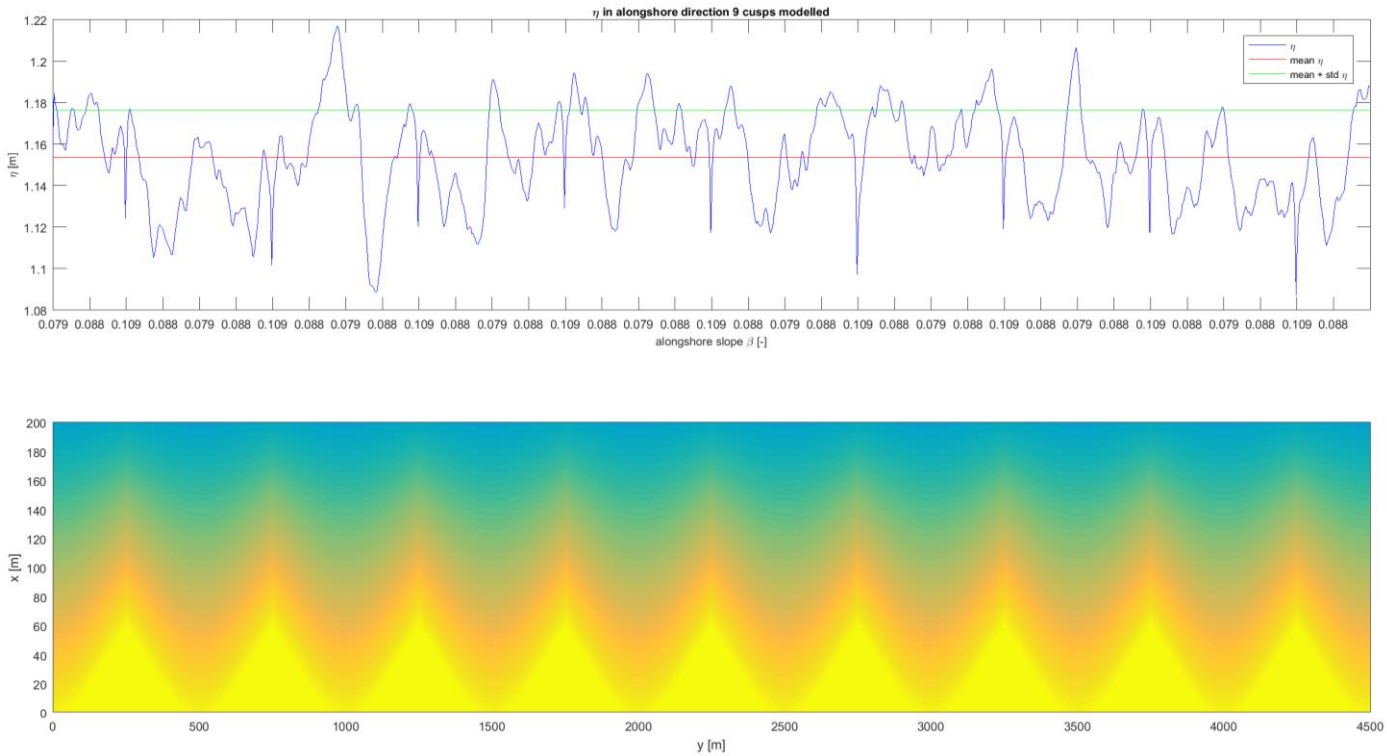

Figure VIII-2: setup along 9 cusps

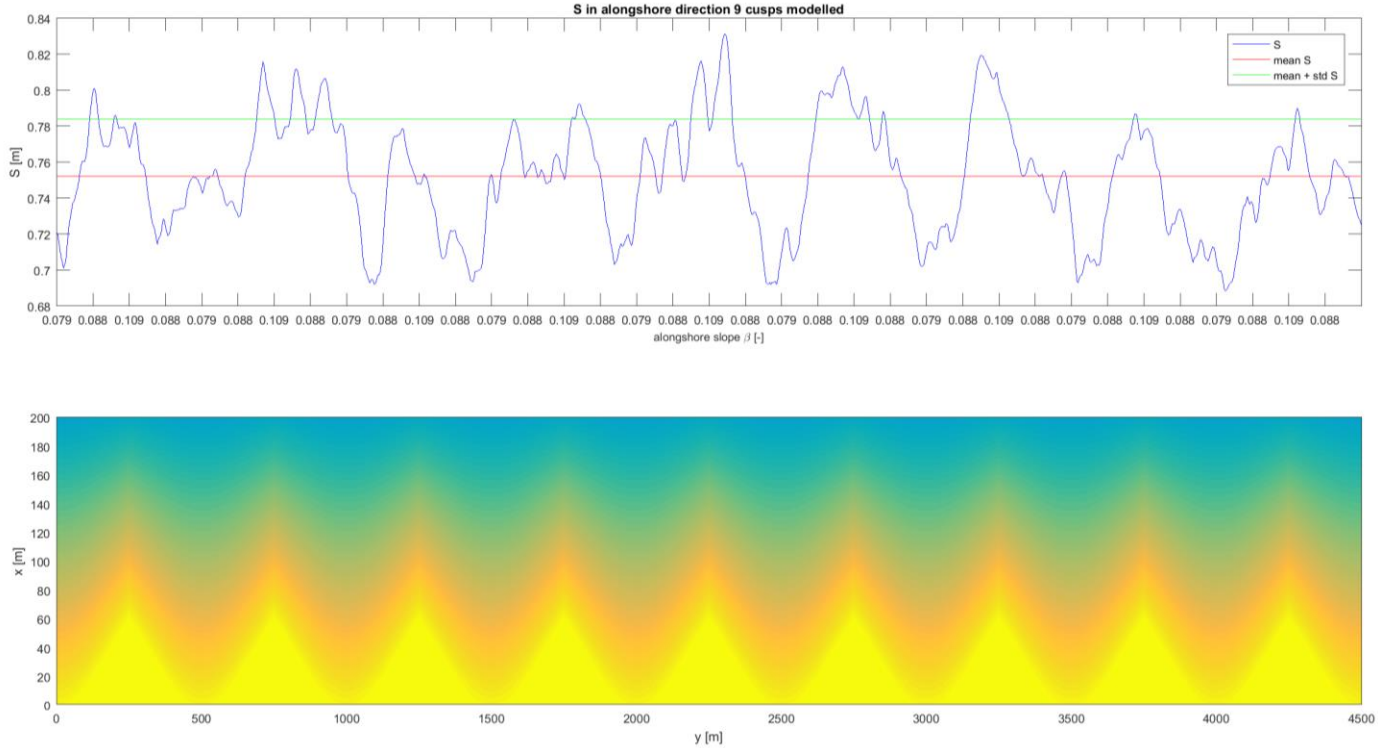

Figure VIII-3: swash along 9 cusps

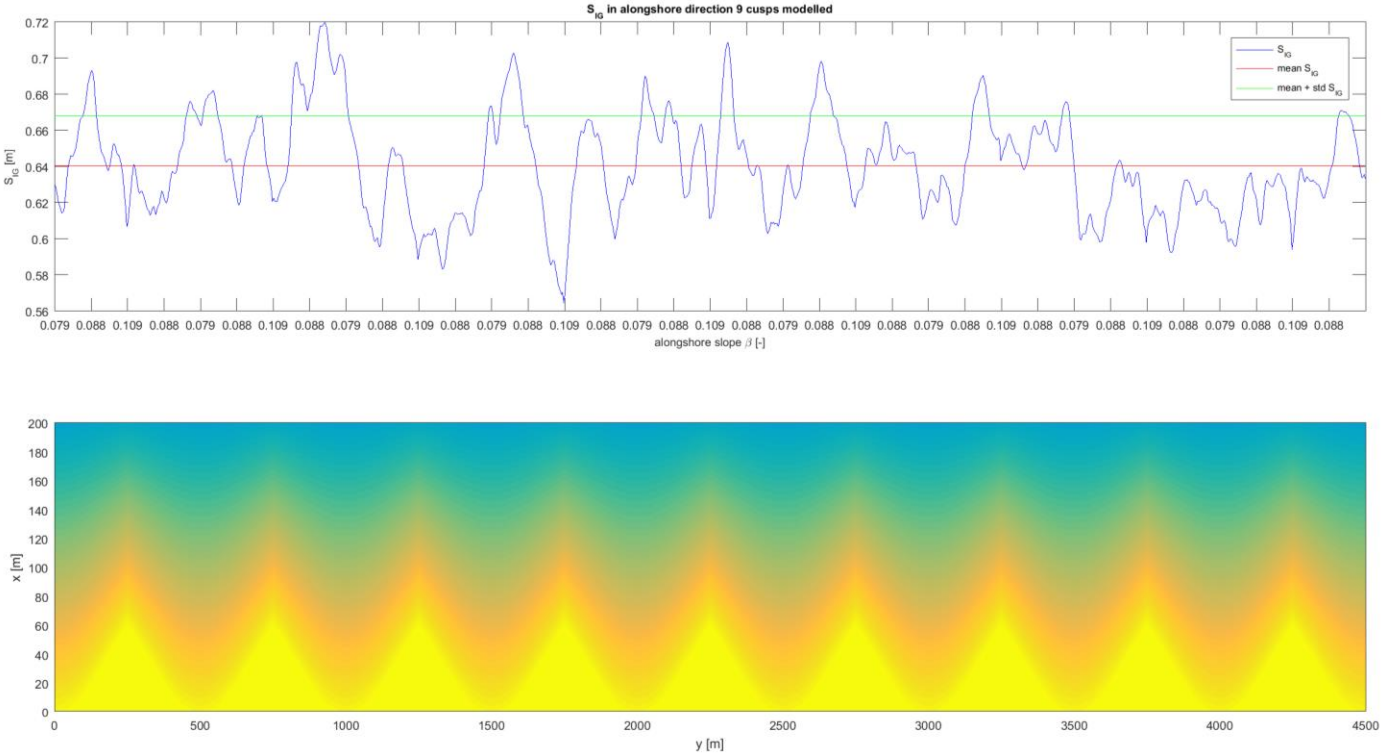

Figure VIII-4: infragravity band swash along 9 cusps

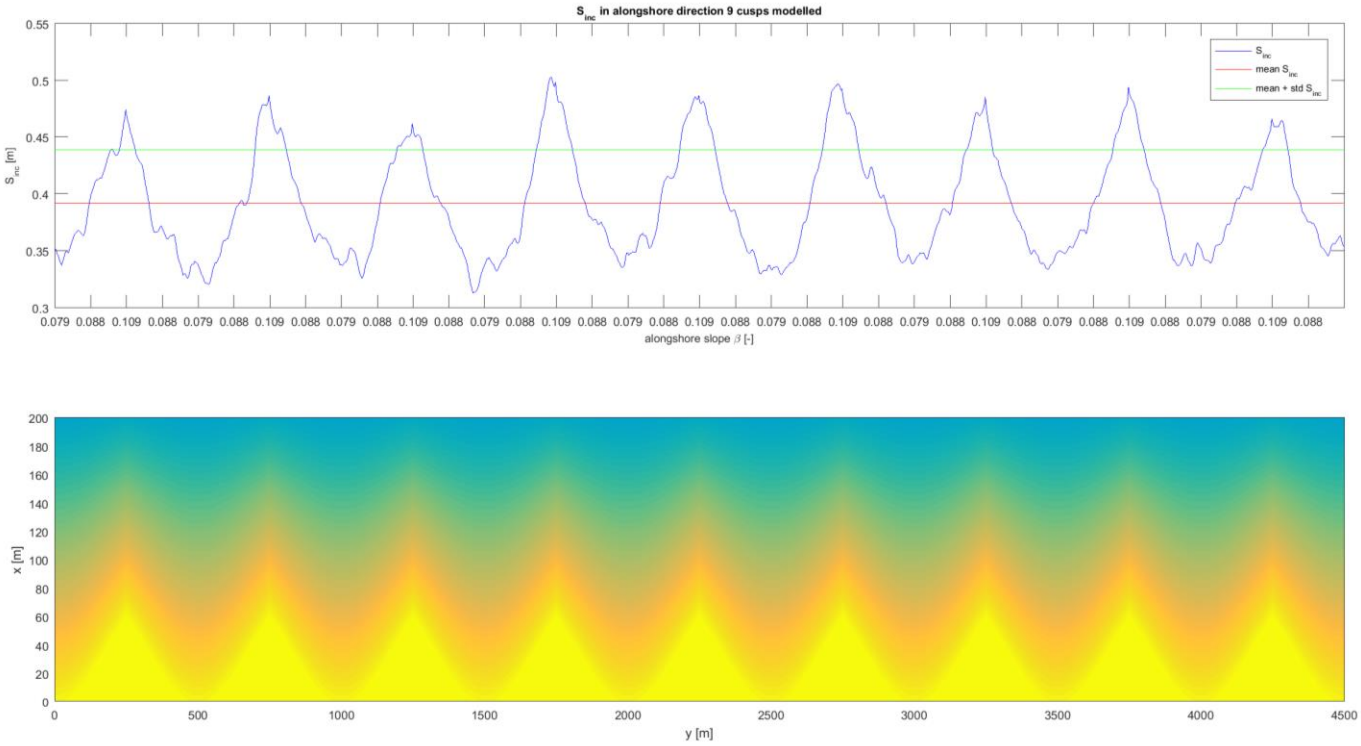

Figure VIII-5: incident band swash along 9 cusps

Appendix IX Sensitivity cusps, extra harmonics

In this appendix an analysis is made of the influence of the sharp gradient at the horns. This sharp gradient can be prevented by adding extra harmonics to the formula in which the beach cusps are generated.

The largest difference can be found when setup is considered.

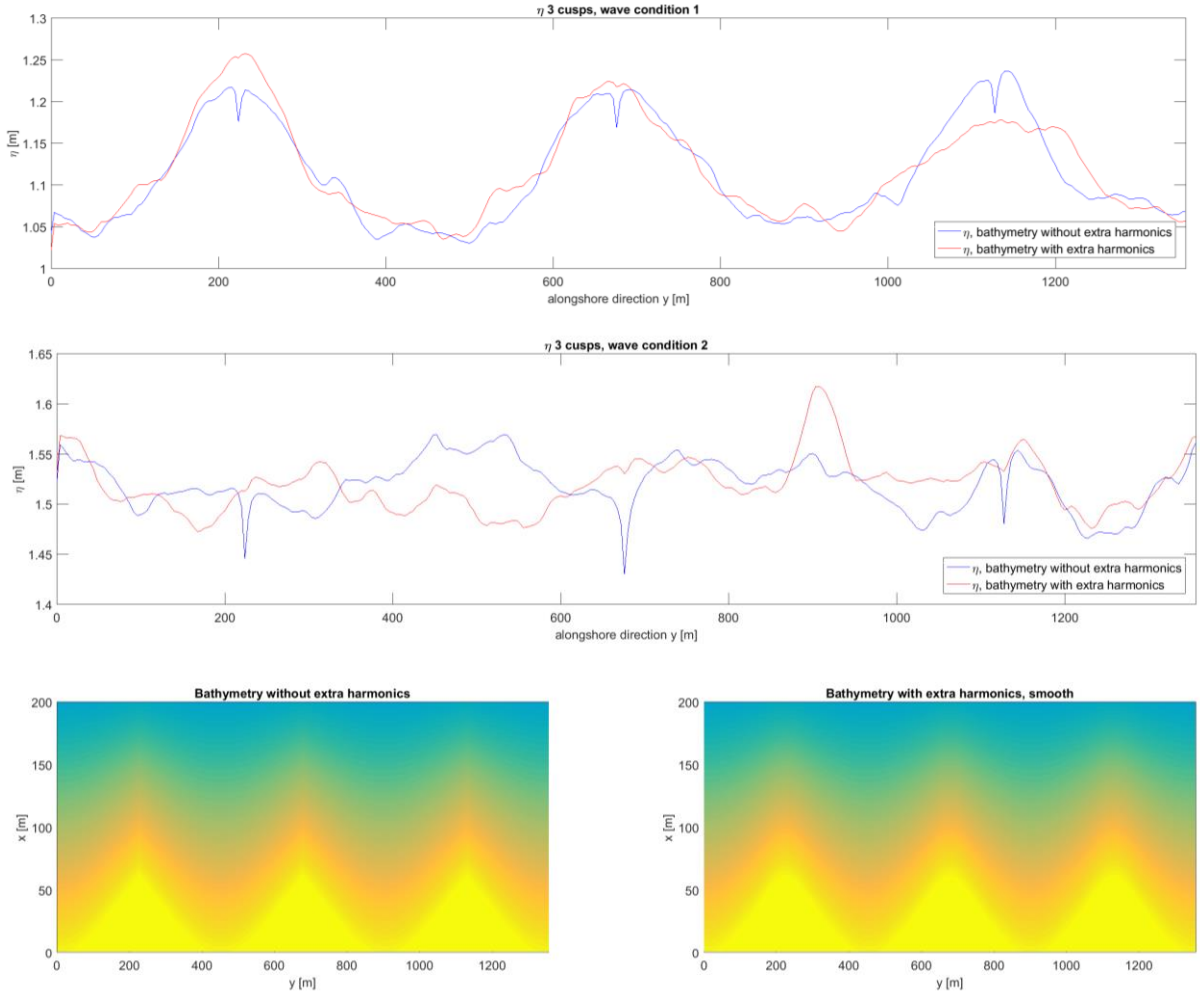

Figure IX-1: difference between results from a bathymetry with and without extra harmonics, upper figure: setup wave condition 1, centre figure: setup wave condition 2, bottom left: bathymetry without extra harmonics, bottom right: bathymetry with extra harmonics

The local downward peaks which are shown in Figure IX-1 are not present when the bathymetry contains extra harmonics. However, the trend remains the same, thus it does not influence the results when conlusions are made about trends along a cusp.

However, the influence of extra harmonics in the bathymetry is not visible for total run-up. This is shown in Figure IX-2.

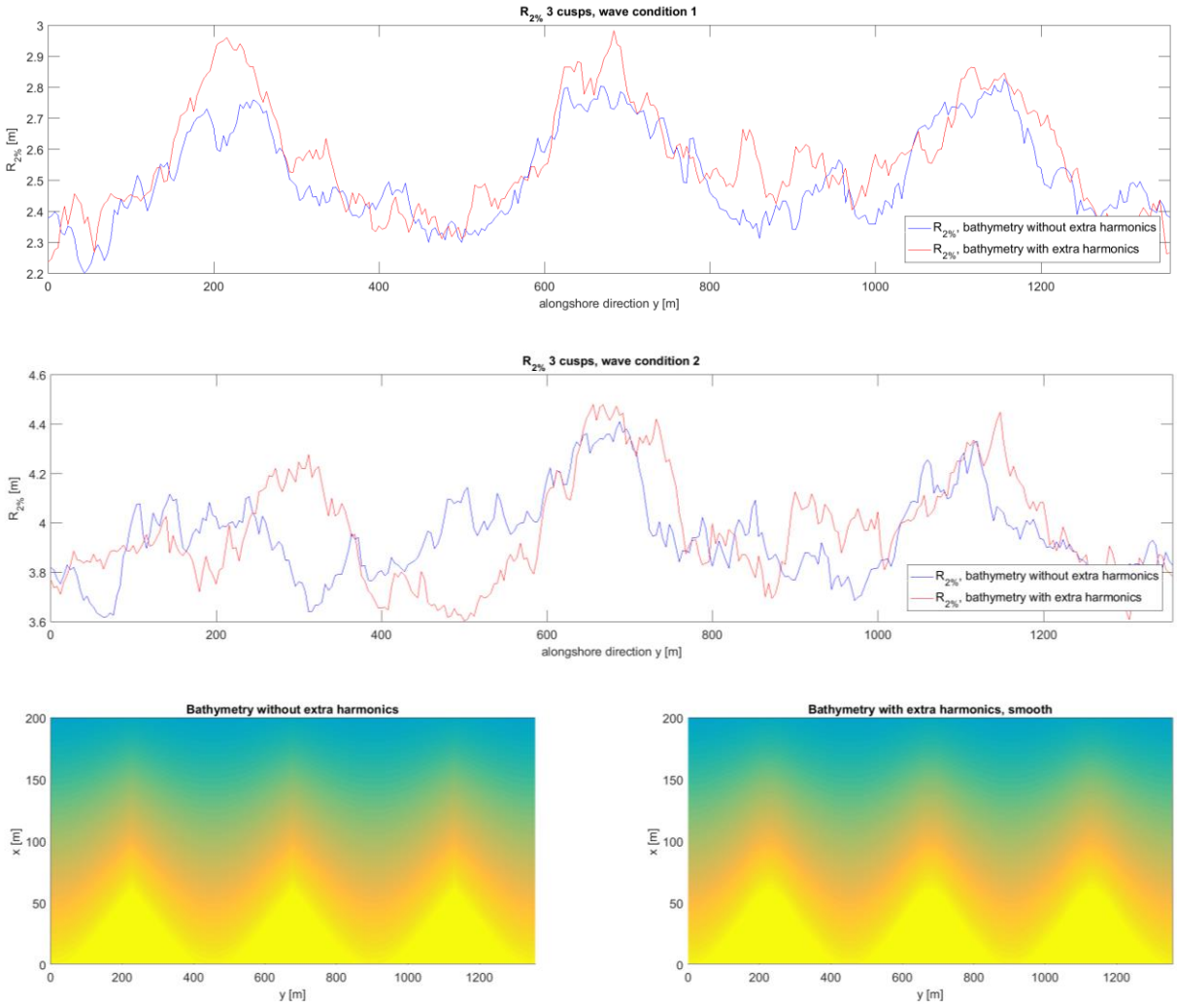

Figure IX-2: difference between results from a bathymetry with and without extra harmonics, upper figure: $R_{2\%}$ wave condition 1, centre figure: $R_{2\%}$ wave condition 2, bottom left: bathymetry without extra harmonics, bottom right: bathymetry with extra harmonics

Thus, extra harmonics does not have a major influence on the results, when setup is considered the local peak are removed. However, for total run-up the influence is not visible. Furthermore for infragravity band swash and incident band swash there is no difference when extra harmonics are added to the bathymetry. Both bathymetries are schematic, thus, for this thesis the bathymetry is used without extra harmonics.

Appendix X Method of determining alongshore maximum

In this appendix it is shown why the method is chosen to express the maximum values with a standard deviation based on the datapoints above the mean of the whole data set.

A comparison is made of the two methods which can be used. The first method is based on taking the mean of for instance R2%. By adding two times the standard deviation a maximum value is generated with a certainty of 95%. However, if the data set contains large peaks in an assymetrical profile it could be better to use twice the standard deviation of the data set which is located above the mean value. This value is added to the mean of the dataset located above the mean of the whole dataset.

The two methods are applied on the first five wave conditions for R2%, setup and swash components. Both methods are lying close together when the maximum value is represented. However, there are some situations in which the maximum value is better represented by taking the standard deviation from the dataset above the mean. This is shown in Figure X-1 and Figure X-2.

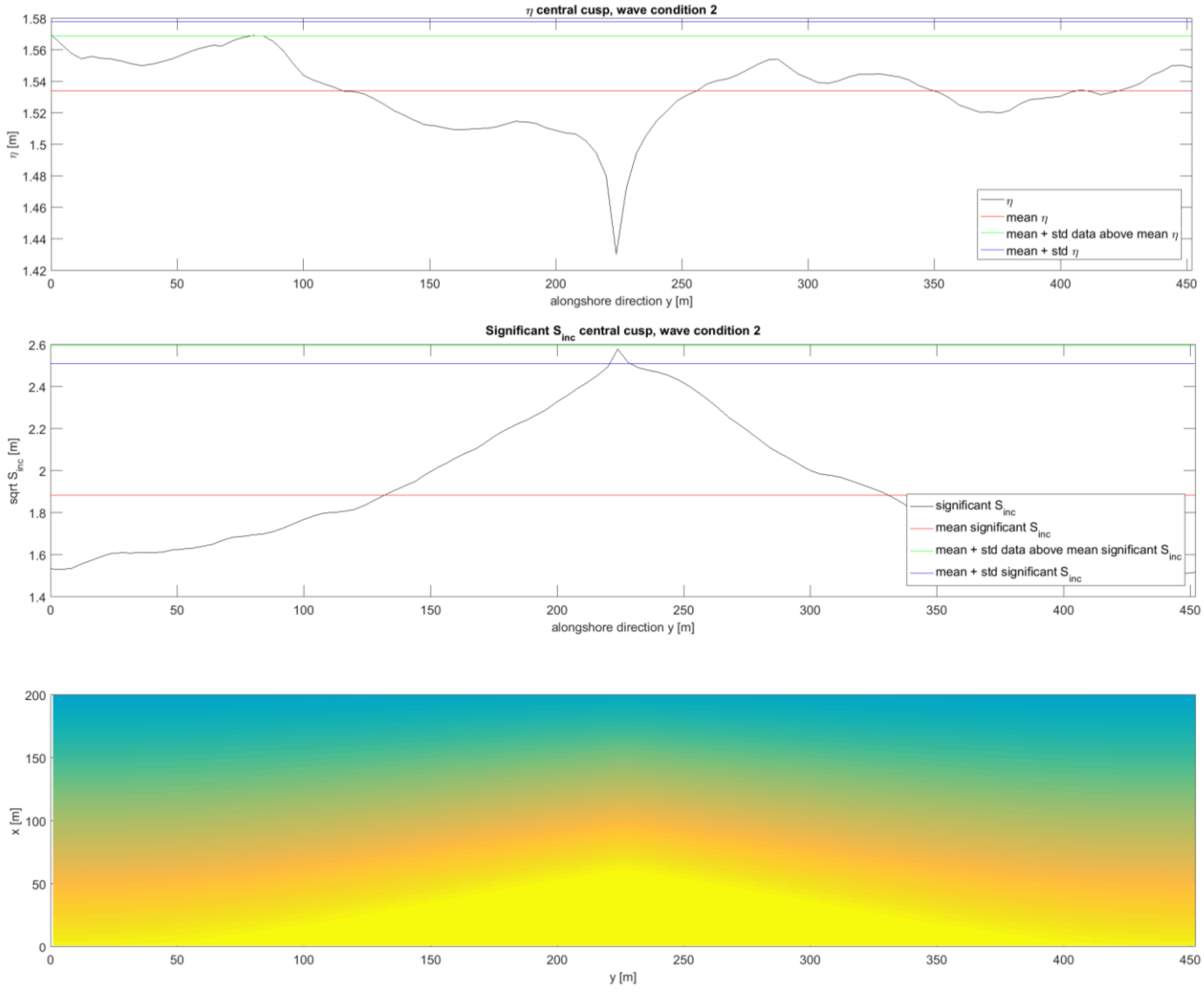

Figure X-1: comparison maximum values for wave condition 2, upper figure: setup, centre figure: incident band swash, bottom figure:

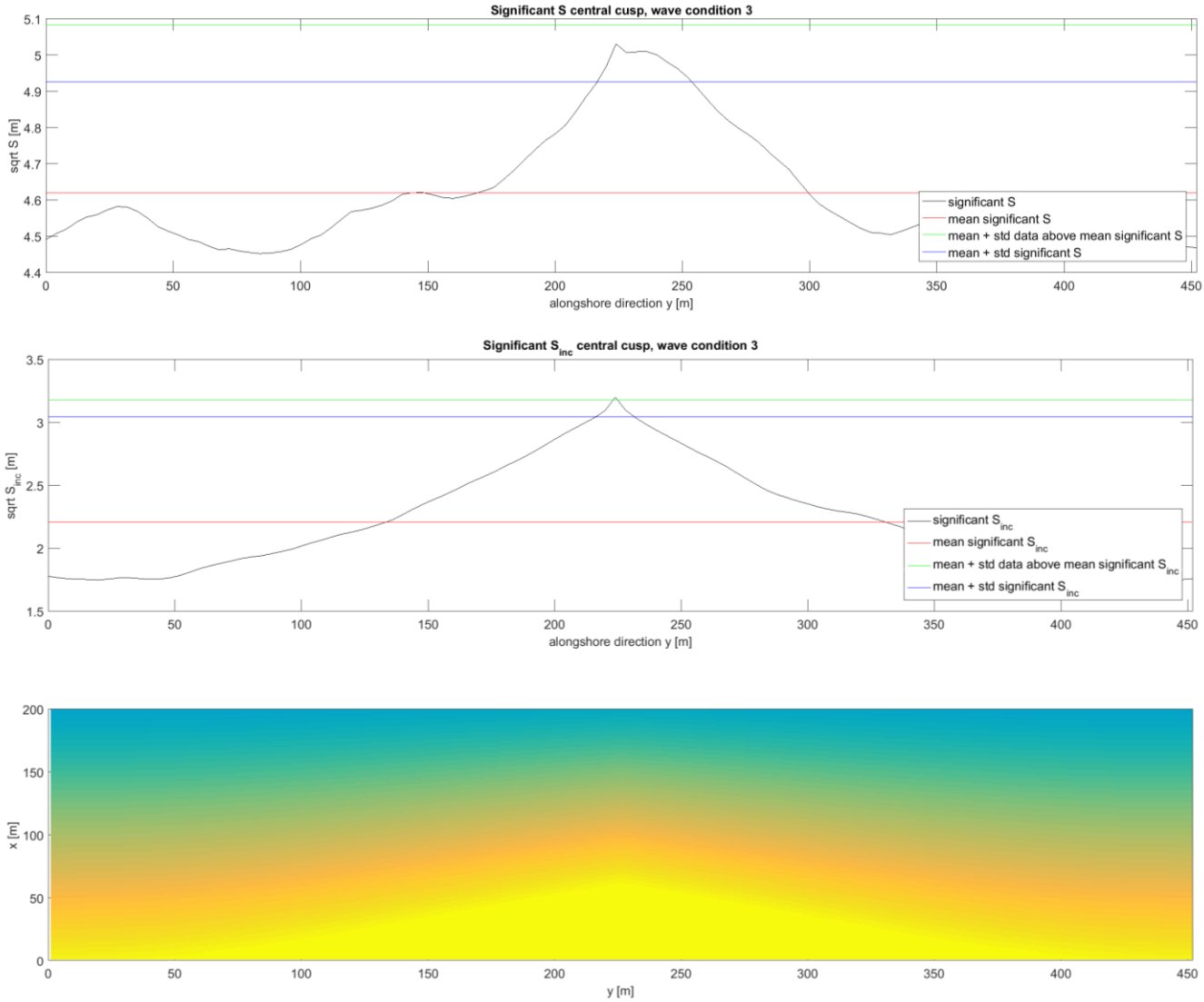

Figure X-2: comparison maximum values for wave condition 3, upper figure: swash, centre figure: incident band swash, bottom figure: bathymetry

Appendix XI Normalized standard deviation (numbers)

Table XI-1 represents the normalized standard deviation of $R_{2\%}$, setup and swash for a cusp length of 452 metres with sandbar (452m SB), 452, 300 and 100 metres.

Calculation number	$R_{2\%}$ 452m SB	452m	300m	100m	Setup 452m SB	452m	300m	100m	Swash 452m SB	452m	300m	100m
1	6,22	6,57	3,98	5,76	11,26	5,63	4,92	6,13	2,86	6,97	5,34	6,00
2	4,44	4,19	2,99	2,88	5,56	1,42	2,67	8,58	3,60	4,01	4,74	1,69
3	2,04	1,91	2,33	4,05	5,42	2,93	4,86	10,30	5,34	3,32	3,36	3,39
4	3,84	3,42	2,87	4,20	6,02	1,81	2,18	6,04	3,07	3,54	2,37	3,10
5	3,11	5,65	3,60	6,05	4,68	1,83	3,31	10,58	3,58	5,98	3,13	4,89
6	4,02	6,26	6,27	4,21	9,51	4,91	3,40	4,33	5,05	6,50	7,23	6,47
7	2,81	6,11	3,25	3,22	3,62	1,53	2,33	8,98	7,49	7,25	4,68	2,93
8	3,53	3,97	4,30	7,27	5,50	1,89	4,46	10,64	6,68	5,12	5,34	3,31
9	4,51	4,53	4,92	4,82	5,32	2,03	1,42	5,21	6,21	4,65	4,98	4,36
10	3,85	4,18	3,60	4,87	5,03	1,59	2,40	10,25	6,14	5,05	3,70	4,32
11	5,17	4,83	5,62	4,25	9,67	4,80	5,60	5,53	4,20	6,57	7,59	6,42
12	3,37	3,71	2,96	5,21	3,44	1,21	2,23	8,46	3,83	4,96	2,65	2,42
13	2,76	3,71	3,68	5,23	4,08	1,42	3,14	9,35	6,72	5,49	4,19	3,41
14	4,12	3,71	4,37	6,48	6,80	2,07	3,22	6,37	2,88	3,42	3,34	5,28
15	4,26	3,91	4,42	5,89	6,67	1,92	3,13	9,02	2,63	3,71	3,94	5,80
16	5,79	7,98	6,81	3,96	8,94	5,21	4,94	4,38	4,74	7,58	8,49	7,85
17	3,22	5,36	2,70	5,11	3,10	1,35	1,85	8,31	7,76	5,68	4,79	3,05
18	5,12	2,42	2,38	6,27	4,39	2,21	3,34	8,32	8,95	5,50	5,40	2,99
19	3,18	7,06	4,55	4,63	4,60	2,37	1,98	5,04	6,63	6,85	4,30	4,91
20	3,29	3,62	3,98	8,25	4,51	2,74	2,47	10,01	5,24	2,92	2,09	6,15
21	4,91	4,76	4,94	4,96	8,08	5,03	3,76	6,06	3,61	4,96	5,62	3,88
22	3,03	5,02	3,41	6,70	3,52	2,82	2,62	11,52	4,72	5,45	3,28	3,13
23	2,65	3,03	3,19	7,56	4,25	2,56	4,37	15,46	5,49	3,92	4,14	3,51
24	5,91	4,55	2,77	7,13	7,40	1,84	2,93	10,18	4,79	3,80	3,13	4,49
25	3,94	5,75	4,26	6,83	5,39	3,26	3,61	12,26	3,56	5,19	3,62	4,04
26	6,09	4,64	6,07	6,26	8,90	4,41	3,78	4,73	7,51	4,88	5,76	7,70
27	2,95	6,08	4,87	6,49	5,03	1,60	2,84	10,36	7,42	6,02	5,49	5,02
28	3,77	4,08	5,25	4,93	6,40	2,86	3,99	11,15	6,25	6,97	5,46	2,26
29	4,63	4,49	5,03	6,10	5,37	2,87	1,61	6,88	6,72	5,92	5,99	7,64
30	2,75	2,88	5,42	5,92	5,12	2,73	4,65	11,32	6,17	3,07	5,40	6,15
31	6,21	6,28	5,40	4,76	9,20	6,74	4,83	6,11	3,67	6,02	3,84	5,41
32	3,98	2,61	3,19	6,54	1,63	1,13	2,45	10,40	6,96	4,24	2,54	2,71
33	2,26	6,09	3,01	7,33	4,87	1,38	4,07	12,17	5,34	6,45	3,35	3,51
34	4,07	3,79	3,82	7,16	6,56	2,63	2,34	8,50	3,58	4,97	3,48	6,65
35	3,40	3,09	3,42	6,96	5,78	2,79	3,61	11,71	4,65	2,14	1,14	5,39
36	5,35	5,98	4,85	6,54	7,76	5,33	4,22	4,68	6,44	6,32	5,11	7,77
37	3,67	5,34	4,42	6,16	2,81	1,21	2,59	9,34	9,85	5,32	4,79	6,05
38	3,06	3,48	3,54	5,97	4,57	2,13	3,66	10,20	8,25	5,26	5,15	3,35
39	3,81	5,30	6,74	7,11	4,96	2,91	2,31	7,09	6,40	5,44	6,50	8,29

40	3,06	3,87	1,89	5,80	4,74	2,76	3,57	8,00	4,66	2,69	1,49	4,60
41	15,30	4,72	3,67	8,42	19,37	5,35	5,78	9,59	11,07	4,03	3,20	7,61
42	7,37	2,50	3,06	12,55	12,21	2,74	4,70	15,83	5,27	3,84	4,32	6,53
43	5,76	3,69	4,92	10,64	9,08	4,13	5,78	18,90	5,97	4,76	5,47	5,98
44	11,83	4,92	4,27	11,21	16,26	2,86	5,33	13,08	8,81	4,22	4,22	7,72
45	3,63	3,37	5,04	13,80	7,86	3,65	6,91	18,50	3,71	4,77	3,26	7,45
46	7,76	9,06	8,95	5,31	11,52	8,19	11,61	8,41	8,24	8,31	7,53	8,81
47	2,59	6,88	5,51	5,31	6,51	3,91	3,13	8,74	8,89	7,58	6,14	5,41
48	4,40	4,67	2,79	4,94	8,05	3,85	4,08	10,48	6,64	7,98	3,24	3,90
49	5,49	7,18	4,90	11,80	8,27	7,57	5,90	12,55	7,14	7,37	5,53	10,59
50	3,55	4,30	7,24	8,97	6,78	2,86	4,06	12,12	6,17	6,08	5,22	8,63
51	12,94	4,41	7,45	5,79	17,27	6,23	6,51	8,96	10,88	3,29	5,56	7,58
52	8,12	3,66	4,98	10,79	10,06	2,24	4,24	15,31	6,62	3,83	4,30	7,41
53	5,59	2,22	5,72	10,69	8,04	2,94	5,60	16,55	6,43	3,36	4,91	4,74
54	11,91	3,75	6,55	12,38	16,85	2,93	5,52	14,81	9,81	2,53	4,46	9,88
55	3,83	3,40	2,54	14,30	9,25	3,75	7,69	20,21	1,74	2,42	4,53	10,09
56	8,29	7,36	8,99	10,65	9,77	8,63	8,47	11,73	10,71	7,03	7,03	10,82
57	4,05	7,79	8,22	6,36	5,26	3,88	3,91	9,09	10,04	7,94	6,93	4,86
58	4,34	5,79	5,31	4,71	8,57	4,07	2,75	8,90	6,57	6,89	4,10	4,23
59	5,10	7,04	6,81	11,23	5,63	6,65	3,82	12,31	7,02	7,00	7,31	9,54
60	3,39	3,25	5,87	8,86	6,58	3,06	4,35	9,13	6,03	6,19	4,23	8,49

Table XI-1: normalized values of the standard deviation in alongshore direction for $R_{2\%}$, setup and swash for 452m cusp bar length, 452, 300 and 100 metres cusp length

Table XI-2 represents the normalized standard deviation of infragravity and incident band swash for a cusp length of 452 metres with sandbar (452m SB), 452, 300 and 100 metres.

Calculation number	Infragravity Swash				Incident Swash			
	452m SB	452m	300m	100m	452m SB	452m	300m	100m
1	8,70	2,89	2,33	6,61	10,51	13,30	13,69	16,98
2	5,99	2,18	2,78	8,31	17,69	16,64	17,37	22,79
3	1,99	2,82	3,18	6,21	19,50	18,97	18,01	26,33
4	7,13	3,64	4,97	10,17	9,64	11,41	10,53	12,28
5	2,49	5,01	2,48	12,32	14,22	15,95	14,54	14,96
6	5,34	3,88	4,64	7,70	11,93	13,63	13,12	16,15
7	3,10	5,52	3,62	7,88	18,63	16,14	18,68	22,25
8	3,73	2,24	4,12	8,63	17,31	18,46	18,68	26,18
9	5,68	2,71	6,00	10,74	10,72	12,17	8,93	13,75
10	3,05	2,87	2,41	11,29	15,64	14,96	12,83	15,59
11	8,40	3,67	3,04	5,62	10,91	12,97	14,72	16,41
12	5,87	3,44	3,62	7,35	17,66	17,32	18,07	22,84
13	2,27	2,05	2,53	8,47	19,87	17,97	19,75	27,39
14	7,13	4,14	7,61	10,82	7,93	10,59	7,88	12,65
15	5,55	3,73	6,71	13,38	14,23	11,74	14,68	15,84
16	5,49	5,38	4,58	4,32	10,80	12,07	14,91	17,19
17	3,23	2,69	2,87	8,59	18,23	16,40	17,81	21,59

18	5,76	2,33	3,20	8,21	17,90	17,42	19,32	24,92
19	4,65	6,55	3,64	10,66	11,18	12,13	11,01	8,65
20	3,05	3,91	4,12	12,84	14,51	12,78	15,26	16,25
21	7,87	2,99	3,20	9,44	12,24	12,24	14,26	15,18
22	4,73	4,32	3,77	11,49	18,59	16,03	15,35	25,59
23	1,82	2,00	3,27	8,91	18,71	18,78	19,73	30,43
24	12,14	2,43	5,76	10,94	9,00	11,62	9,93	11,81
25	4,18	4,28	3,41	11,40	17,54	15,11	15,87	19,76
26	9,24	1,57	2,60	8,04	13,29	11,81	12,88	15,80
27	3,90	3,84	5,60	11,42	18,11	17,42	17,94	22,15
28	4,16	4,50	3,64	7,38	15,59	18,44	20,64	26,30
29	5,41	7,29	5,92	11,03	11,69	11,93	10,69	9,85
30	4,35	1,70	5,71	12,83	15,35	13,89	15,51	17,61
31	8,57	2,86	2,09	5,73	11,53	12,89	11,91	16,28
32	5,08	3,35	5,54	10,86	19,37	15,98	17,27	24,39
33	2,52	4,00	3,19	9,25	19,85	17,97	19,52	29,82
34	7,19	4,61	2,83	12,49	6,39	10,67	11,51	11,43
35	2,89	2,58	3,28	11,53	14,01	12,23	14,42	17,46
36	4,81	4,70	3,79	9,82	13,72	12,82	10,21	16,10
37	5,36	4,94	5,26	11,95	20,28	18,04	18,77	23,43
38	5,46	2,14	3,73	9,33	18,92	18,93	19,08	26,11
39	3,93	6,56	6,54	12,87	11,93	11,88	9,89	8,40
40	2,83	3,97	1,63	10,59	16,22	12,60	12,22	17,46
41	18,48	5,66	4,22	16,15	11,12	11,97	11,59	16,65
42	7,51	2,85	4,95	13,24	19,28	18,32	18,85	27,01
43	5,22	3,86	4,71	10,25	21,13	19,67	22,17	34,47
44	14,06	3,38	3,93	14,38	7,59	13,57	12,99	16,64
45	2,35	3,74	2,91	13,32	17,45	18,33	15,37	27,83
46	9,61	7,18	5,91	15,64	12,47	13,05	12,16	13,78
47	6,01	5,84	4,54	10,64	18,46	17,75	18,00	21,00
48	5,42	6,64	1,91	6,84	15,67	16,72	18,41	25,79
49	4,83	6,69	4,91	14,63	12,85	14,62	13,11	10,36
50	4,43	4,58	3,81	13,86	16,64	16,97	15,81	17,22
51	19,03	3,29	8,43	14,12	10,44	12,68	10,95	14,73
52	8,83	2,89	5,16	14,00	20,39	18,00	20,33	28,75
53	5,25	2,28	3,94	8,92	19,53	20,09	19,72	33,01
54	13,78	3,23	4,71	14,98	4,57	11,06	14,09	14,63
55	3,68	1,72	5,41	14,49	18,16	15,43	16,92	24,62
56	10,79	5,39	5,42	16,90	14,55	12,59	12,29	13,19
57	6,03	6,54	6,36	8,15	20,56	17,74	18,72	21,25
58	5,60	5,56	3,13	7,79	15,36	16,73	19,85	25,21
59	5,10	6,54	7,21	12,43	14,80	11,77	10,36	10,73
60	4,61	5,64	4,22	12,98	15,03	12,65	13,86	16,31

Table XI-2: normalized values of the standard deviation in alongshore direction for infragravity band swash and incident band swash for 452m cusp bar length, 452, 300 and 100 metres cusp length

Appendix XII Normalized standard deviation (plots)

Appendix XII-i Normalized standard deviation for 300 m cusp

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-1, plotted versus wave height.

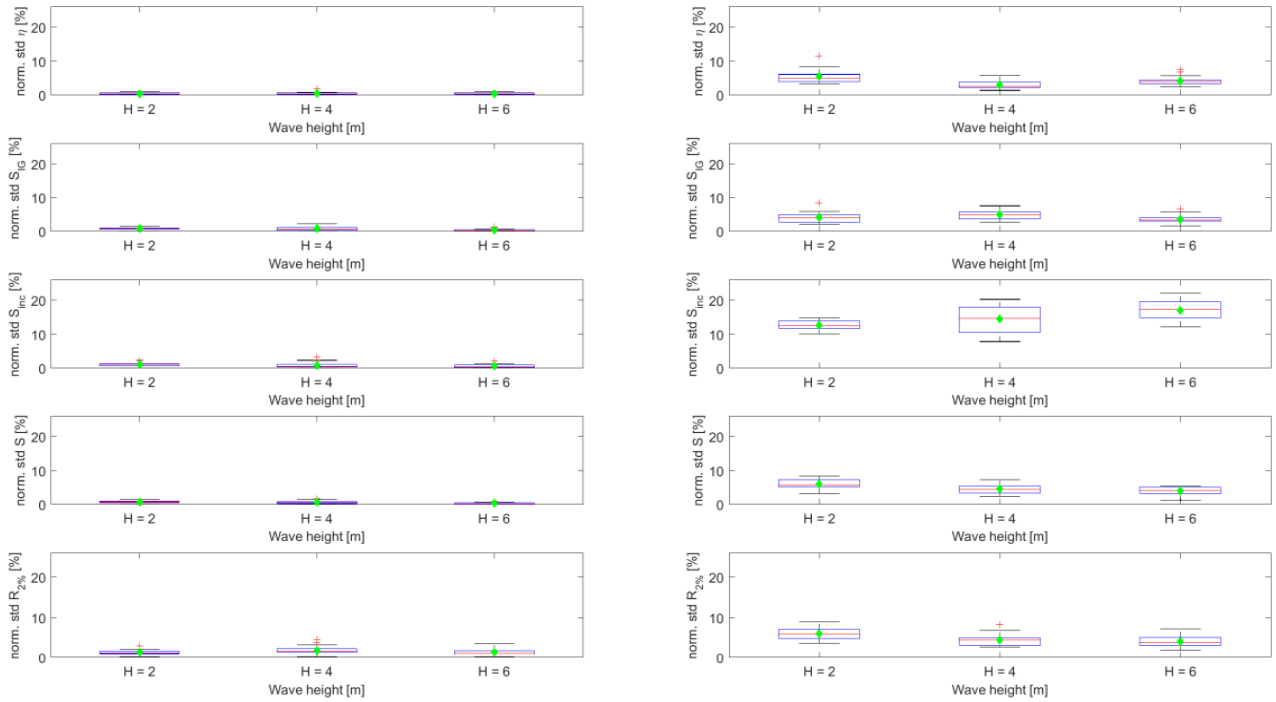

Figure XII-1: boxplots normalized standard deviation in alongshore direction versus wave height for 300 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-2, plotted versus steepness.

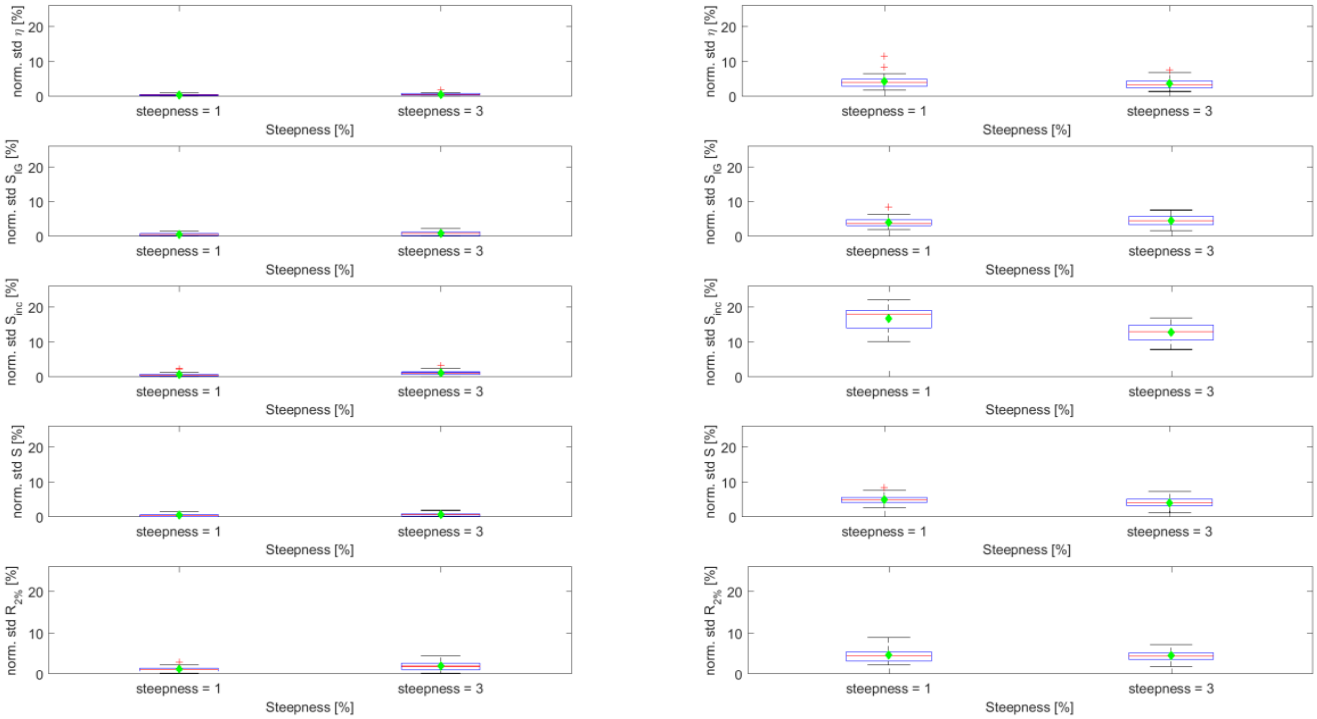

Figure XII-2: boxplots normalized standard deviation in alongshore direction versus steepness for 300 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

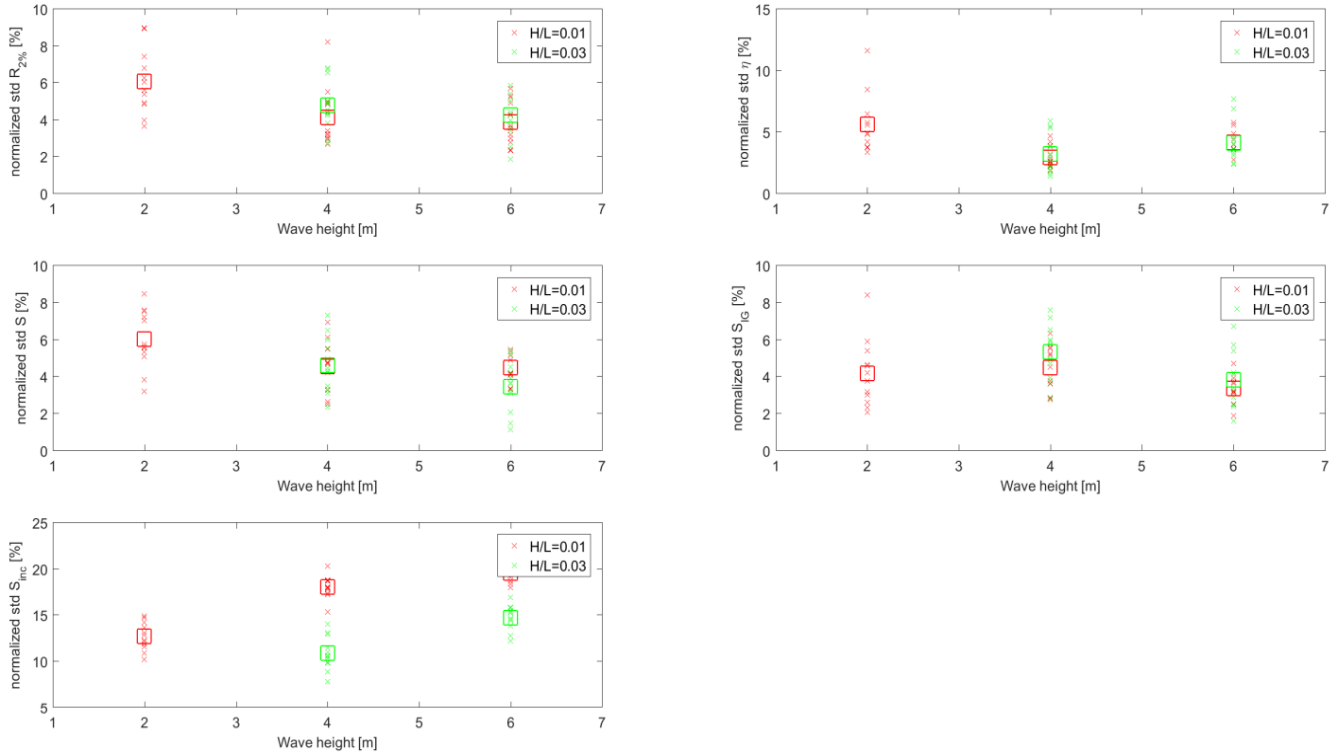

Figure XII-3: normalized standard deviation in alongshore direction versus wave height for 300 m cusp, red: steepness 1%, green: steepness 3%, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-5, plotted versus angle of incidence.

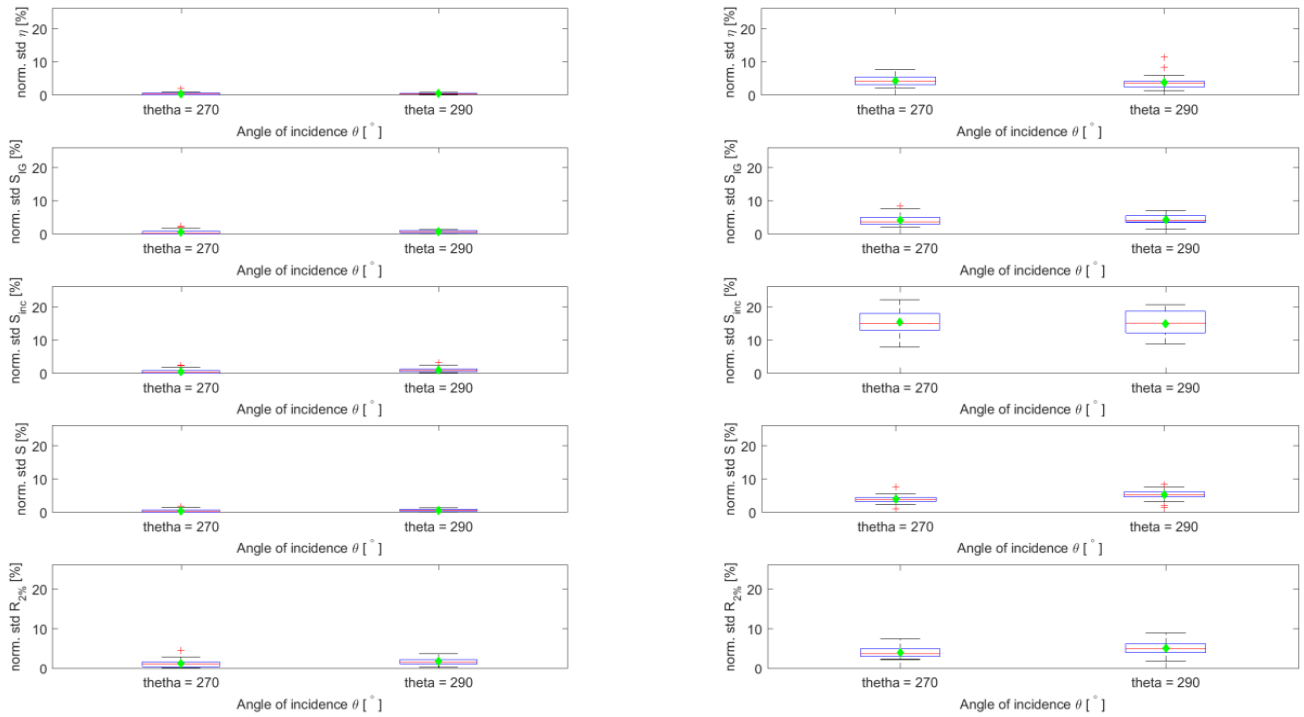

Figure XII-5: boxplots normalized standard deviation in alongshore direction versus angle of incidence for 300 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

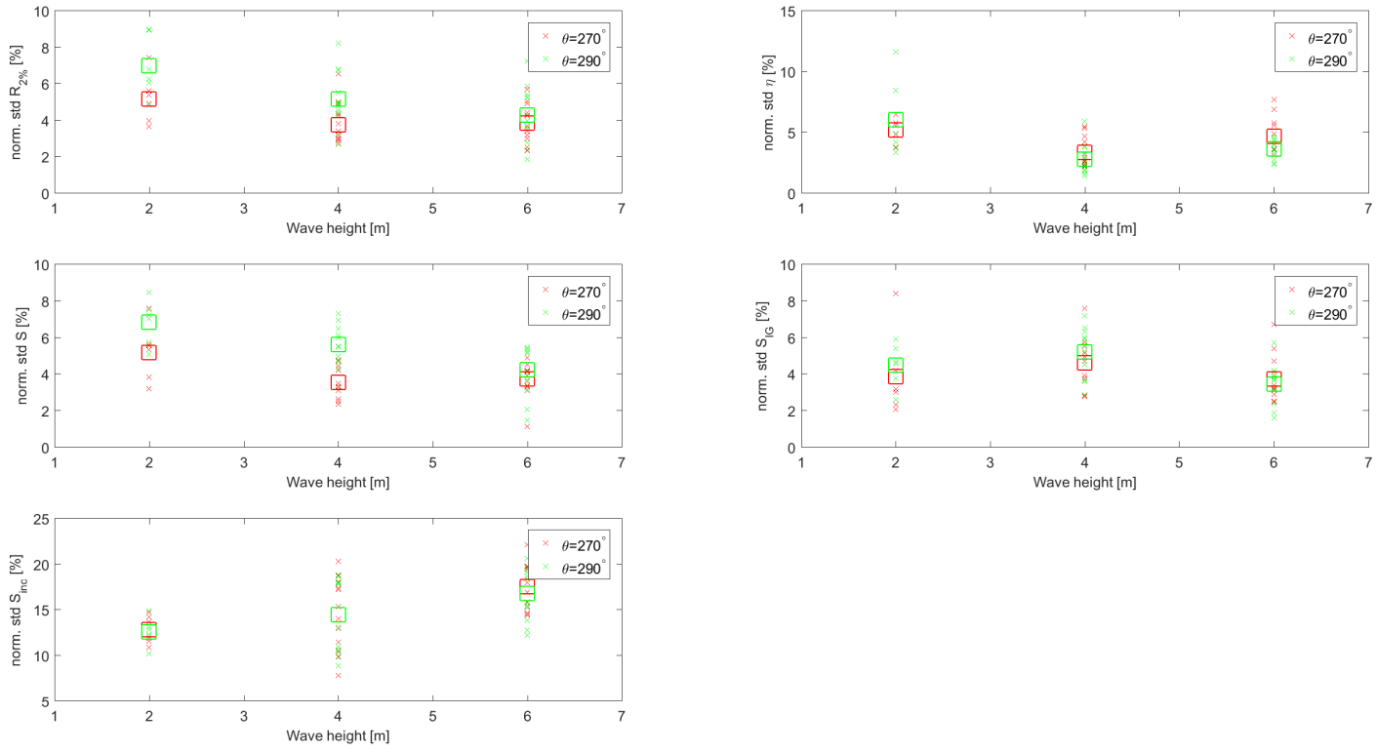

Figure XII-4: normalized standard deviation in alongshore direction versus wave height for 300 m cusp, red: angle of incidence 270 deg, green: angle of incidence 290 deg, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-6, plotted versus frequency spreading.

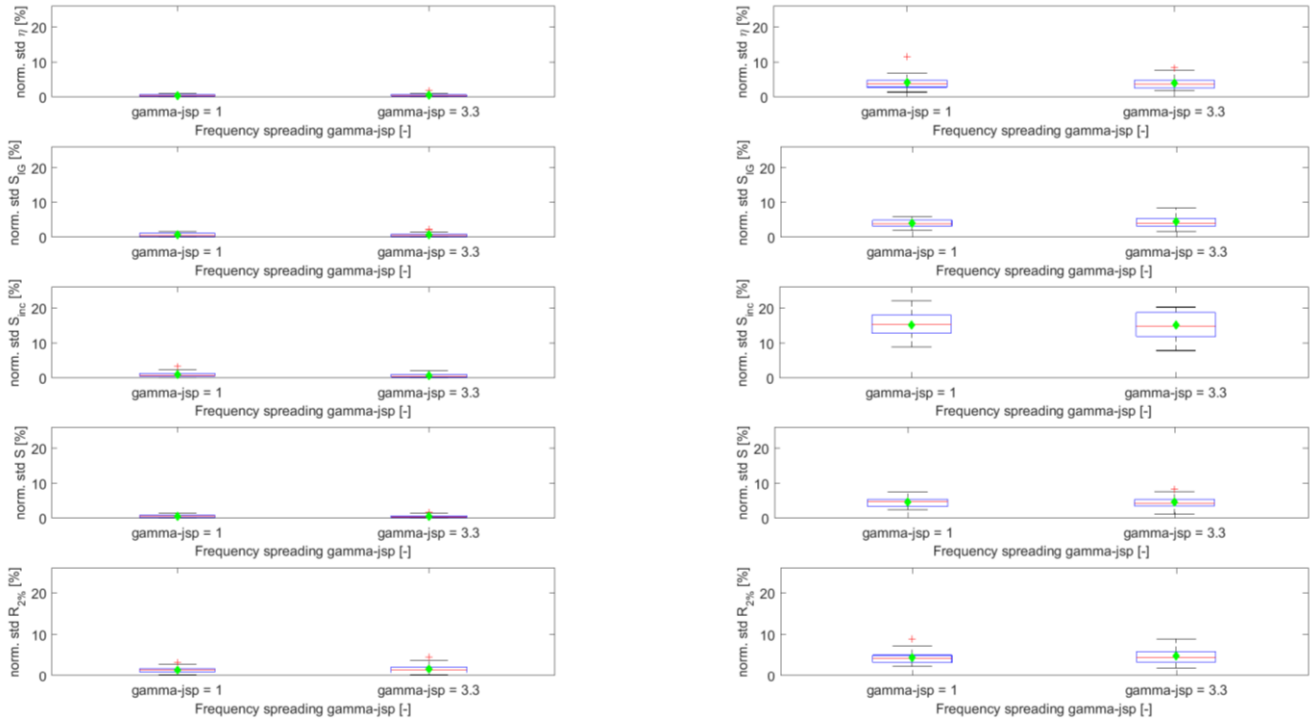

Figure XII-6: boxplots normalized standard deviation in alongshore direction versus frequency spreading for 300 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

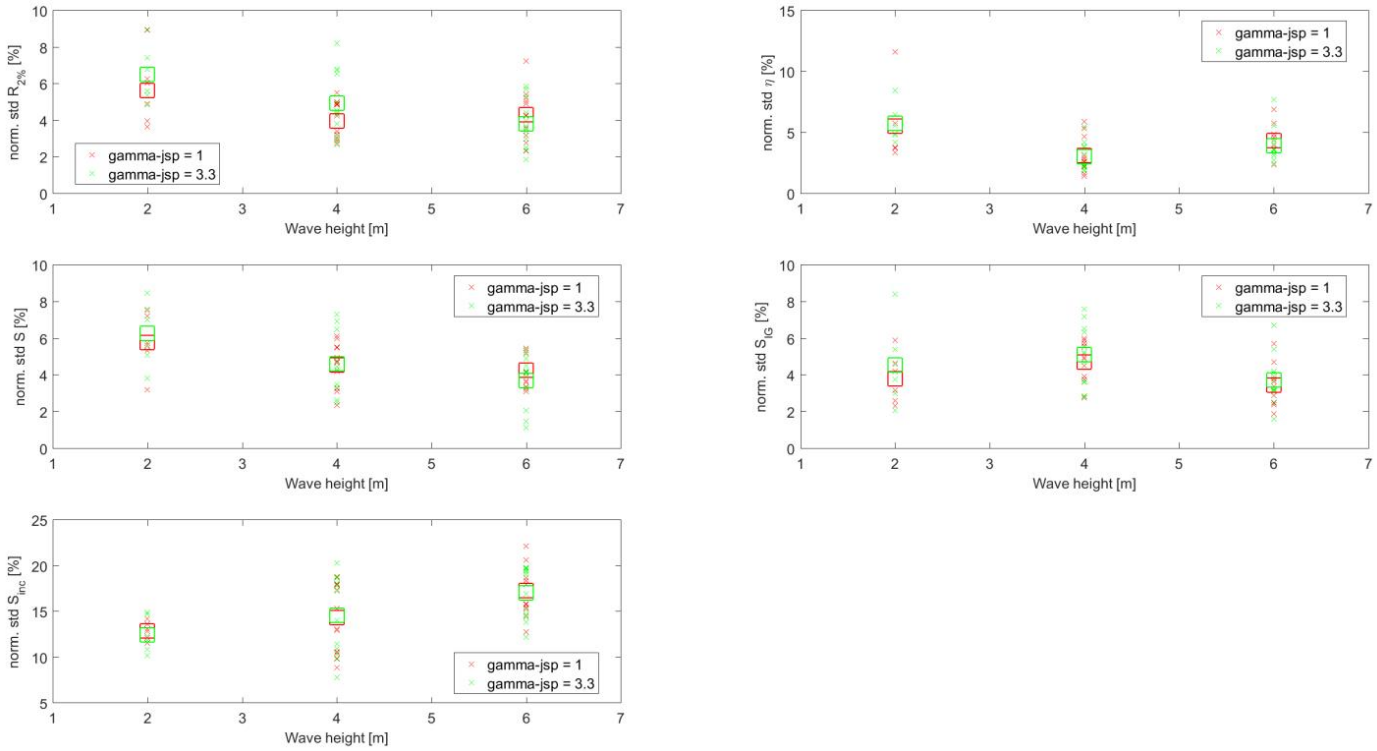

Figure XII-7: normalized standard deviation in alongshore direction versus wave height for 300 m cusp, red: frequency spreading 1, green: frequency spreading 3.3, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-8, plotted versus directional spreading.

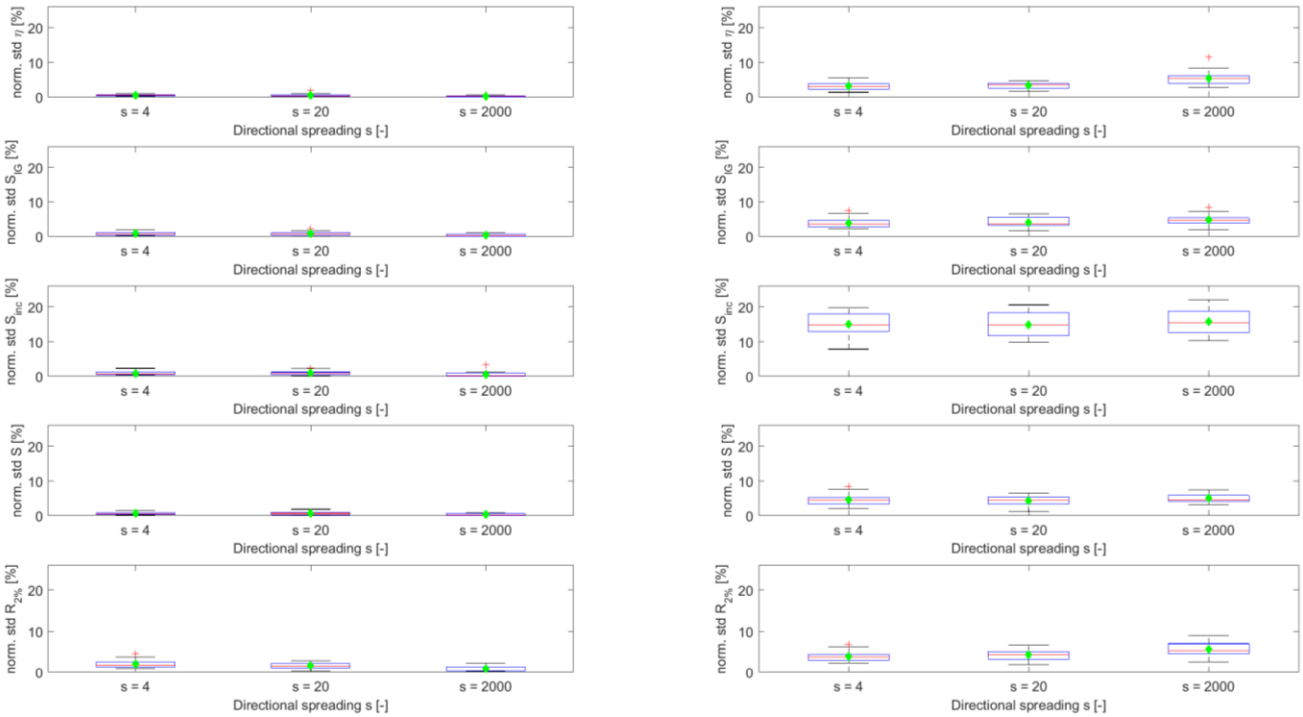

Figure XII-8: boxplots normalized standard deviation in alongshore direction versus directional spreading for 300 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

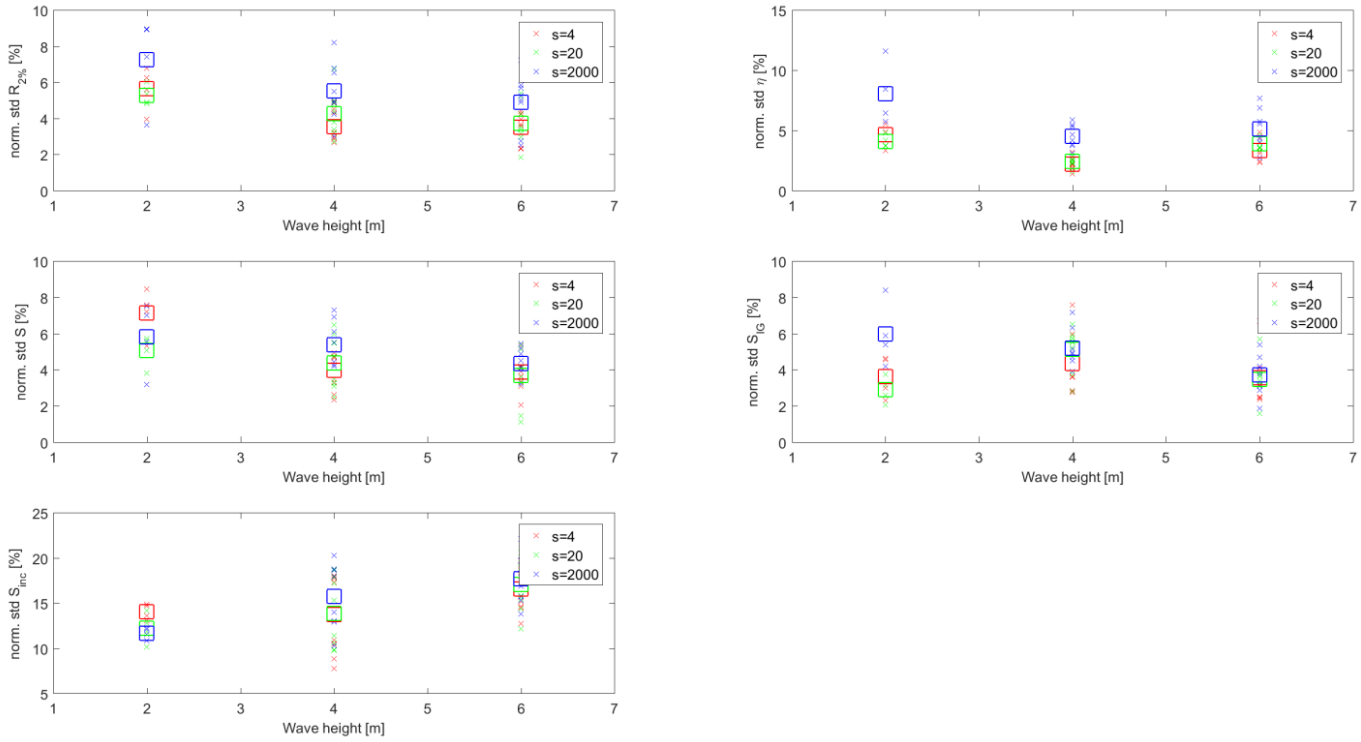

Figure XII-9: normalized standard deviation in alongshore direction versus wave height for 300 m cusp, red: directional spreading 4, green: directional spreading 20, blue: directional spreading 2000, squares represents the mean value

Appendix XII-ii Normalized standard deviation for 100 m cusp

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-10, plotted versus wave height.

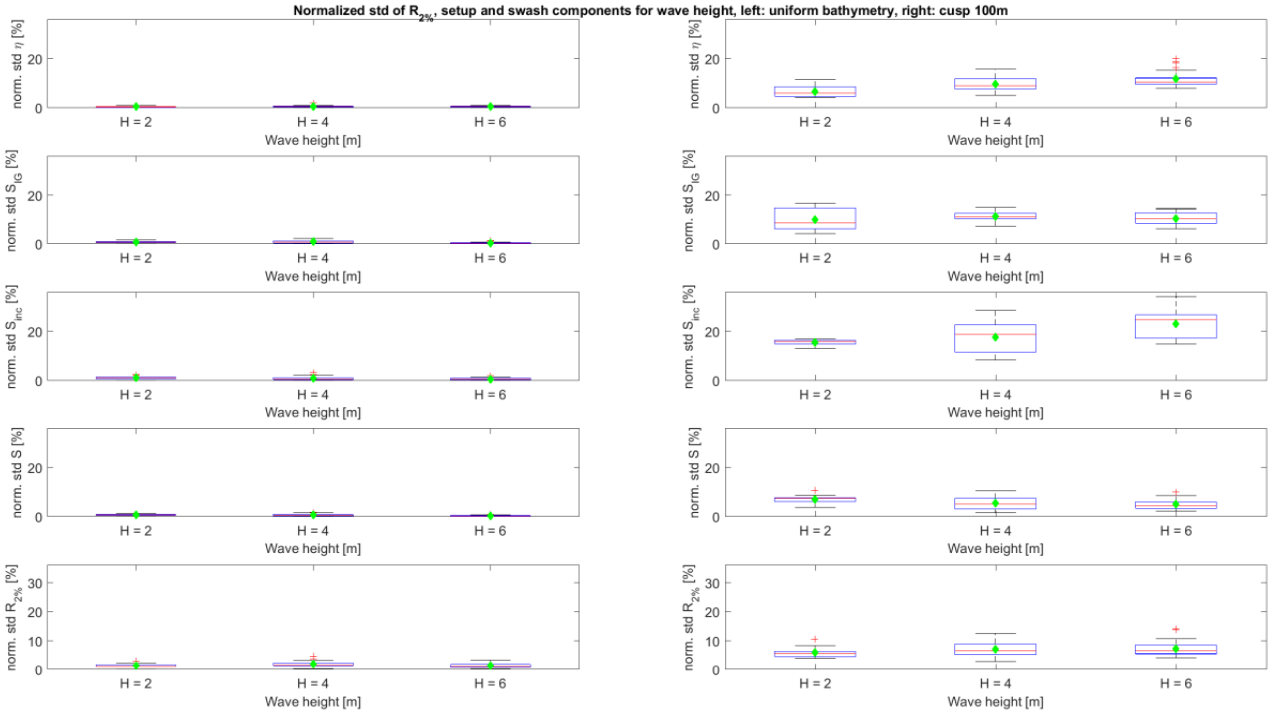

Figure XII-10: boxplots normalized standard deviation in alongshore direction versus wave height for 100 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-11, plotted versus steepness.

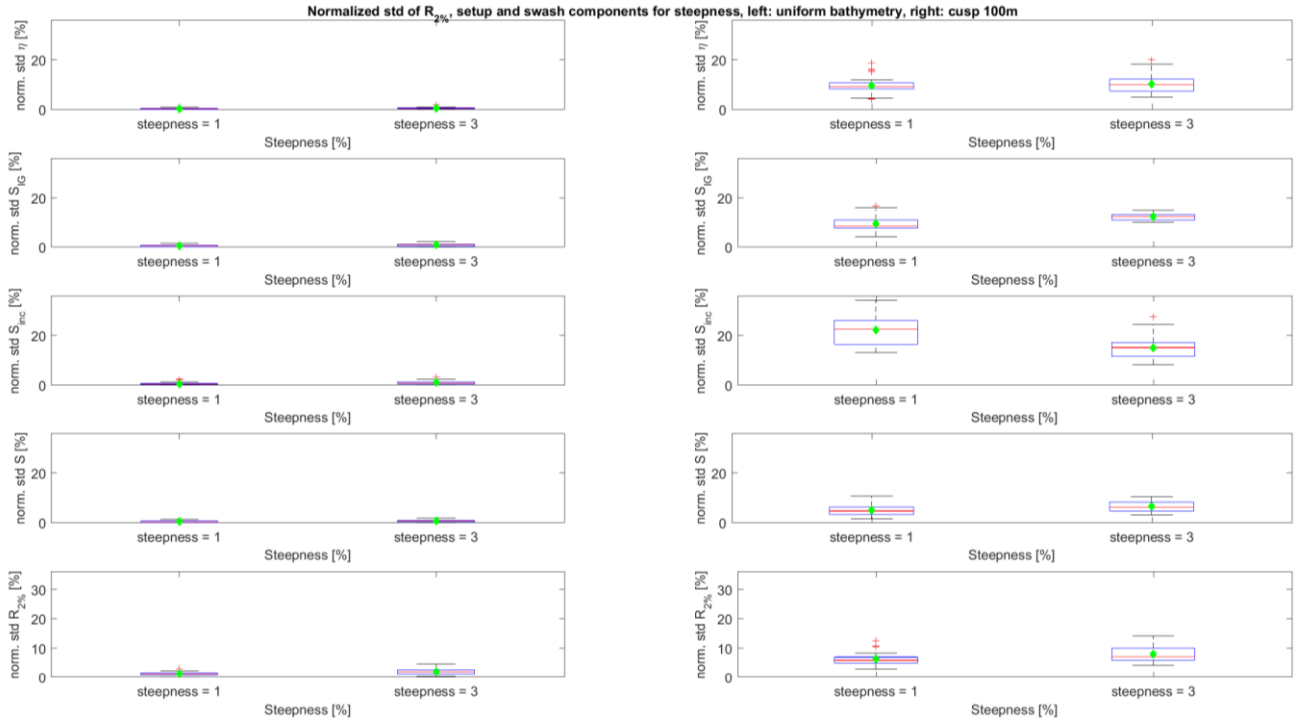

Figure XII-11: boxplots normalized standard deviation in alongshore direction versus steepness for 100 m cusp, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

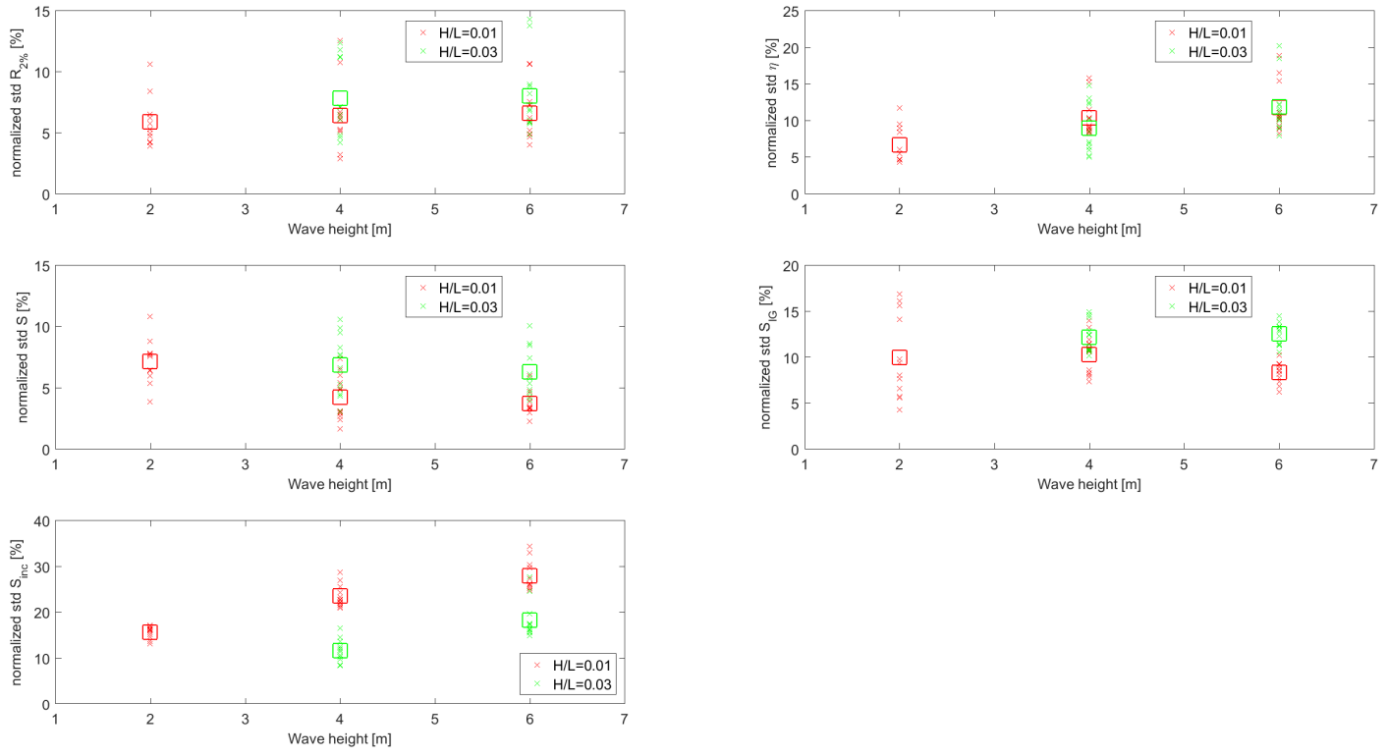

Figure XII-12: normalized standard deviation in alongshore direction versus wave height for 100 m cusp, red: steepness 1%, green: steepness 3%, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-13, plotted versus angle of incidence.

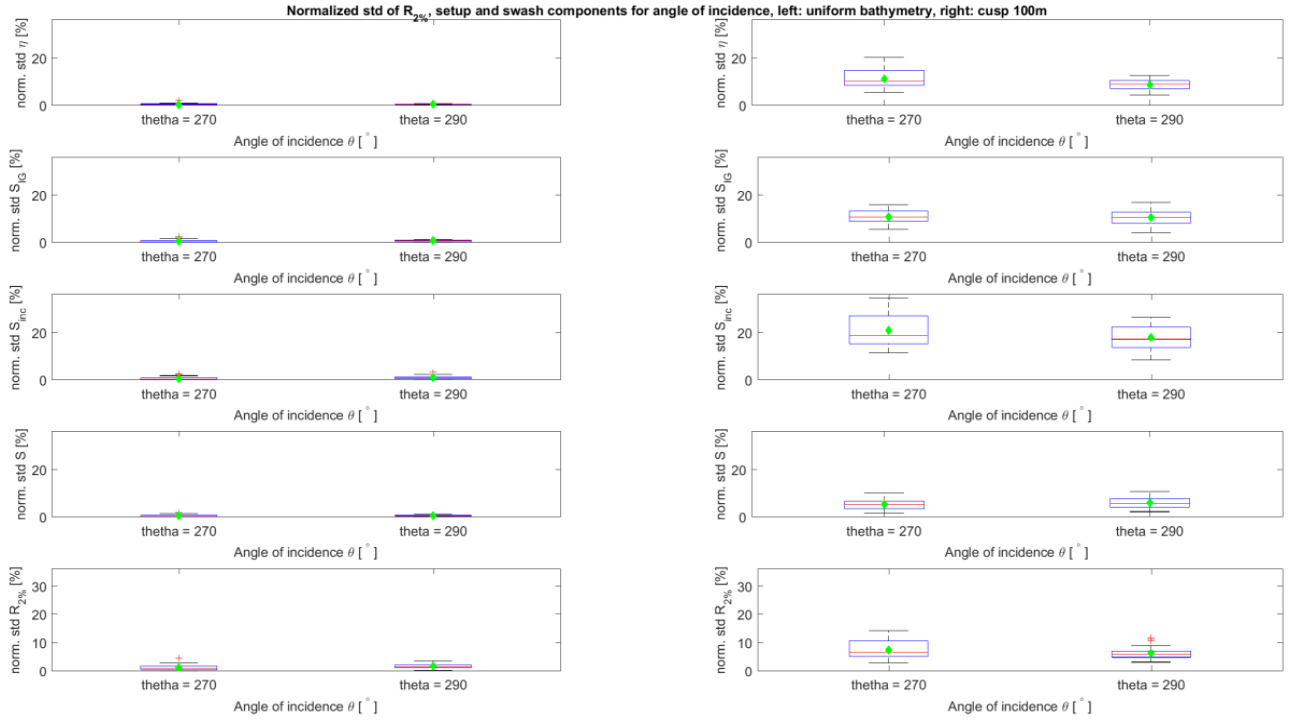

Figure XII-13: boxplots normalized standard deviation in alongshore direction versus angle of incidence for 100 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

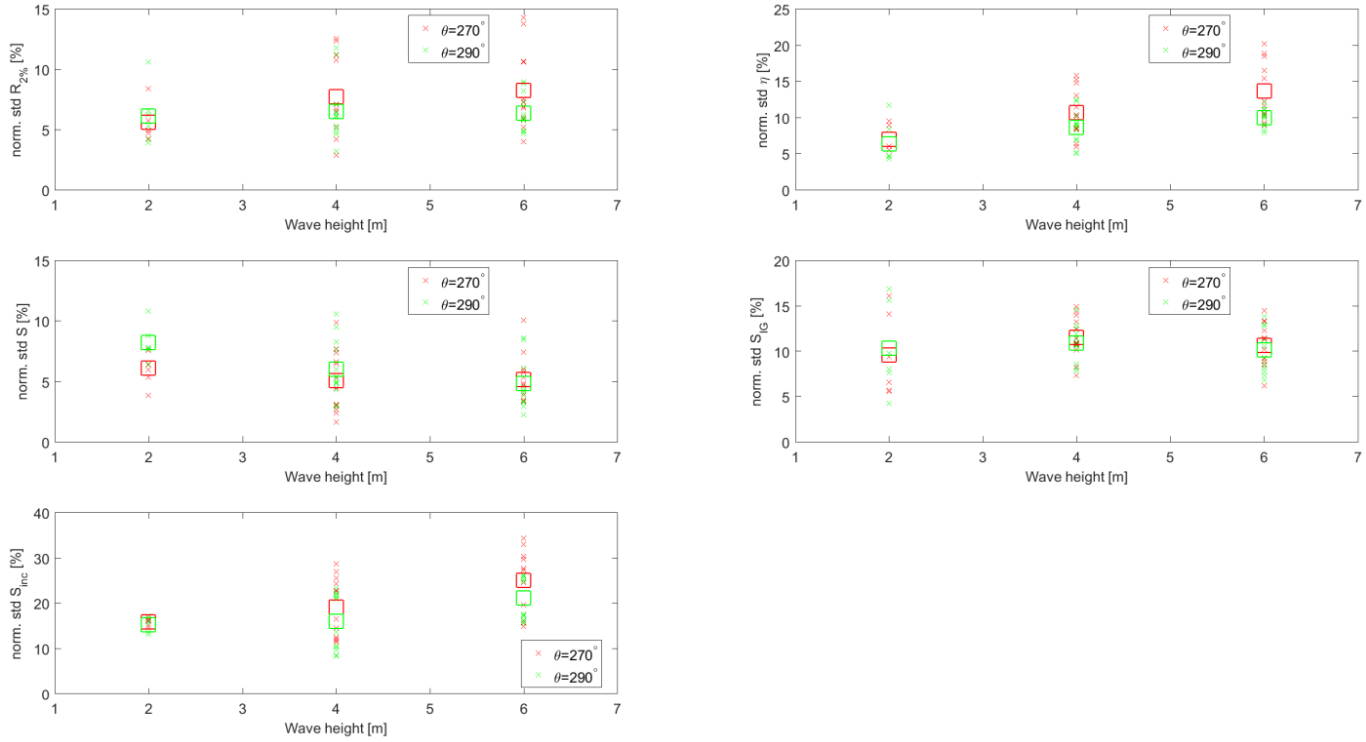

Figure XII-14: normalized standard deviation in alongshore direction versus wave height for 100 m cusp, red: angle of incidence 270 deg, green: angle of incidence 290 deg, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-15, plotted versus frequency spreading.

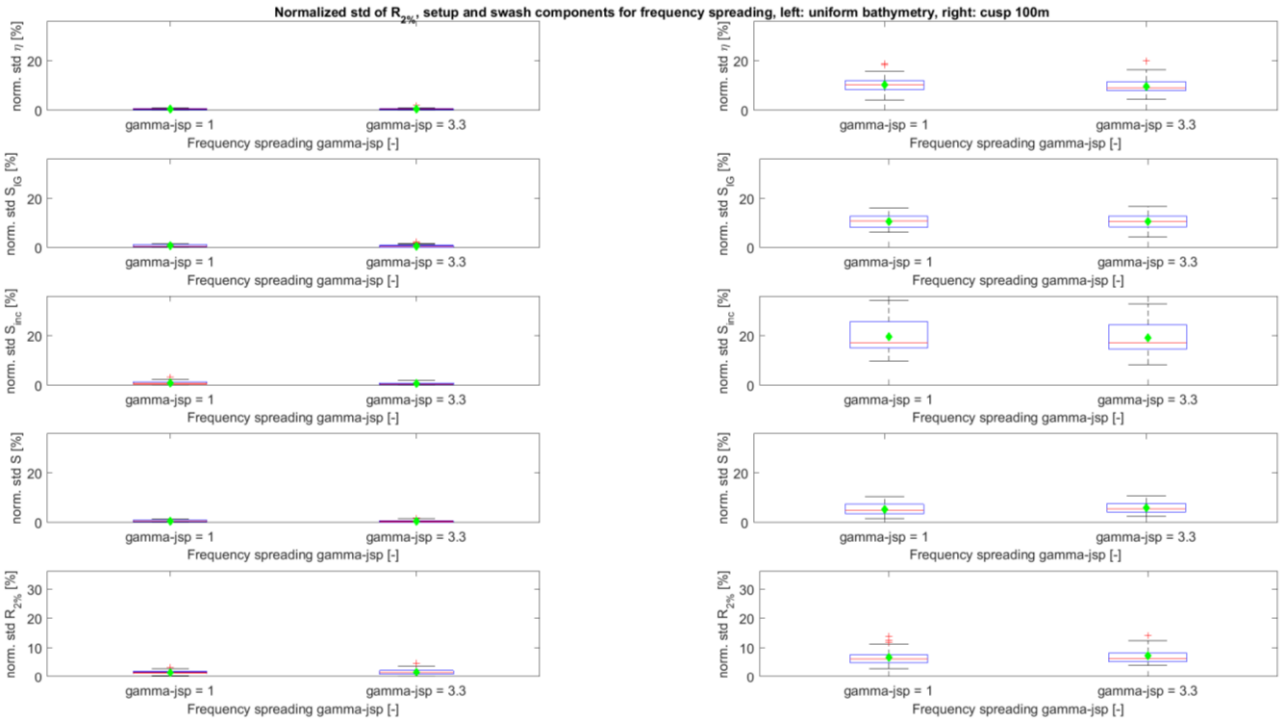

Figure XII-15: boxplots normalized standard deviation in alongshore direction versus frequency spreading for 100 m cusp, R2% upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

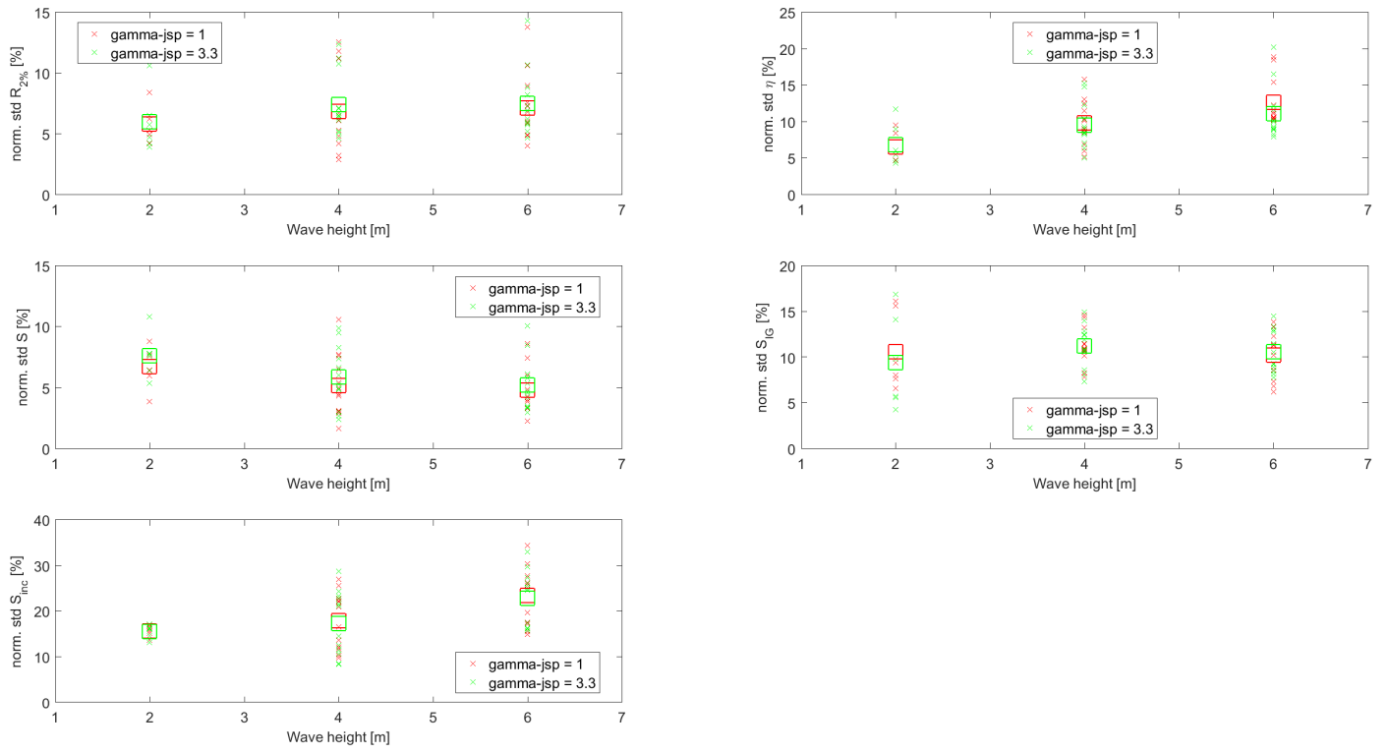

Figure XII-16: normalized standard deviation in alongshore direction versus wave height for 100 m cusp, red: frequency spreading 1, green: frequency spreading 3.3, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-17, plotted versus directional spreading.

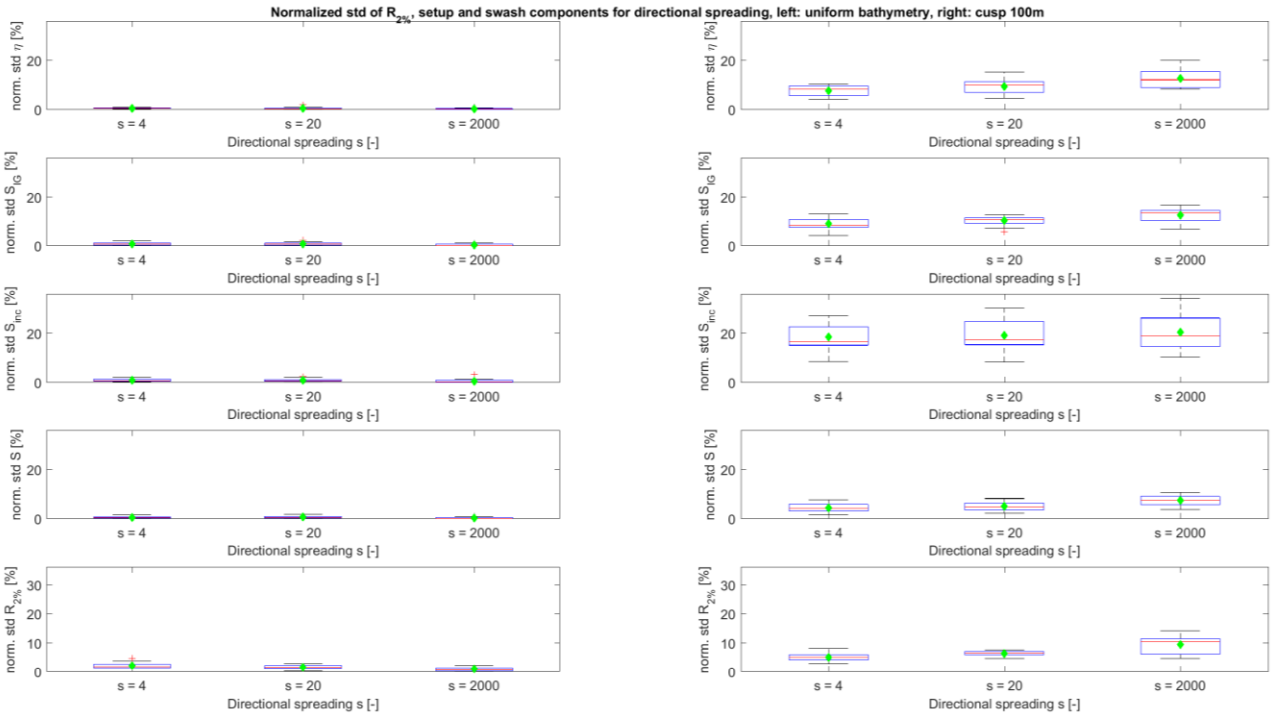

Figure XII-17: boxplots normalized standard deviation in alongshore direction versus directional spreading for 100 m cusp, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

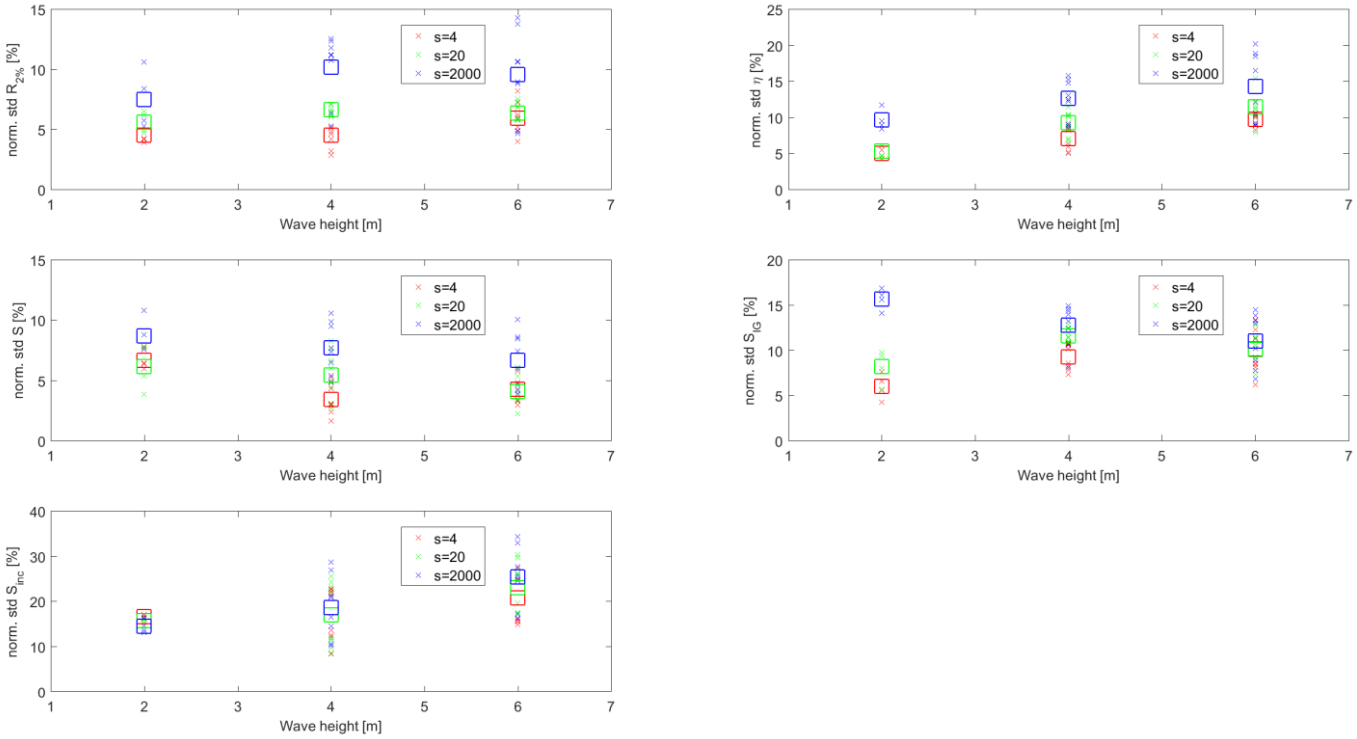

Figure XII-18: normalized standard deviation in alongshore direction versus wave height for 100 m cusp, red: directional spreading 4, green: directional spreading 20, blue: directional spreading 2000, squares represents the mean value

Appendix XII-iii Normalized standard deviation for 452 m cusp bar system

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-19, plotted versus wave height.

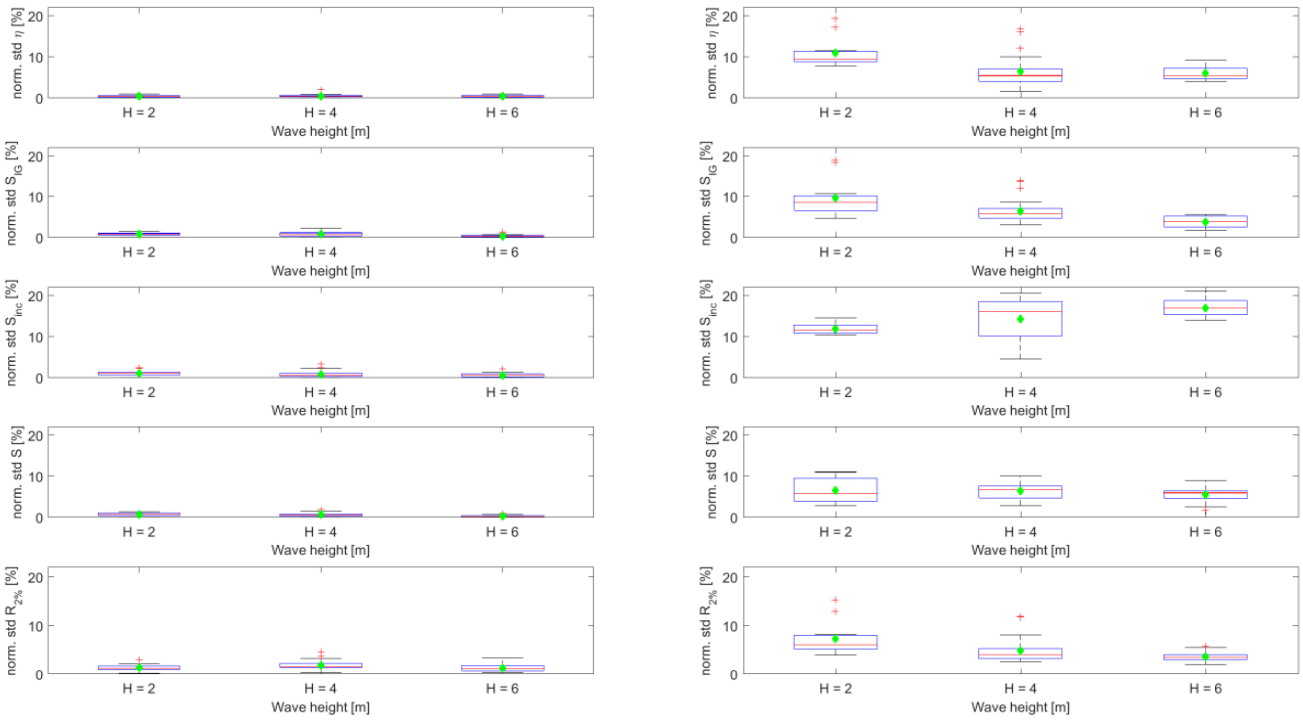

Figure XII-19: boxplots normalized standard deviation in alongshore direction versus wave height 452m cusp bar system, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-20, plotted versus steepness.

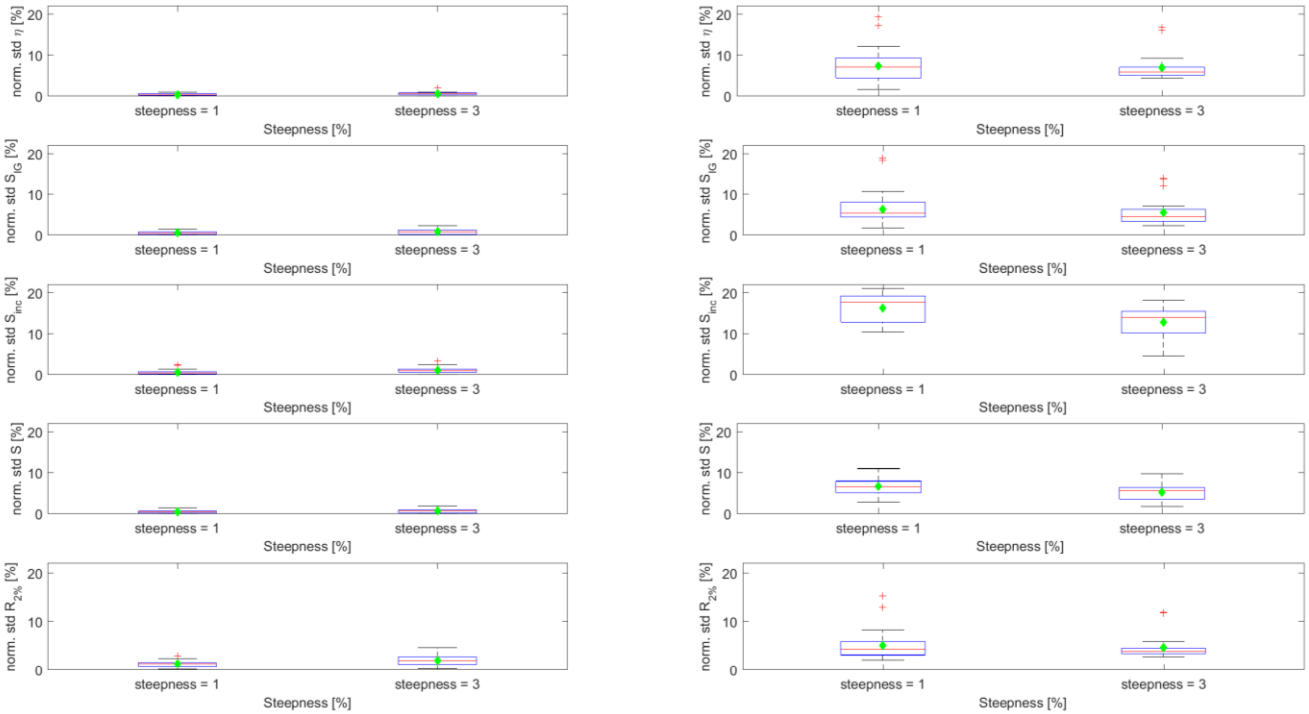

Figure XII-20: boxplots normalized standard deviation in alongshore direction versus steepness 452m cusp bar system, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

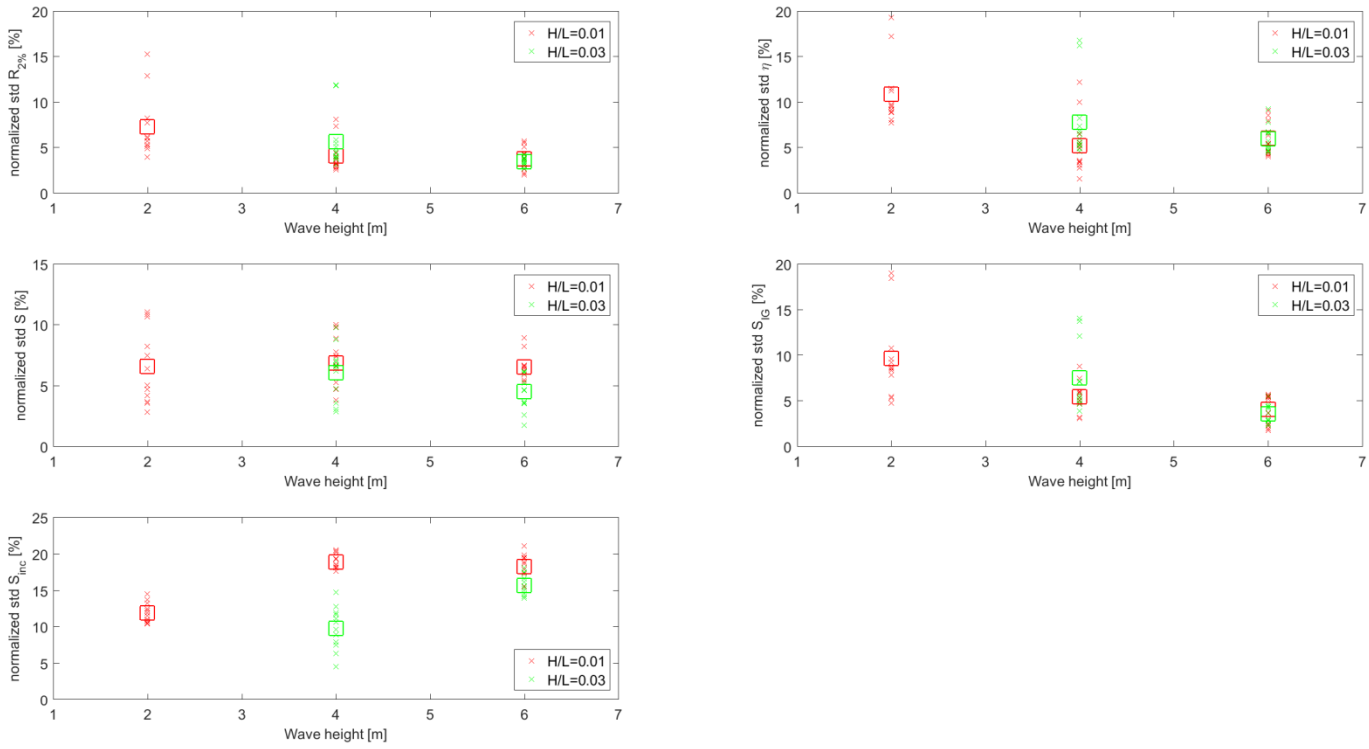

Figure XII-21: normalized standard deviation in alongshore direction versus wave height 452m cusp bar system, red: steepness 1%, green: steepness 3%, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-22, plotted versus angle of incidence.

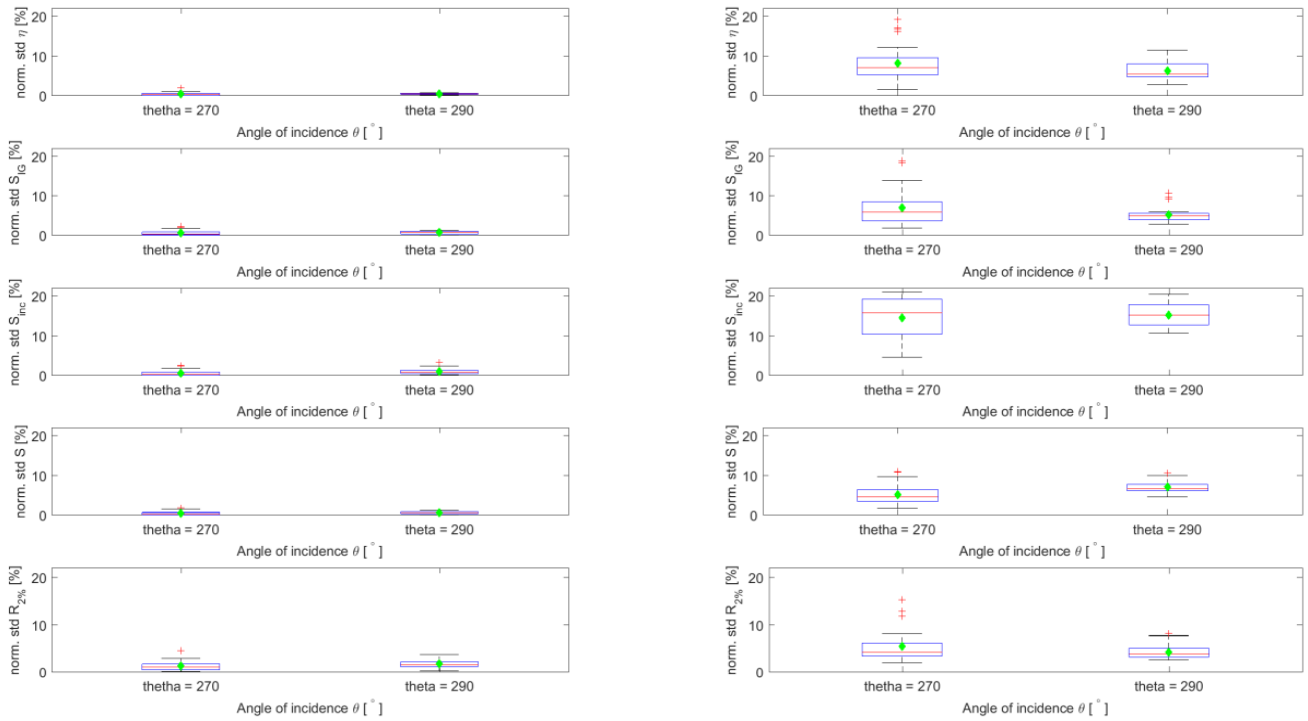

Figure XII-22: boxplots normalized standard deviation in alongshore direction versus angle of incidence 452m cusp bar system, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

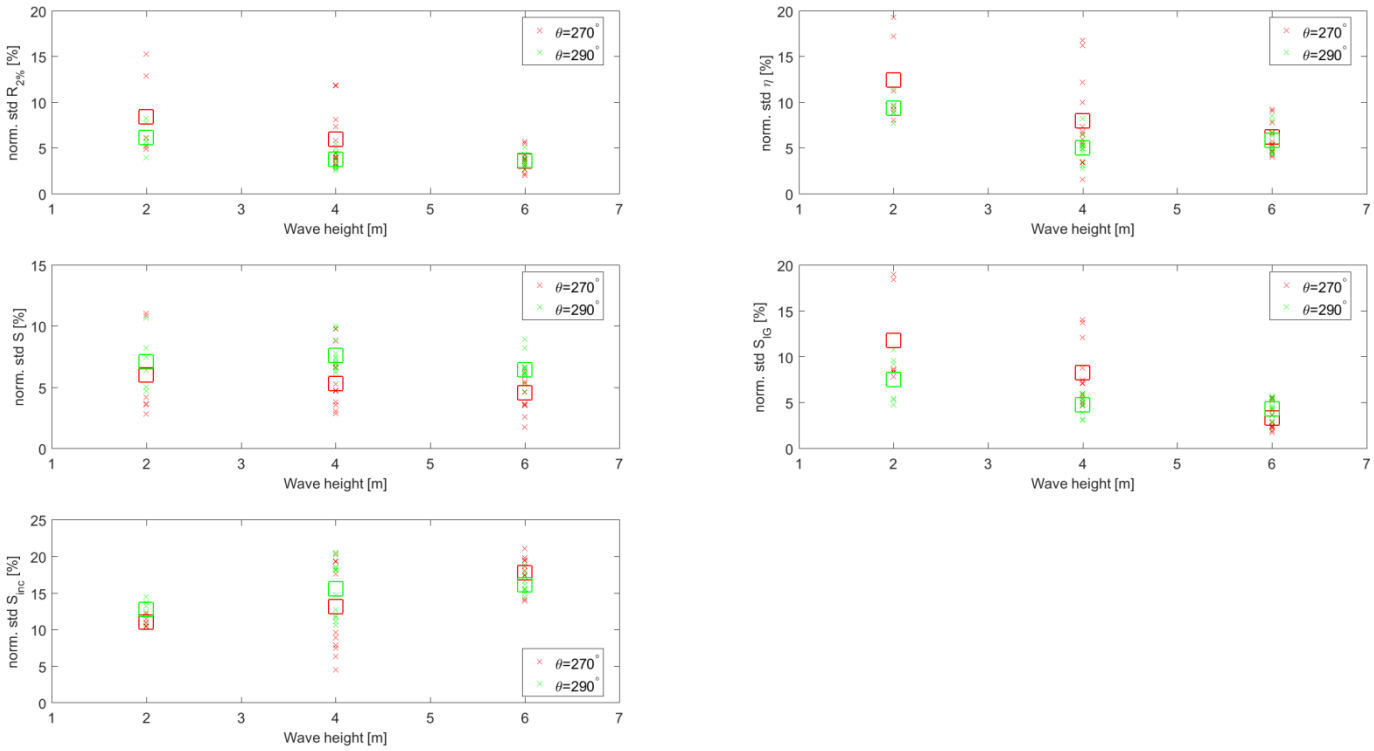

Figure XII-23: normalized standard deviation in alongshore direction versus wave height 452m cusp bar system, red: angle of incidence 270 deg, green: angle of incidence 290 deg, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-24, plotted versus frequency spreading.

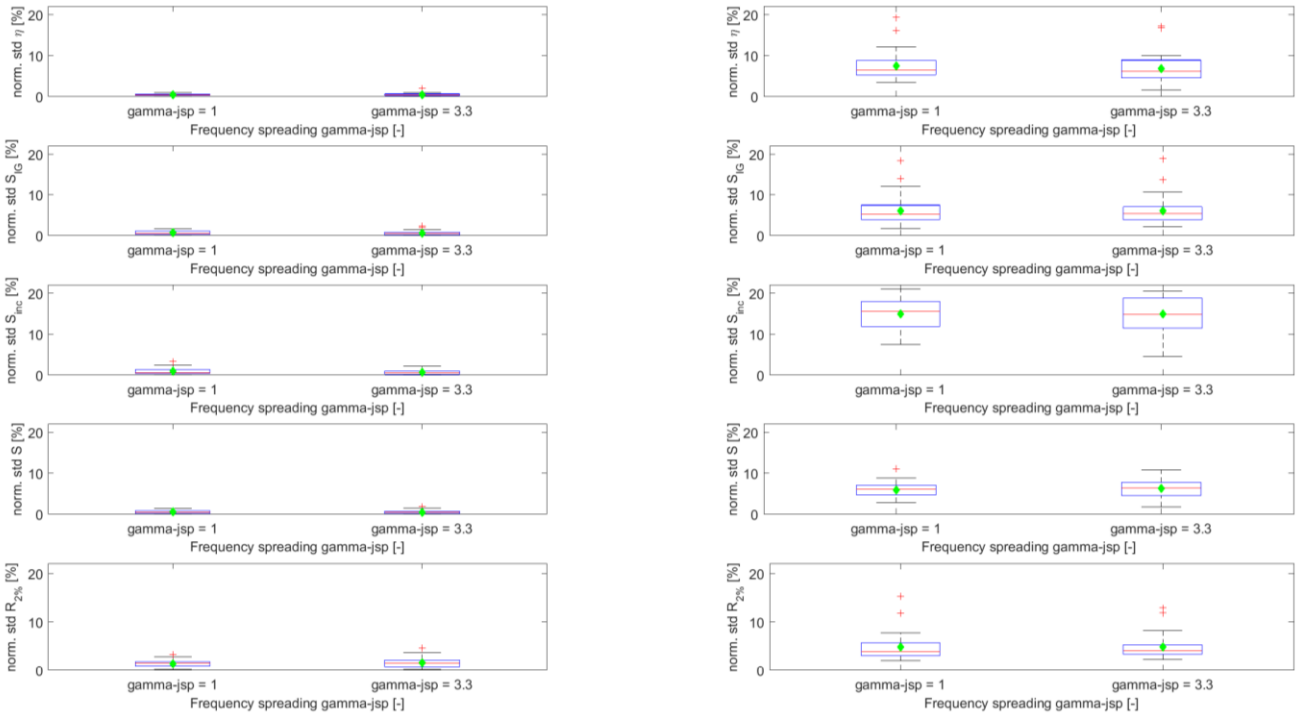

Figure XII-24: boxplots normalized standard deviation in alongshore direction versus frequency spreading 452m cusp bar system, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

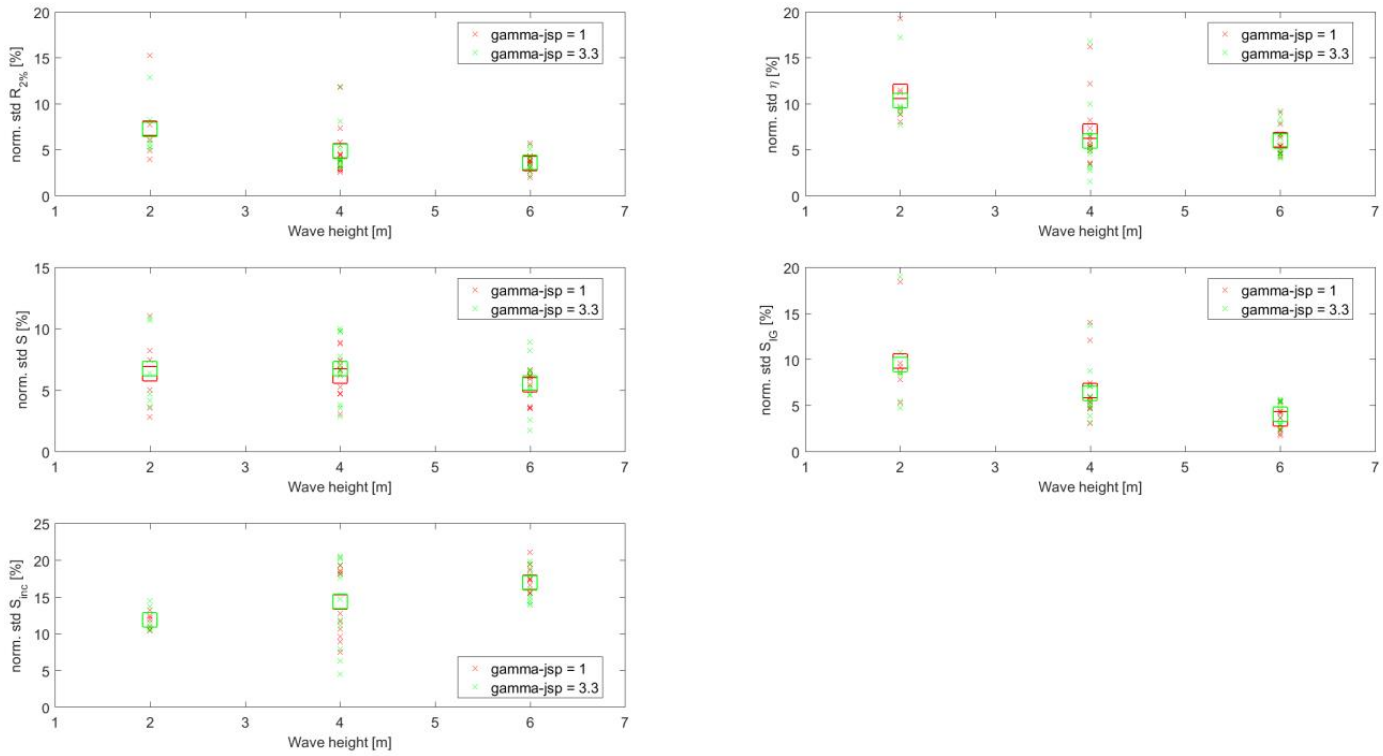

Figure XII-25: normalized standard deviation in alongshore direction versus wave height 452m cusp bar system, red: frequency spreading 1, green: frequency spreading 3.3, squares represents the mean value

Boxplots of the normalized standard deviation in alongshore direction are shown in Figure XII-26, plotted versus directional spreading.

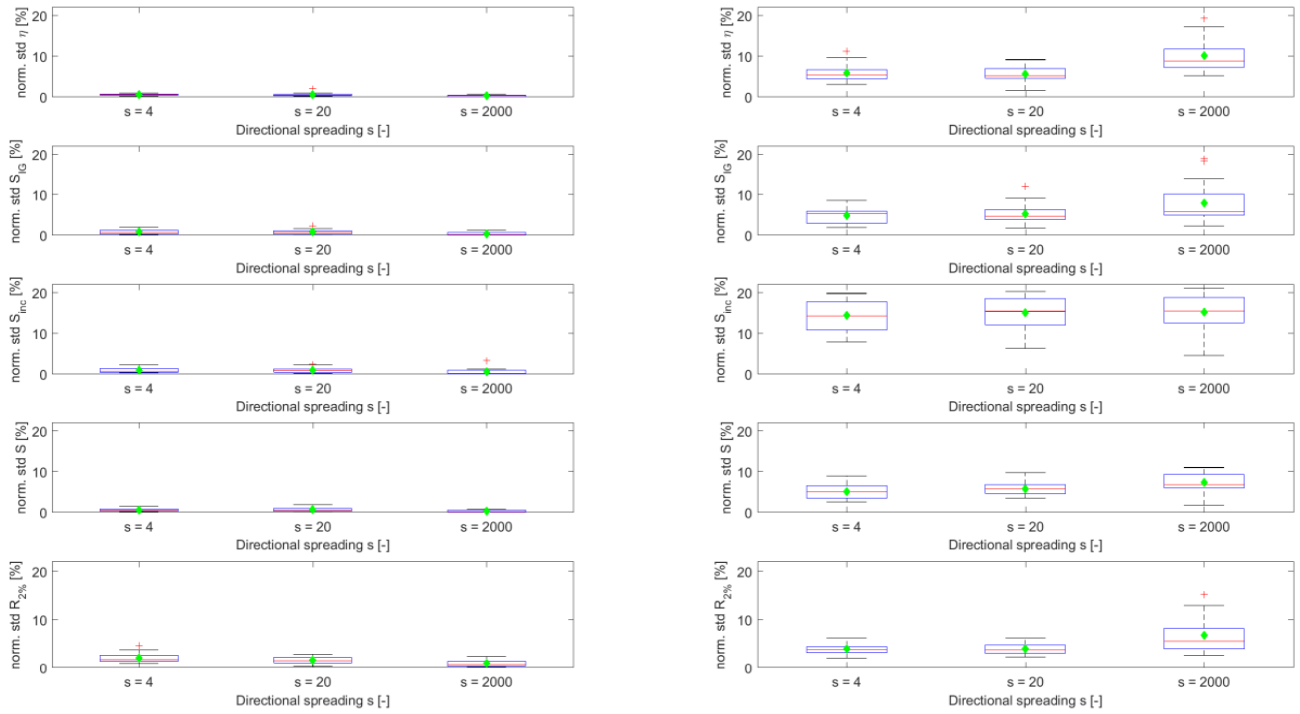

Figure XII-26: boxplots normalized standard deviation in alongshore direction versus directional spreading 452m cusp bar system, $R_{2\%}$ upper left, setup upper right, infragravity band swash lower left, incident band swash lower right, swash bottom. The green diamond represents the mean value.

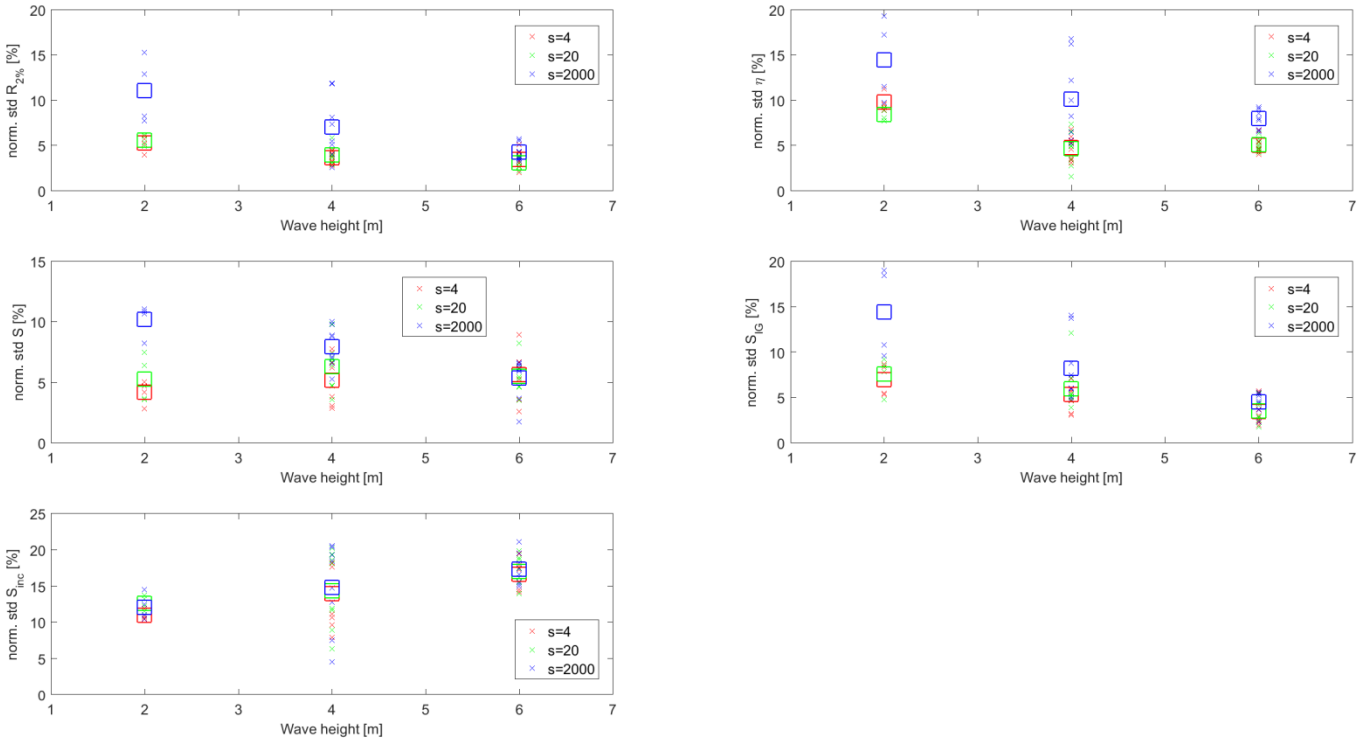

Figure XII-27: normalized standard deviation in alongshore direction versus wave height for 452m cusp bar system, red: directional spreading 4, green: directional spreading 20, blue: directional spreading 2000, squares represents the mean value