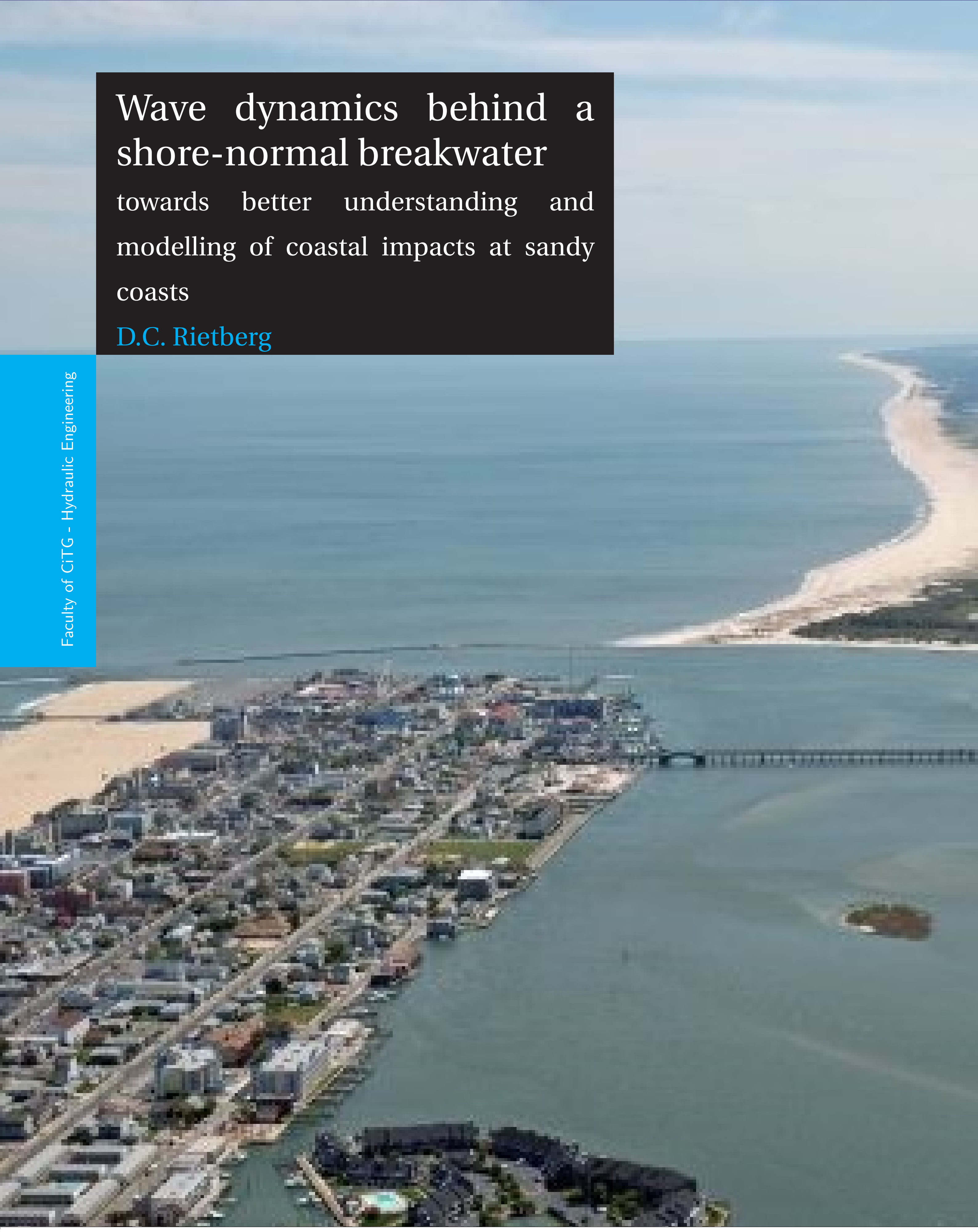

Wave dynamics behind a shore-normal breakwater

towards better understanding and modelling of coastal impacts at sandy coasts

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Technology

Challenge the future

WAVE DYNAMICS BEHIND A SHORE-NORMAL BREAKWATER

TOWARDS BETTER UNDERSTANDING AND MODELLING OF COASTAL IMPACTS AT SANDY COASTS

by

D.C. Rietberg

in partial fulfillment of the requirements for the degree of

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ABSTRACT

Shore normal breakwaters are constructed in coastal zones both for beach protection (erosion reduction) and port development (wave sheltering). These breakwaters have an effect on the waves, the (wave-driven) currents and hence, the sediment transport along the coast. The waves and tide force an equilibrium sediment transport along the coast in a natural unaltered coast. When breakwaters are constructed this sediment transport in the alongshore direction is (partially) blocked. This results in accretion at the updrift side of the breakwater and coastline retreat at the lee-side. Coastal erosion behind a breakwater can result in floods, destroy property or simply narrow the beach. Not only the short term effects of these structures (what happens during and short after construction) are important, also the long term effects need to be known; because the breakwaters are built for decades, coastal influence of these breakwaters needs to be known for these time-scales as well. Therefore it is relevant to investigate the scale (in time and space) of these adverse effects beforehand.

In coastal engineering, numerical models are used to predict the impact of coastal constructions like breakwaters. Highly detailed models which take all physical processes into account will result in accurate predictions but need large computation times. Simplified models have smaller computation times, are more suitable for coastal impact predictions on larger spatial (10 - 100 km) and temporal (decades) scale but are less accurate.

The objective of the thesis is to improve the coastline model predictions at the lee-side of a shore-normal breakwater at decadal scale. This was done by reviewing different wave model approaches. This research focused on (1) understanding of what wave processes are important for the coastline change and (2) an advice on what models to use for which conditions and how to the improve model predictions.

The approach of this thesis is triple. First, different modelling approaches for wave modelling, varying in computation time and usability are compared to a very accurate model that will be used as ground truth. The three models that are used are SWASH (Simulating Waves till Shore) model (Zijlema et al., 2011), SWAN (Simulating WAves Nearshore) model (Booij et al., 1999) with and without the diffraction module and the Unibest-CL+ model with the Kamphuis module for diffraction (Huisman, 2014; Kamphuis, 1992; WL | Delft hydraulics, 1994) without and with refraction (refraction is added with the Snell's law for refraction). The wave conditions will vary in direction, and both short crested waves and long crested waves will be modelled. In this step the accuracy of these models for different wave conditions can be analysed. The second step is to get a better understanding of the processes that are involved in the wave modelling. This information can be used to improve the accuracy of model approaches with small computation times. The last step is to see how the wave modelling influences the prediction of sediment transport and thus the coastline change at the lee-side of a breakwater.

Some of the interesting conclusions are:

- The influence of the sheltering on the wave height and wave direction is different for long crested waves with a small directional spreading and short crested waves with a large directional spreading. For cases with long crested waves all wave components get sheltered. This results in very little wave energy behind the breakwater. For short crested waves (especially with a small angle to the coast) the breakwater blocks not all wave components. This gives much more wave energy behind the breakwater. The

direction of the waves directly behind the breakwater is towards the breakwater because those wave components don't get blocked.

- The influence of diffraction is strongly correlated with the difference in wave energy in and outside the sheltered area. Diffraction does not play an important role for short crested waves. As explained the large directional spreading results in more wave energy in the sheltered zone resulting in smaller energy differences between the sheltered and the non-sheltered zone. Even SWAN without diffraction gives a good representation for short crested waves. For long crested waves the influence of diffraction is large. There is a much larger difference in wave energy between the sheltered and the non-sheltered zone.
- SWAN model approach (with and without diffraction) is for cases with short crested waves a good model approach: the wave height, wave direction and the sediment transport are well modelled. Also the setup differences are very similar to the ground truth model. For cases with a small directional spreading SWAN (with and without diffraction) is not very accurate. For these cases the diffraction is more important this is not well modelled by the SWAN model, also with the diffraction module turned on. There is not enough wave energy in the sheltered area nor is the wave direction well represented.
- Kamphuis with refraction models the wave height for the case with a large directional spreading reasonable good. For the cases with a small directional spreading the wave height is not accurate. Weirdly this is the opposite for the wave direction: For cases with a small directional spreading the wave direction is well modelled but for cases with large directional spreading the influence of wave sheltering is not modelled very well resulting in poorly modelled directions in the sheltered zone. With a modification for the directional spreading in the wave direction the Kamphuis module can be used very well for cases with large directional spreading.

PREFACE

Before you lies the Thesis "Wave dynamics behind a shore normal breakwater. Towards better understanding and modelling of coastal impacts at sandy coasts". It was written to fulfil the graduation requirements of my Master of Science degree in Hydraulic Engineering with specialization Coastal Engineering at the faculty of Civil Engineering at the Delft University of Technology. I would like to express my gratitude to those who supported me during the process of my graduation.

First of all, I would like to thank my committee members: Marcel Stive, Marcel Zijlema, Bas Huisman and Wiebe de Boer. Your guidance throughout the research and writing was of high value for me to develop my thesis and my skills in scientific research and reporting. Thank you for all your time and patience!

My gratitude also goes out to Deltares that supported my research with guidance, computational capacity and valuable advice. To the TU Delft for providing a master study that fulfilled all my academic wishes.

In Delft, I had a wonderful time, meeting lots of close friends in the best years of my life until now. Thanks to all the friends for the many, many fun times and a special thanks to those who helped me finish this thesis.

Special thanks also to Josette Dijksman for always believing in me, never stopping to support me and creating a smile in moments of need.

Last but not least, I am very happy that I always had the support of my parents and sister both for my studies and my personal development. Repaying all this support is impossible, but I know that finishing this thesis is a start.

D.C. Rietberg
Delft, November 2017

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1

INTRODUCTION

Shore normal breakwaters are constructed in coastal zones both for beach protection (erosion reduction) and port development (wave sheltering). These breakwaters have an effect on the waves, the (wave-driven) currents and hence, the sediment transport along the coast. In a natural unaltered coast the waves and tide force an equilibrium in sediment transport alongshore. When breakwaters are constructed this sediment transport in the alongshore direction is (partially) blocked. This results in accretion at the updrift side of the breakwater. At the downdrift side the forcing (by the waves) is not in equilibrium with the sediment transport, thus sediment is picked up and the coastline retreats (Bosboom and Stive, 2015). Figure 1.1 (left) shows the wave driven schematisation of the coastline change round a long shore normal breakwater (Bosboom and Stive, 2015). Figure 1.1 (right) shows the coastline change after construction of a harbour due to wave driven currents for a climate (including bypassing and setup driven sediment transport) (Mangor, 2004).

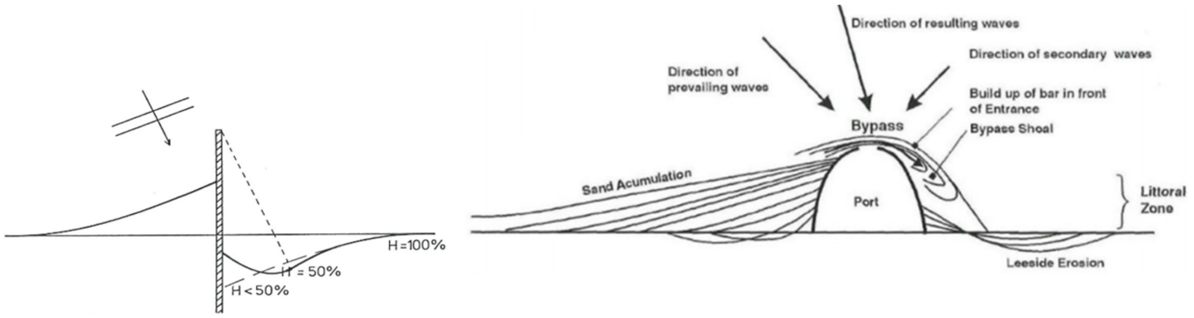

Figure 1.1: Left the schematisation of the coastline after a breakwater is constructed (Bosboom and Stive, 2015), right coastline evolution for a wave climate (Mangor, 2004)

For good coastal zone management it is important to know the effects of coastal constructions beforehand, as the coast is an area with high land value and dense infrastructure. Coastal erosion behind a breakwater as seen in figure 1.1 can result in floods, destroy property or simply erode the beaches and all its leisure space. Not only the short term effects of these structures (what happens during and short after construction) are important to know, also the long term effects need to be known: The breakwaters are built for and the coastal influence of these breakwaters needs to be known for these time-scales as well. Therefore, it is relevant to investigate the spatial and temporal scales of adverse effects beforehand.

In coastal engineering, numerical models are used to predict the impact of coastal constructions like breakwaters. Detailed models which take all physical processes into account will result in accurate predictions but need large computation times. Simplistic models have smaller computation times, are more suitable for coastal impact predictions on larger spatial (10 - 100 km) and temporal (decades) scale, but are less accurate. This study investigates the trade-off between accuracy and computational time in the modelling of wave processes behind a shore normal breakwater.

1.1. PROBLEM DEFINITION AND OBJECTIVE

Common practice in coastal engineering (Kaminsky et al., 2001; van Koningsveld et al., 2006) is to use a spectral wave model like SWAN (Booij et al., 1999) to model the offshore to nearshore wave transformations. The output of the spectral wave model then used for modelling sediment transport and coastline evolution with a one dimensional coastline model like Unibest CL+ (WL | Delft hydraulics, 1994) or with 2D/3D process based models like DELFT3D (Hydraulics, 2006).

The advantage of the first approach (the spectral wave model combined with the one dimensional coastline model) is the accurate wave modelling and fast computation times of the alongshore sediment transport and coastline change. Although this model approach allows us to predict the large-scale coastal impact (both in space and in time) of human interventions, not all processes that influence the coastline change in the lee-side are included. This may result in a mismatch between the modelled and actual coastline change behind a breakwater (van der Salm, 2013). Three phenomena that are not included are:

- Wave processes such as diffraction, flow wave interaction (in the spectral wave model);
- Vertical (cross shore) wave processes like undertow (in the spectral wave model);
- Two dimensional transport patterns such as eddies behind the breakwater, setup induced sediment transport and two dimensional bypassing (by the one dimensional coastline model).

This thesis studies the wave processes behind a shore normal breakwater that drive the alongshore sediment transport and, therewith coastline change. The offshore to nearshore wave propagation and the relative effects of these nearshore waves on the sediment transport are investigated. Tidal processes are not included in this research, as this is modelled by flow models.

In this thesis a long breakwater is defined as a breakwater which completely stops the sediment transport. The subject of this research is the wave propagation behind a shore normal breakwater with a straight coastline. Because this thesis is about understanding physical wave transformations and not about a statistical analysis no full climate is computed.

The objective of the thesis is to improve the coastline change predictions of models at decadal scale. This is done by reviewing the common practice and a new, very fast, module for sheltered lee-side wave computations and by investigating different wave processes that can improve the wave modelling. The outcome of the research will be (1) understanding of which wave processes are important for coastline change and (2) advice on what models to use for which conditions and how to the improve model predictions.

1.2. RESEARCH QUESTIONS

The main research question of this thesis is:

Which wave processes should be represented in the model approach to improve the decadal scale coastline modelling behind a shore normal breakwater in a computational efficient way?

With the subquestions:

- Which wave processes are relevant for the decadal coastline evolution at the lee-side of a shore normal construction? (Chapter 2)
- What is the best modelling approach for the different wave conditions? (chapter 4)
- What is the influence of the relevant wave processes on the wave transformation for the different wave conditions? (Chapter 4)
- What are the implications of these different wave model approaches for decadal scale coastline evolution modelling? (Chapter 4)

1.3. APPROACH AND REPORT OUTLINE

The objective of this thesis is studied in three steps. First four different modelling approaches for wave modelling, varying in computation time and usability, are compared to a very accurate model that will be used as ground truth. The wave conditions will vary in direction and directional spreading. In this step the accuracy of these models for different wave conditions can be analysed. The second step is to get a better understanding of the processes that are involved in the wave modelling. This information can be used to improve the accuracy of model approaches with small computation times. The last step is to study how this relates to sediment transport and thus the coastline change at the lee-side of a breakwater.

The theoretical background of this study is presented in chapter 2; it gives an overview of the important hydrodynamic processes involved. The third chapter is on methodology. It details the numerical models that are used, the setup is of these models, the tests that are done with it, and how this information is analysed. Chapter four then gives the test results and the last chapter gives conclusions, recommendations and some suggestions for further research.

2

THEORETICAL BACKGROUND

In the next chapter the theoretical background of this thesis is given; The important theoretical knowledge to understand this thesis. First the Waves are described followed by the sediment transport and the coastline change. At the end a short overview of important literature is given.

2.1. WAVES

WAVE GENERATION

The waves of interest for this thesis are wind generated waves. The waves result from wind blowing over the water surface. The wave height, wave direction and period of the generated wind depend on the wind speed, the duration and the fetch (length over which the storm has blown) of the storm. The waves that are created consist of many waves each having their own wave height, wave period and wave direction, this is shown in figure 2.3.

Waves that are locally generated have a large directional and frequency spreading: the wave components differ largely in direction and frequency. Because the storm is around the area of interest waves come from many directions. And because the distance from the storm to the area of interest is small there is not a lot of frequency dispersion. These waves are called sea waves and are short crested waves, figure 2.1 shows short crested waves.

Waves that are generated by storms far away have much smaller directional and frequency spreading because the waves have dispersed from their generated location: Only the waves directed from the storm towards the area of interest will reach it, and the waves with different frequencies travel in different phase speeds which results in more uniform waves than for the sea waves. These waves are called swell waves and are long crested. Figure 2.2 gives a good idea of long crested waves.

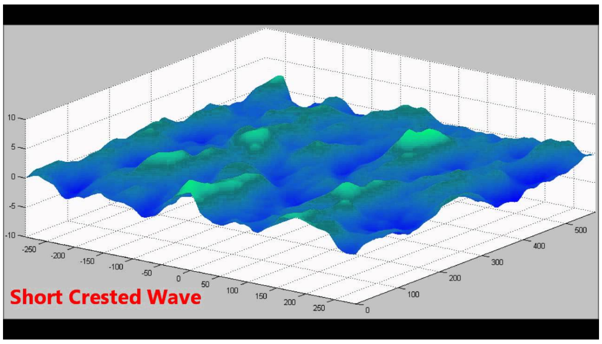

Figure 2.1: Short crested waves

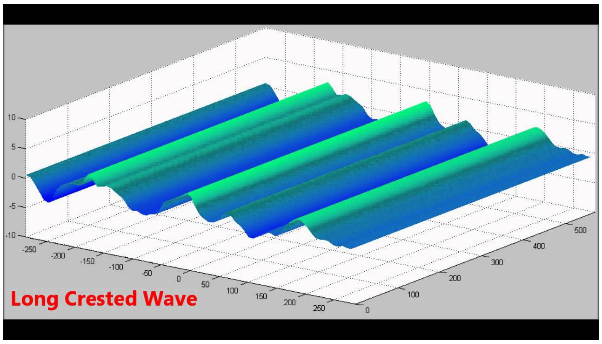

Figure 2.2: Long crested waves

WAVE SPECTRUM

The wave spectrum is a statistical description of a wave field with all its wave components (Holthuijsen, 2007). It describes the direction, the wave energy and the wave frequency of all the wave components. The Figure 2.4 shows a spatial representation of a spectrum. Directional spreading is the difference in direction of the wave components. The directional spreading is described by the cosine power (Longuet-Higgins and Steward, 1964).

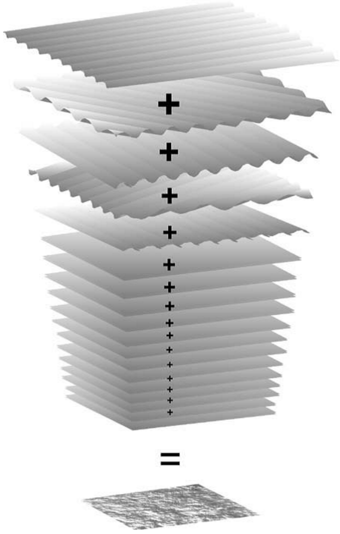

Figure 2.3: Harmonic wave components that sum up the random moving waves travelling across the ocean surface with different periods, directions, amplitudes and phases (Holthuijsen, 2007)

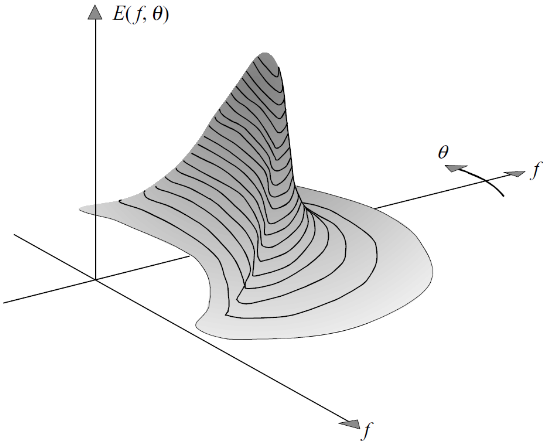

Figure 2.4: Two-dimensional spectrum of wind-generated waves (shown in polar co-ordinates)) (Holthuijsen, 2007).

SHOALING

Shoaling is caused by the fact that the group velocity, changes when reaching shallow waters. Under stationary conditions, a decrease in wave group velocity must be compensated by an increase in energy density in order to maintain a constant energy flux. Shoaling waves will also exhibit a reduction in wavelength while the frequency remains constant. The wave propagation speed will be affected by the bottom when the water depth becomes less than about half the wavelength.

REFRACTION

Refraction is the change of wave direction due to the difference in depth along the wave crest, resulting in a difference in the wave velocity. Refraction is due to the change in depth, like in shoaling and therefore only present close tot the coast. The velocity of the wave is positive correlated with the depth. The propagating wave crest turns towards alignment with the bottom contour lines.

In the 17th century Willebrord Snellius described light that refracted from one medium to another. For water waves the same rule for refraction can be used. Formula 2.1 shows this formula for parallel depth contour lines. It shows that waves approaching the coast turn towards the coast and always come in at an angle of 90 degrees.

$$\frac{sin(\theta)}{c} = Constant \qquad \text{along a wave ray for parallel depth contour} \tag{2.1}$$

In which Theta is the angle of the wave and c the velocity of the wave group.

SHELTERING

Behind a shore normal breakwater there is a sheltered zone with little wave energy. This is due to the blockage of the waves by the breakwater. As explained waves consist of many wave components, depending on the direction and the directional spreading some waves get completely bocked and some partly. Figure 2.5 shows the sheltering for two cases with the same average direction but with a different directional spreading. In the case with the short crested waves (top one) some wave components don't get blocked at all. This means that there is more wave energy behind the breakwater. For the case with the long crested waves (bottom) there is an area close to the breakwater where all wave components are blocked. Due to refraction an diffraction however wave energy turns towards this area.

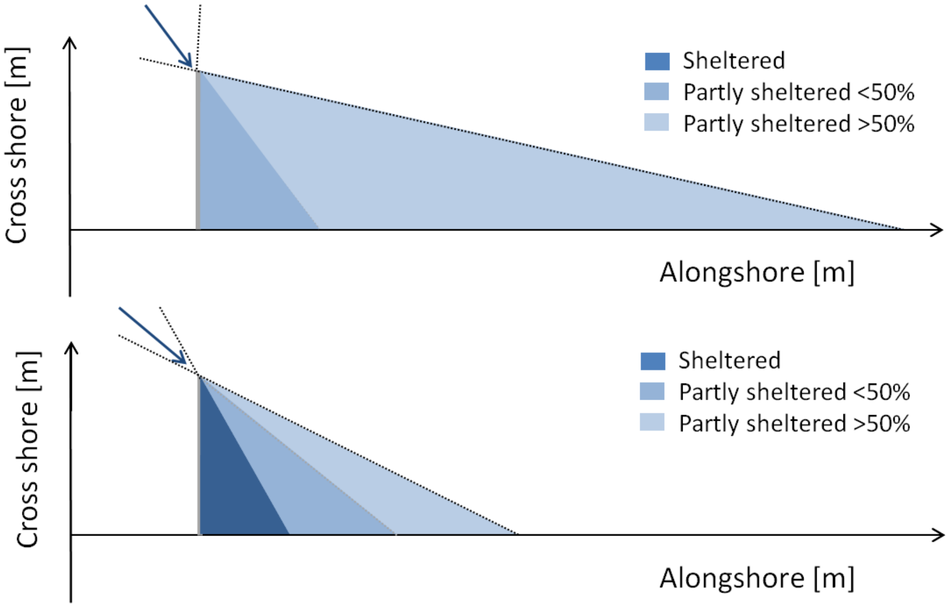

Figure 2.5: Sheltering behind a shore normal breakwater for cases with a large directional spreading (top) and small directional spreading (bottom)

Diffraction

Diffraction is the wave energy transport along a wave crest due to abrupt changes in bottom profile or obstructions. When a propagating wave hits a breakwater under an angle the uninterrupted part of the wave continues and there is a sheltered zone with little waves behind the breakwater. Because of this wave vacuum the waves diffract in that direction. This results in circular wave crests in the sheltered zone with the wave at the tip of the breakwater as the source and in all the directions behind the breakwater the same wave speed.

“(Goda, 1985) states that analytical methods such as (Penney and Price, 1952), developed for calculation of diffraction for regular waves, cannot properly describe irregular wave diffraction. Goda proposes instead an “angular spreading method” which simply assumes that part of the directional wave spectrum is blocked by the structure.” (Kamphuis, 1992).

CURRENT INDUCED REFRACTION

"The phenomenon of current-induced refraction is essentially the same as depth-induced refraction: the wave turns towards the area with lower (absolute) propagation speed of the crest (i.e., relative to the fixed bottom), which is now affected not only by the depth but also by the ambient current (the component of the current in the wave direction Un)." (Holthuijsen, 2007)

2.2. SEDIMENT TRANSPORT

Sediment transport is defined as “the movement of sediment particles through a well defined plane over a certain period of time.” (Bosboom and Stive, 2015). In sandy coasts sediment particles will start moving when a so-called critical velocity (or critical shear stress) is exceeded. This bed shear stress is the result of the combined wave-current motion, but it could be said that the turbulent wave motion brings the sediment in suspension and the current motion transports the sediment.

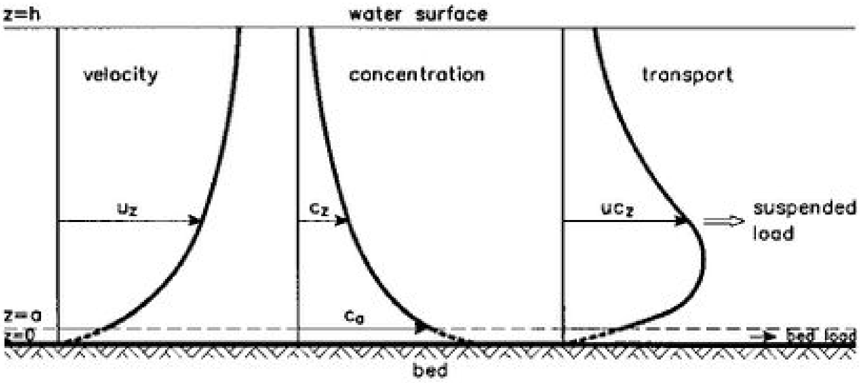

Figure 2.6: Verticle distribution of velocity (left), concentration (middle) and transport (right)

The currents transport the suspended sediment particle; this can be a tidal current, wave current or wave driven current. Figure 2.6 shows the sediment transport in the water column. There are also secondary effects that influence the sediment transport like water level setup driven currents, undertow currents, density currents and in shallow water also wave orbital motion, asymmetric and skewed waves.

For the decadal morphological change the wave driven current due to oblique incident waves is the most important forcing for the sediment transport. Behind a breakwater also the setup driven currents play an important role. Both of these transports are driven by the radiation stress (in alongshore and cross shore direction).

RADIATION STRESS

There are two radiation stresses that will result in wave induced sediment flows. The alongshore balance between the oblique incoming waves and the alongshore radiation stress ($S_{xy} = n * cos\theta * sin\theta * E$). The two most important factors for the forcing of this alongshore current are: the wave height and the wave direction 2.2. The second balance is the cross shore balance between the incoming waves with the bottom friction; resulting in the cross-shore radiation stress ($S_{xx} = (n - 1/2 + ncos^2\theta) * E$). This cross shore radiation stress results in a local wave-induced set-up. Set-up differences along the coast will lead to a flow from locations with higher set-up to locations with lower set-up. The nearshore wave height, wave direction and wave induced set-up are therefore the most important wave characteristics to research. Figure 2.7 shows the resulting alongshore transport and wave induced setup.

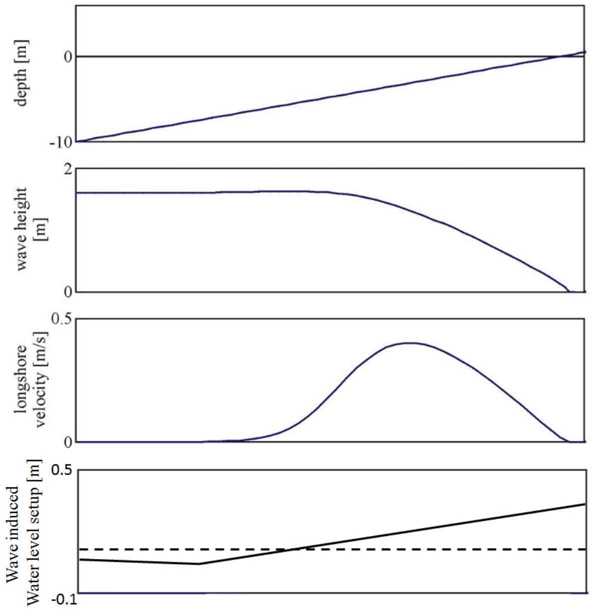

Figure 2.7: The influence of reducing depth on the wave height, the alongshore transport and the wave induced setup

COASTLINE CHANGE

Alongshore variation of the sediment transport results in sedimentation or erosion; when the sediment transport decreases sedimentation occurs and when the sediment transport increases erosion occurs. The expected coastline change behind a shore-normal breakwater is shown in figure 2.8.

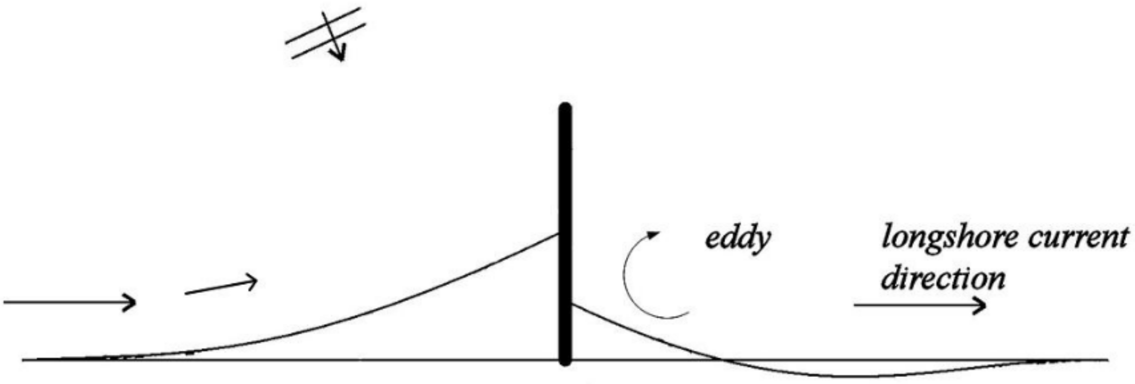

Figure 2.8: Coastline change around a shore normal breakwater due to alongshore sediment transport and wave induced setup driven transport

2.3. PREVIOUS RESEARCH

The up-drift side of a breakwater is very well understood, however at the lee-side a lot more processes play a role. (Bruun, 1995) is an article that describes the development of the downdrift erosion for cases in Florida, USA an update of this paper is (Bruun, 2001). In this paper a distinction between the short and the long distance development of the erosion pit. The short distance erosion forms shortly after construction of the breakwater due to wave effects and eddy's behind a breakwater while the long distance erosion is mainly formed by the return to the equilibrium state of the sediment transport. These papers also describes a bump in the erosion that will be found later in this thesis.

The diffraction of the waves behind the breakwaters in Unibest with the Kamphuis module is calculated with a transmission coefficient as in (Kamphuis, 1992). Kamphuis defined three wave regimes with easy formulas to calculate the wave transmission. The three formula's for the transmission coefficient are stated below.

$$Kd = 0,68 + 0,008 * \theta \qquad \text{for} \qquad 0 \geqslant \theta > -90 \tag{2.2}$$

$$Kd = 0,71 + 0,037 * \theta \qquad \text{for} \qquad 40 \geqslant \theta > 0 \tag{2.3}$$

$$Kd = 0,83 + 0,017 * \theta \qquad \text{for} \qquad 90 \geqslant \theta > 40 \tag{2.4}$$

In this equations the θ is the difference in direction between the incident direction and the line along the wave height is needed.

"It is noted that the local climates can be generated only for locations at the shoreline. In this approach, it is also assumed that a flat bottom, from the tip of the groyne to the position of the local climate, is present. Currently there is no possibility to change these parameters. The approach therefore implicitly assumes that a flat bed (i.e. no refraction and wave breaking) and diffraction for the whole profile, as if it is as sheltered as at the shoreline." (van der Salm, 2013)

3

METHODOLOGY

This chapter explains the methodology to investigate the relevance of the different wave processes for the wave dynamics behind a shore normal breakwater. For this purpose three types of numerical models are used. This chapter explains why these models are chosen, which tests are done, and what the settings of these models are. The last part of this chapter will give the analysis methods.

3.1. NUMERICAL MODEL CHOICE

Basically, in this study three different numerical models are used: the SWASH (Simulating Waves till Shore) model (Zijlema et al., 2011), the SWAN (Simulating WAves Nearshore) model (Booij et al., 1999) with and without the diffraction module and the Unibest-CL+ model with the Kamphuis module for diffraction (Huisman, 2014; Kamphuis, 1992; WL | Delft hydraulics, 1994) without and with refraction (with Snell's law) from now on referred to as the Kamphuis module.

These three models are chosen for their own strength. The SWASH model is used as a ground truth. This means that its results will be seen as the truth, to which the other model outputs will be compared. The big advantage of using a model as ground is that the wave conditions can be changed and effects of these different conditions can be researched. The SWAN model is used to research (1) the importance of the 2D wave calculations (2) the different wave processes; in SWAN a lot of these processes can be turned on and turned off and the effects of these processes on the coastline change can be tested. The Kamphuis module is fast but simple. This thesis will study (1) for which wave conditions this model is a good representation and (2) what changes can be made to increase its accuracy for other conditions.

SWASH

As explained, the SWASH model will be used as the ground truth for this thesis. Although the computation time for this model is very large it has the most comprehensive wave computations available. It is a phase-resolving model that solves the Reynolds-averaged Navier-Stokes equations (Zijlema et al., 2011). Phase-resolving means that in these models the sea surface is resolved, i.e. the surface is covered with a grid which is fine compared with the wave length, and the gridded values of the vertical displacement ζ(x,y,t) are computed. Because the Navier-Stokes equations for water waves are solved, all hydrodynamic processes are per definition included.

SWAN

The SWAN model (Simulating WAves Nearshore) is a third generation phase-averaged model for the evolution of wind-generated waves in coastal waters (Booij et al., 1999). The computation times of SWAN are about a factor 100 smaller than for the SWASH model (hours versus days) and this makes it a lot more suitable for everyday cases. The big difference between SWASH and SWAN is that SWAN is a phase-averaged hydrodynamic model. In these models the statistics of the sea surface is computed, i.e. on points of a grid the action or energy spectra are computed. This results in the fact that different wave processes are parameterized.

Although not included in earlier versions, the diffraction is implemented in SWAN (from version 40.41 onwards) by adding a diffraction parameter δE to the expressions for the group velocity components, cg,x and cg,y and to the turning rate cθ in the propagation schemes. The accuracy and reliability of the diffraction in SWAN is debatable. Common practice is not to use the diffraction module in SWAN. This thesis will research for which conditions SWAN with diffraction is a better model approach than without diffraction.

KAMPHUIS MODULE

The third model is Unibest-CL+ (WL | Delft hydraulics, 1994). The Unibest-CL+ model is a one dimensional sediment transport model that is often used for the sediment transport for large scale (time and space) coastline change predictions. The model can also calculate the offshore to nearshore wave transformations, this is a one dimensional calculation (no alongshore wave-wave or wave-structure interaction) and is therefore not capable for lee-side shielded wave calculations.

This thesis will research a version of the Kamphuis wave-sheltering method (Huisman, 2014; Kamphuis, 1992) that can calculate the nearshore wave characteristics of lee-side shielded waves. The Kamphuis formula is used to compute the wave height and direction at the lee-side of the breakwater. One of the most important disadvantages of the Kamphuis formula is that it is based on the diffraction diagrams of Goda (Goda et al., 1978) and these are for a flat bottom. When using the Kamphuis module it therefore assumes a flat bottom from the breakwater tip until the shore. This means that there will not be any refraction from the breakwater tip till shore. Therefore there is no refraction and shoaling and breaking in Kamphuis module. To model the nearshore hydrodynamics accurately the Snell's law will be applied for the refraction.

Table 3.1: Overview of the computations in the three models

	SWASH	SWAN	Kamphuis
Computation time	days	hours	minutes
Computation dimensions	2D (or 3D)	2D	1D
Wave transformation	Navier-Stokes equations	2D action balance	1D (Battjes and Janssen, 1978)
Bottom friction	Manning	(Hasselmann, 1973)	
Breaking	Maximum steepness	1D (Battjes and Janssen, 1978)	N/A
Shoaling	Navier-Stokes equations	1D (Battjes and Janssen, 1978)	N/A
Refraction	Navier-Stokes equations	Action-balance equation (Dingemans, 1997; Whitham, 1974)	N/A
Diffraction	Navier-Stokes equations	Optional: phase-decoupled refraction-diffraction approximation (Holthuijsen et al., 2003)	Kamphuis
Directional spreading	Navier-Stokes equations	JONSWAP	Kamphuis

3.2. CASE DESCRIPTIONS

In this section the case and the model configurations that apply to all models are described. After that the specific configurations for the different models will be presented.

BATHYMETRY AND BOUNDARY CONDITIONS

All three models are set up with the same bathymetry and lay-out. A straight coastline with a shore normal breakwater of 1000 meter long. The bottom profile is a Dean depth profile (Dean, 1991) with an A of 0.0086 because this is a good representation of a Dutch sandy coast. Figure 3.1-left shows the domain of the models and figure 3.1-right shows the cross shore depth.

The Kamphuis module uses a flat bottom from the breakwater tip till shore because it is based on the diffraction diagrams of Goda (Goda et al., 1978); this is shown with the dashed line.

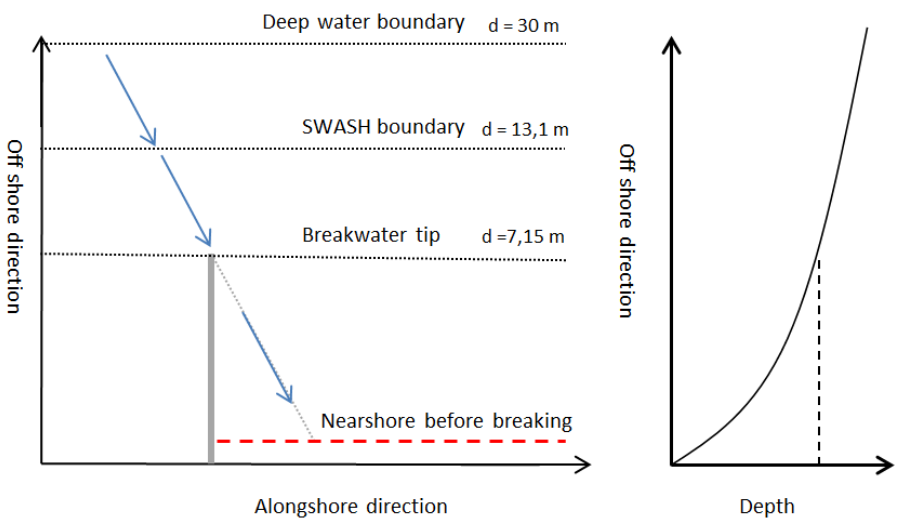

Figure 3.1: The domain of the models and the cross shore depth, the dashed line is the depth that the Kamphuis module uses.

In SWAN, a JONSWAP-spectrum is applied at the deep water boundary (at the top of the domain) (Hasselmann et al., 1980). SWAN computes the propagation of the waves from deepwater to the SWASH domain and to the breakwater tip for the Kamphuis module. The deepwater wave height, wave direction, wave period and directional spreading are shown table 3.2 with a JONSWAP peak enhancing factor of 3.3 (this is the default setting and representative for the North Sea) .

Table 3.2: Overview of deep water wave conditions

	Wave height [m]	Wave direction [deg.]	Wave period [s]	Directional spreading [-]
Case 1	1	15	6	2
Case 2	1	30	6	2
Case 3	1	45	6	2
Case 4	1	15	6	10
Case 5	1	30	6	10
Case 6	1	45	6	10

3.3. APPROACH

The approach to study the research questions is in three steps: (1) What is the accuracy of the nearshore wave height and direction (and Wave induced setup for SWASH and SWAN) (2) For which cases should the hydrodynamics be computed with which of the five model approaches (3) What processes should be better represented in the model approaches. The four model approaches are compared to the SWASH model.

EXAMINING MODELING APPROACHES

By comparing four modelling approaches to SWASH it is studied what the best modelling approach is for the different wave conditions. The wave conditions that are studied are given in table 3.2. This is studied by comparing and analysing the computed wave height and wave direction of the four modelling approaches just outside the breaking zone (where the waves force the alongshore transport). The wave induced setup is compared on the coastline (where the wave induced setup is largest and force the current). The modelling approaches that are studied are:

1. SWASH (this will be used as the ground truth)
2. SWAN without diffraction module
3. SWAN with the diffraction module
4. The Kamphuis Module for wave sheltering (in the following referred to as Kamphuis)
5. The model as in four, with refraction calculations of Snell's law (in the following referred to as Kamphuis with refraction)

INFLUENCE OF THE WAVE PROCESSES

With the models the influence of the wave processes given in chapter 2 is studied. The processes that will be studied are: Sheltering, diffraction and current induced refraction. The goal is to get a better understanding of the wave processes, for which conditions the wave processes have a large influence and what the influence is on the nearshore wave characteristics.

First the sheltering is studied for short crested waves and long crested waves. Because SWAN does not compute diffraction the difference of the nearshore wave charateristics between the case with short crested waves and long crested waves is due to the difference in how much of the wave get blocked.

Second the wave diffraction is studied. For what conditions does diffraction play an important role. How much does the diffraction influence the nearshore wae characteristics. This is done by comparing SWAN (without diffraction) to the SWASH model (with diffraction).

Third the current induced refraction is studied. SWASH models the currents and the waves in SWASH are under influence of this current induced refraction. When there are large rip currents this can change de direction of the waves. An important question is for which conditions rip currents occur.

ANALYSIS OF THE RELATIVE SEDIMENT TRANSPORT RATES

After the nearshore hydrodynamics is analysed, the resulting sediment transport is studied. As described in Chapter 2 the sediment transport is forced by the wave height and the wave direction. According to the CERC formula for straight parallel depth contours (Bosboom and Stive, 2015) the sediment transport is: $S \sim sin(2\theta_b) * Hs^2$, where θ is the direction Hs is significant waveheight. This formula is used to compare the relative sediment transport in the different model approaches. The sediment transport differences result in a coastline change. The relative coastline change can therefore also be analysed. Three factors can be analyzed by this sediment proxy: The length of the erosion pit, the surface area of the erosion pit and the shape of the erosion pit. The sediment proxy calculated from the different model outcomes gives a good indication which model is best to use for what conditions.

3.4. SWASH MODEL SETUP

The SWASH model is the most expensive model of the three, the computation time is the longest. This asks for a small domain that can just compute the area of interest behind the breakwater. The boundary conditions of the SWASH model are computed with the SWAN model. For realistic wave conditions at the boundary of the SWASH model, the SWAN model is used to model the waves from the linear deep water wave (d/h<20) to the SWASH boundary.

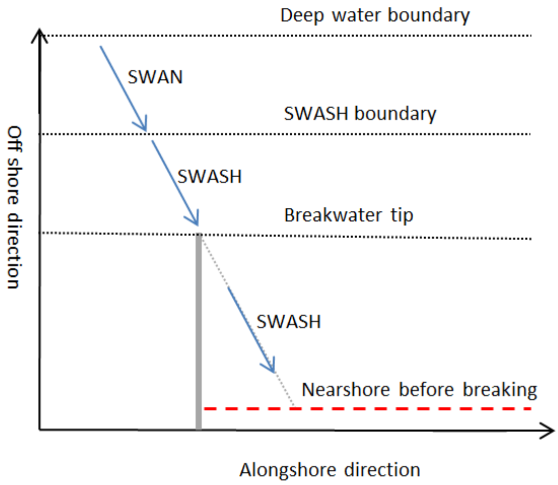

Figure 3.2: SWASH modelling approach

Grid and bathymetry

The SWASH model uses a rectangular grid. The total size of the grid in X direction is 4100 meter and in Y direction 1600 meter. To exclude boundary effects the grid is extended far enough that these lay out-side the area of interest. Because the waves come in at an angle from the top of the grid, the breakwater should be situated far enough to the right so that all the wave directions due to directional spreading are arriving at the breakwater tip.

SWASH is a phase-resolving model which needs many grid cells per wavelength to compute the vertical displacement at every location in time. According to the SWASH user manual (Swash, 2011) there is a minimum of 50 grid cells per wavelength in the direction of the wave for low waves H/d < 1. Because the wavelength is 50 meter at the boundary the grid cells need to be 1 meter in the direction of the wave. This results in $\Delta X = 2m$, $\Delta Y = 1m$.

The bottom grid gives the input for the bottom. Because the bottom contour lines are parallel to the coast the bottom grid cells can be over the full length of the domain. The y-direction of the bottom grid is divided into 70 grid cells giving a $\Delta Y = 20$ meter.

In this study the interaction between the breakwater slope and the waves is not included, but only the wave damping effect that the breakwater has on the local wave field. For numerical reasons it's easier for the SWASH model to compute the interaction between an area with very low porosity than for a steep slope. Therefore, the breakwater is modelled as a non-permeable porosity grid (n=0.1).

BOUNDARY CONDITIONS

The SWASH model can only have one boundary with waves, this is the north boundary. As explained the domain needs to be wide enough to have all the wave components applied at the boundary in the area of interest around the breakwater. The wave transformations from deep water to the SWASH boundary are done with SWAN. At the left and right boundary is a sponge layer. This sponge layer will damp out the waves leaving the model. The model boundaries are reflective boundaries and without these sponge layers the waves would reflect back into the model.

SPIN-UP TIME

Spin-up time is the time needed for the model to get from a zero state to a state of statistical equilibrium under the applied forcing. This means that the elevation in the whole domain is zero at t=0 s; the model then starts to propagate waves through the domain until the waves are everywhere. Before the state of statistical equilibrium is reached the results are not representative and should not be taken into account.

According to the SWASH user manual the spin-up time should be at least 500 waves, for these cases this is 50 minutes.

TIME STEP

Phase resolving models are computed in time. For each time step the change of elevation in that time step is added to the elevation of the last time step. This time step needs to be as large as possible to have fewer computation steps (hence, faster computation times). However when this time step is to large numerical instability will occur. To prevent this numerical instability the courant number should be smaller than one, because a Courant number (Courant et al., 1928) larger than one means that the information is propagating through more than one grid cell at each time step. This means that the time-integrator does not have time to properly interpret what is physically happening, which means that the solution will become unstable and the model will blow up. For cases with non-linear breaking the SWASH user manual advises a courant number of 0.5. The model automatically divided the time step by two when the Courant number is higher than the specified time step.

Table 3.3: Overview settings SWASH

Grid size in X	2 m
Grid size in Y	1 m
Cyclic period boundary	50 min
Friction coefficient (manning)	0.019
Courant number	0.2<c<0.5
Duration time SETUP and Hs are computed	60 min
Initial time step	0.1sec

POST PROCESS

The significant wave height, setup and wave direction needs to be calculated over a certain period. The SWASH model can do this calculation for the significant wave height and the setup but the direction needs to be done by own post-processing. For a time series resulting in the statistical significant wave height at least 600 waves need to be included (SWASH user manual (team, 2010)). With a deep water wave period of 6 seconds this results in about 60 minutes.

WAVE DIRECTION

The wave direction cannot be calculated by the SWASH model, therefore a new post-processing script needed to be made. The data that is used to calculate this wave direction is the vectorial current velocity of the water. This variable consists of the current flow and the flow due to the orbital motion of the wave.

In cases with only waves and no flow the water particles make a vertical circular motion. (Holthuys, ref). This motion follows the waves at the wave crest and returns in the wave trough. The wave direction is the direction of this orbital motion. Because only one layer is used in the SWASH model this is a back and forth going motion. The wave direction is calculated by averaging the velocity of this orbital motion over time. When this back and forth going motion is averaged there is no flow, and therefore no direction. Therefore the motions forwards and backwards are added together before the average direction of this motion is taken. The wave direction is the mean weighted angle of this circular motion over time.

In cases with waves and flow the current velocity consists of the current and the orbital motion of the waves. As explained, the orbital motion of the wave is a back and forth going motion (for a case with one layer) and the average of this motion over time is zero. Therefore the flow direction will be the average of the current velocity over time. The wave direction can be calculated by subtracting the average flow velocity from the output variable: the current velocity. After the flow velocity is subtracted the wave direction can be calculated in the same way as described in the last paragraph; see figures 3.3 to 3.6.

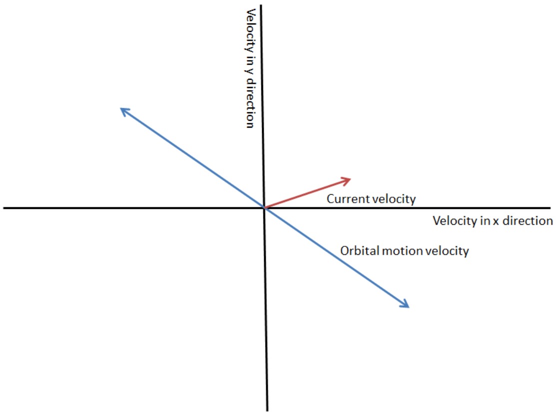

Figure 3.3: 2-dimensional water movement: the current and the orbital motion

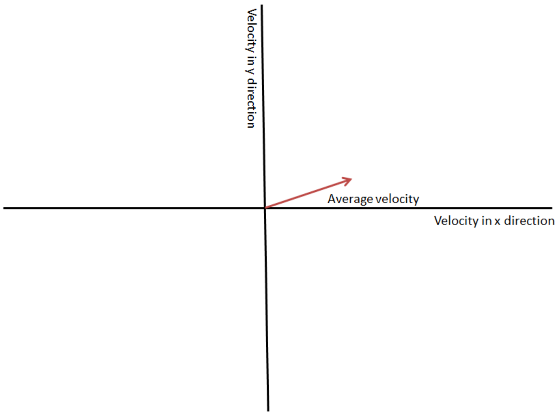

Figure 3.4: Average velocity over time

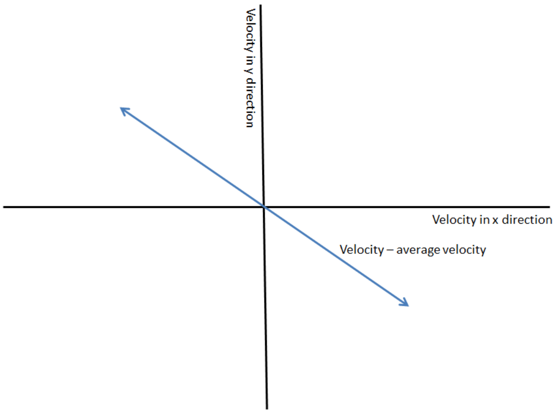

Figure 3.5: Orbital motion of the water, this is the velocity minus the average velocity

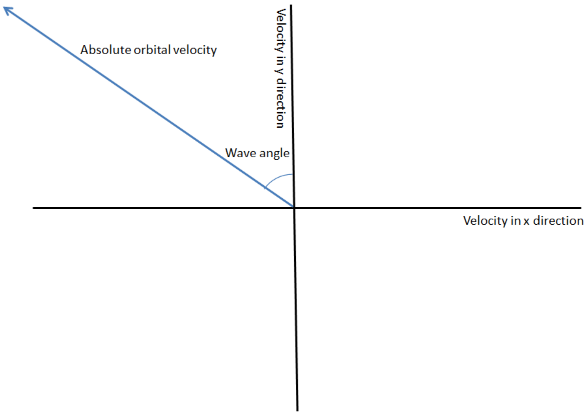

Figure 3.6: Absolute average orbital velocity

$$Dir = atan\frac{avg(|velocity_{y,t} - \overline{velocity_y}|)}{avg(|velocity_{x,t} - \overline{velocity_x}|)} \tag{3.1}$$

One of the limitations in post-processing is the amount of data that is created. Therefore there are 24000 data points (Δx, Δy = 10 m) with 12 time steps per wave (Δt=0.5 s) and over the total time over which the direction is averaged of 60 minutes (about 600 waves).

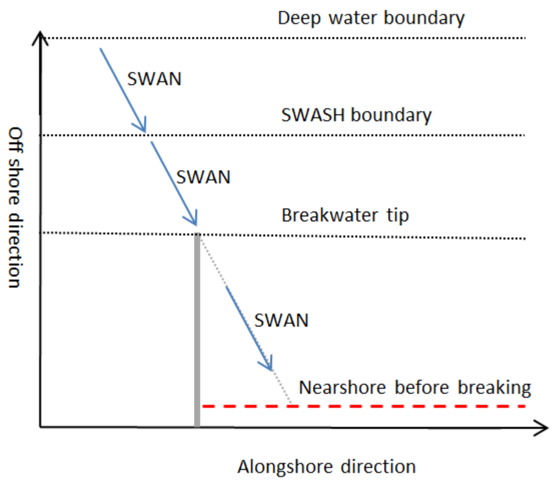

Figure 3.7: swan modelling approach

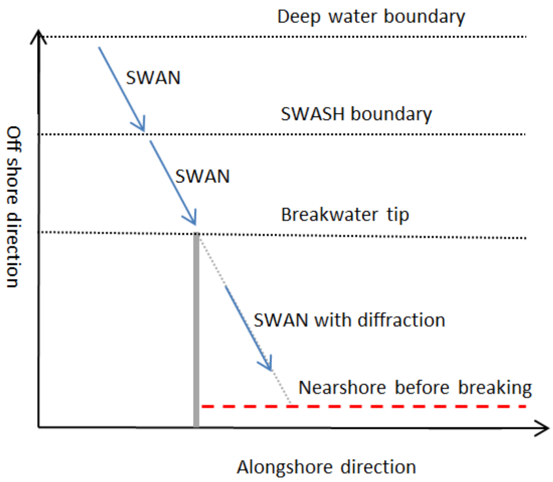

Figure 3.8: swan modelling approach with diffraction

3.5. SWAN MODEL SETUP

THREE NESTED GRIDS

The SWAN model contains three grids that are nested into each other. The largest grid models the offshore waves to more nearshore waves while the smallest grids are needed for the stability of the diffraction behind the breakwater. Table 3.3 shows the most important characteristics of the three grids. The grid cell size of the smallest grid needs to be 1/5th to 1/10th of the wavelength. The SWAN manual states: "The process diffraction can only be solved accurately when a detailed grid is applied. Several studies (e.g. (Ilic, 1994)) have shown that the grid size should be about 1/5th to 1/10th of the wave length" (SWAN user manual pg 45, (Team et al., 2007)). The grid size of the main grid should never be larger than five times the nested grid, this explains the other grid sizes.

Table 3.4: Overview settings SWAN

	Large grid	Medium grid	Small grid
Length x	13000 m	3500 m	2100 m
Length y	5200 m	2200 m	1600 m
Delta (x,y)	100 m	20 m	4 m
No of dir. Bins*	90	90	90
No of freq bins	48	48	48

*number of directional bins in a 180 degree sector (delta dir = 2 degrees)

The size of the large grid in X direction is 13 km, to be certain that the wave climate at the boundary of the medium grid is uniform and because of a small computation time for the large grid. The size of the large grid in y direction is 5200 meter, to convert offshore linear deep water waves to nearshore waves. With the given depth profile this results in a boundary 5,2 km offshore. The small grid is just the domain of interest, the area which interacts with the breakwater, and especially the lee-side of the breakwater. The very small grid cells result in a larger computation time so the grid size should be as small as possible without leaving out important information.

The medium grid contains the area around the breakwater and the leeside of the breakwater. In x direction the grid is from x = 4500 meter till x = 7500 meter. In the y direction it is from the coast until y = 1700 meter. The size of the medium grid cells is Δ (x,y)=20 meter. The smallest grid only models the area around the breakwater, the area of interest for this research. This area needs a small grid-size to be able to compute the diffraction. The small grid-size is Δ (x,y)= 4 meter.

BOUNDARY CONDITIONS

At the top boundary of the large grid the boundary wave conditions are applied. The left boundary and the right boundary are simply open. In the table 3.2 the different boundary conditions for the different tests are given for the wave height, wave period and wave direction are given.

PHYSICAL PARAMETERS

For SWAN, most of the processes that are possible to include or exclude are the same for all tests because these are not the topic of this research. Table 3.5 shows these processes and their characteristics for the best case. For a list of what these processes are exactly see the SWAN manual. To research different processes these parameters might be changed. These cases will be given in the next section.

Table 3.5: Overview settings of the physical processes for SWAN

Process	Settings in validation case	Explanation
GenModePhys	3	
Breaking	true	Breaking modelled
BreakAlpha	1.0000000e+000	
BreakGamma	7.3000002e-001	
Triads	false	Non-linear Triad wave wave interactions are not modelled
TriadsAlpha	1.0000000e-001	
TriadsBeta	2.2000000e+000	
WaveSetup	true	The wave-induced setup is modelled
BedFriction	jonswap	The bed friction formula's of Hasselmann et al. (1973) are used
BedFricCoef	6.7000002e-002	
Diffraction	true	Diffraction is on
DiffracCoef	2.0000000e-001	
DiffracSteps	5	
DiffracProp	true	
WindGrowth	false	There is no wave growth trough wind
WhiteCapping	Komen	The formula's of komen are used for the Whitecapping
Quadruplets	false	
Refraction	true	The wave refraction is modelled
FreqShift	true	Wave frequency shifts are modelled
WaveForces	dissipation 3d	

NUMERICAL SETTINGS

The accuracy of the SWAN model is set to 99,9 per cent, to ensure that all grid cells are computed well. Also the change rate of the Hs and the Tp are changed to a value that creates a model that has a 99,9 per cent accuracy. The values of these settings can be found in table 3.6.

3.6. KAMPHUIS MODULE MODEL SETUP

The Kamphuis module is a can be used to do fast calculations of the lee-side wave transformation. This section will give an overview of the setup of this module. The Kamphuis calculations are incorporated in Unibest CL+, therefore some of the settings are in Unibest and some are in the module.

GRID

The grid of the Unibest model consist of cross-rays, not of grid cells because it is a one dimensional model. These rays are 500 meters apart but in the stretch behind the breakwater, at the stretch of interest, the rays are

Table 3.6: Overview of the numerical settings SWAN

Process	Value	explanation
DirSpaceCDD	0.5	Scheme for the directional space. 0,5 creates a trapezoidal scheme
FreqSpaceCSS	0.5	Scheme for the frequency space. 0,5 creates a trapezoidal scheme
RChHsTm01	0.2	Relative change between Hs and Tm01
RChMeanHs	0.2	Relative change Hs
RChMeanTm01	0.2	Relative change Tm01
PercWet	99,9	Accuracy in 99,9 per cent of the wet grid points
MaxIter	20	Maximum iterations

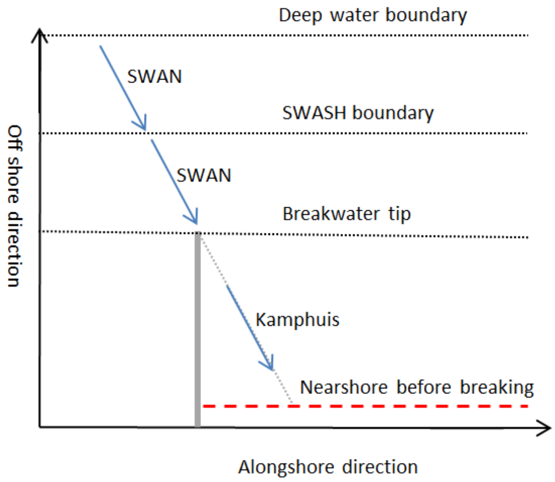

Figure 3.9: Kamphuis modelling approach

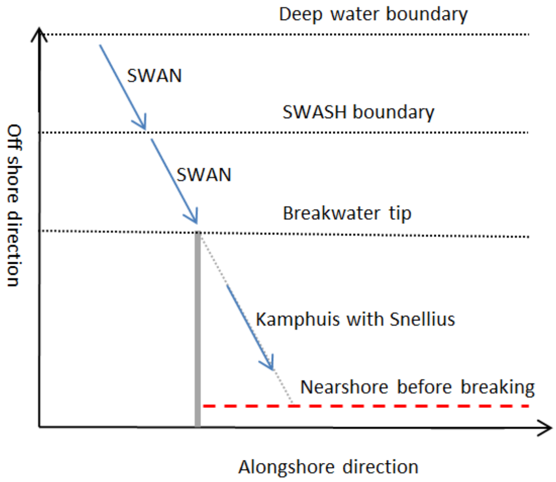

Figure 3.10: Kamphuis modelling approach with Snell's law

200 meters apart. These rays are divided into 20 grids per ray making the grid distance behind the breakwater 10 meters.

BOUNDARY CONDITIONS

The conditions used for the Kamphuis module are the wave conditions at the breakwater tip. The SWAN wave model is used to calculate the wave conditions at the breakwater tip.

The depth profile from the breakwater tip to shore is flat, the depth of the breakwater tip is 7,15 meter. This is described by Huisman (Huisman, 2014). For the diffraction behind the breakwater Unibest uses the Kamphuis formula's (Kamphuis, 1992). Because the bottom from the breakwater tip until the shore is flat not refraction will occur.

4

MODEL RESULTS

In this chapter the model results are presented, analysed and discussed. In 4.2 the results of the five model approaches, given in section 3.3, are presented. Section 4.3 describes offshore the different wave processes involved in the wave transformation. An analysis of the relative influence of the different model approaches on the sediment transport is given in 4.4.

4.1. INTRODUCTION

The goal of this chapter is to answer the research questions 3, 4 and 5 stated in section 1.2. In this chapter the model results are presented, analyzed and discussed. First the results of the five model approaches, given in Chapter 3, will be presented to understand how the different models preform. The goal is to find the preferred model approach for different offshore wave conditions. The second section will be about analysis of the different wave processes involved in the wave transformation. The goals of this section is to get a better understanding of the relative influence of the different wave processes on the wave transformation. The third section is an analysis of the relative influence of the different model approaches on the sediment transport.

4.2. EXAMINING MODEL APPROACHES

This section describes the output of the five model approaches described in Chapter 3 (SWASH, SWAN, SWAN with the diffraction module, Kamphuis and Kamphuis with refraction) for the transition from the deepwater to the nearshore waves. First, the wave transformation in space is given (only SWASH and SWAN), followed by the resulting nearshore wave characteristics for three different offshore wave directions and two different cases of directional spreading.

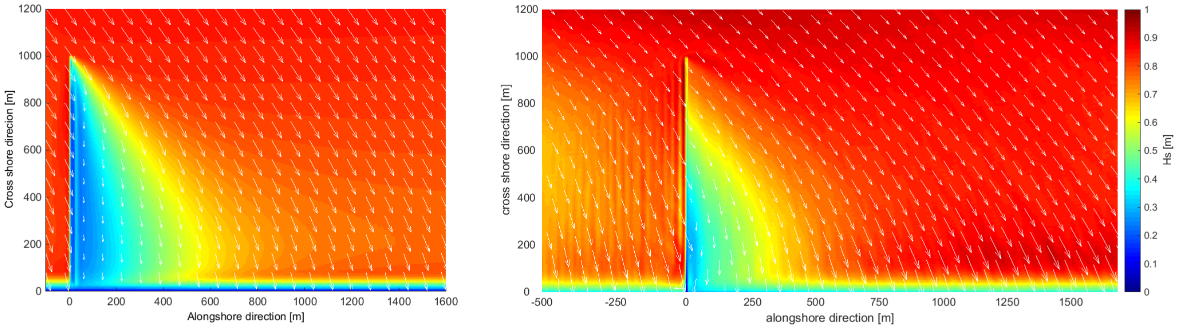

Figure 4.1: Spatial overview of the wave height and the wave direction in SWAN (left) and SWASH (right). The wave height is shown in colours and the wave angle is shown in arrows. The offshore wave conditions are: Hs = 1 m, Dir = 45 degrees, Tp = 6 seconds and directional spreading m = 2 (or 31.5 degrees).

Figure 4.1 shows the spatial wave transformation from the offshore SWASH boundary at y=1200 m to the coast, around and especially behind a breakwater for SWASH and SWAN. The figure aims to give an overview of the spatial differences between the models and the influence of the breakwater. Both the wave height (in colours) and the wave direction (in arrows) are shown. The wave conditions will be described at the north boundary, halfway the breakwater and near the shore just before breaking. The nearshore waves (just before breaking) of cases with short crested and long crested waves for different incoming wave directions will be further investigated and elaborated in the next paragraphs.

As explained in chapter 3, SWAN computed the wave transition from deepwater to the SWASH boundary. At y=1200 the waves come in at an angle of 38 degrees to the north and have a significant wave height of 0.93 meters. Due to refraction the waves turn seven degrees toward the coast. The decrease in wave height is due to wave shoaling; in this process the wave height in the cross shore direction first decreases and then increases close to the coast (Longuet-Higgins and Steward, 1964), the shoaling factor (reduction factor due to shoaling) is in this case about 0.94 [-]. At the right boundary the SWASH model shows waves at an angle towards the breakwater due to boundary effects. The main research area is from the breakwater until 1500 meters from the breakwater and these boundary effects are outside this area.

Halfway the breakwater at y = 500 the sheltered waves directly behind the breakwater (0<x<250m) have turned to about 0 degrees to the north in the SWASH model and about 10 degrees in the SWAN model due to diffraction and (partially) sheltering of the waves with a large directional spreading. In both models the sheltered area shows reduced wave heights: about 0.4 to 0.5 m. In the area from 250 to 500 meters from the breakwater the effects are less but both the wave direction is turned and the wave height is decreased. Due to the large directional spreading (m=2) the waves coming in at a higher angle are blocked by the breakwater while the waves coming in more from the north are not blocked by the breakwater and reach the point just behind the breakwater. This has both an effect on the average wave angle as well as the average wave height. The big difference between the two models is the gradient of the wave height in alongshore direction. At the distance of 500 to 1000 meters from the breakwater, and a distance of 500 meters from the shore the effects of the breakwater are still noticeable in a decreased wave height but the wave direction is not influenced a lot by the breakwater. In the non-sheltered area (x>1000 m) the waves turn towards the coast due to refraction and the wave height does not decrease.

SHORT CRESTED WAVES

The results for wave height, wave direction and wave induced setup for short crested waves near the shore are given in figure 4.2 to 4.4. The nearshore wave characteristics are studied because the waves will force the sediment transport. To study the wave height nearshore just outside the breaking zone because the energy dissipation due to breaking changes the waves so much that the transformation processes cannot be studied anymore.

Wave breaking is steepness induced breaking in SWASH, this means that when the waves are too steep they fall forward and the wave breaks. In SWAN it is depth induced breaking (Battjes and Janssen, 1978), this means that waves are assumed to be breaking when the depth is about 0.73 times the wave height. Breaking in the SWASH model starts about 90 meters from the coastline (at a depth of about 2 meters) and in the SWAN model at 50 meters from the coastline (at a depth of about 1.4 meters). The nearshore waves are compared at y=100 m to be sure to be outside the breaker zone.

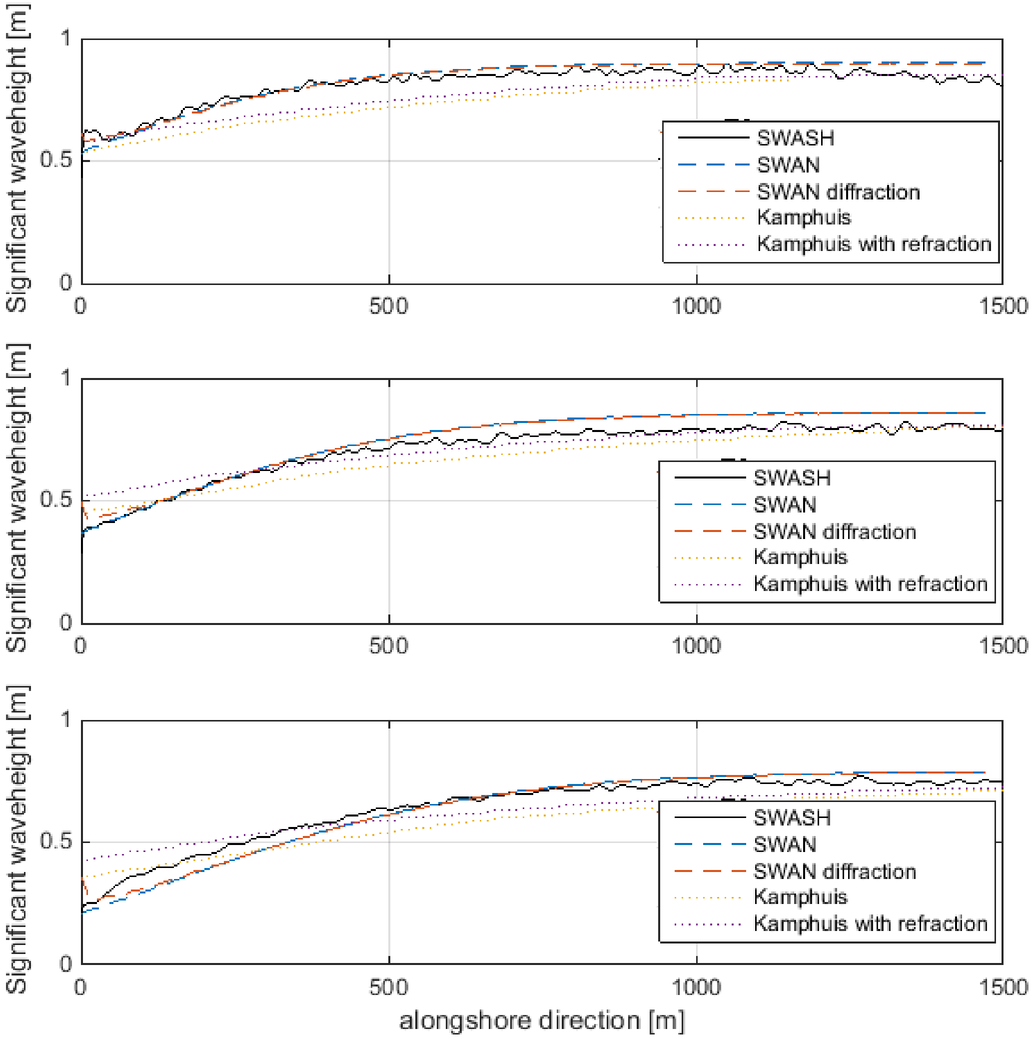

Figure 4.2: Wave height alongshore at y=100 m for the five model approaches: SWASH, SWAN, SWAN with diffraction, Kamphuis and Kamphuis with Refraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 2 (or 31.5 degrees).

Comparing the nearshore wave height of the SWAN model approaches with the SWASH approach, it can be concluded that the model results show similar results in both the wave height and the gradient of the wave height over the alongshore direction. In the case of the deepwater wave direction of 45 degrees, it can be noticed that there is some energy diffracted into the sheltered area which the SWAN models (both with and without diffraction) do not show.

Compared to the SWASH model, the Kamphuis module (both with and without refraction) shows a lower alongshore gradient in wave height. For all three cases the wave height directly behind the breakwater is about 0.5 meter. For the cases with the direction of 30 and 45 degrees this is different in the SWASH model (about 0.4 and 0.3 m).

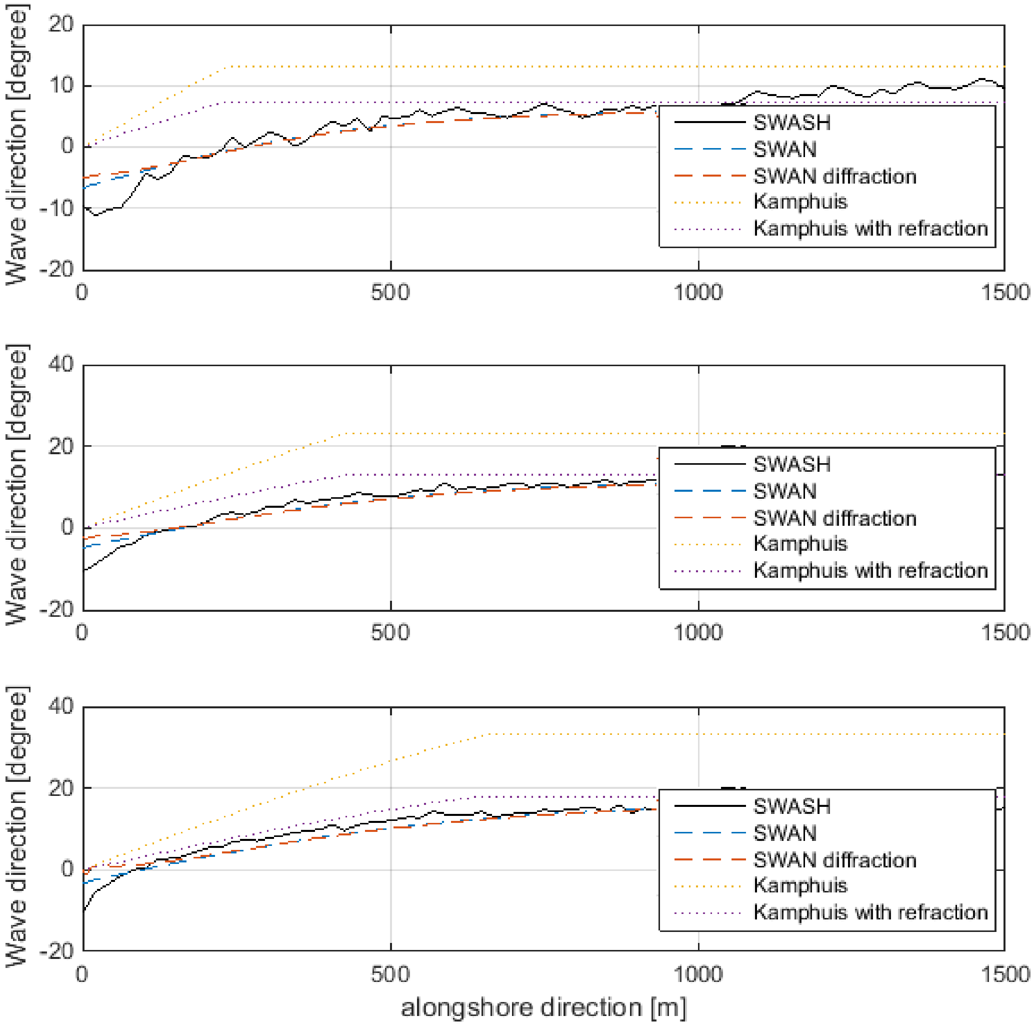

Figure 4.3: Wave direction alongshore at y=100 m for the five model approaches: SWASH, SWAN, SWAN with diffraction, Kamphuis and Kamphuis with Refraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 2 (or 31.5 degrees).

Figure 4.3 shows the wave direction alongshore for 3 different wave directions with a directional spreading of m=2 (or 31.5 degrees). Compared to the ground truth model (SWASH) the results from the SWAN models appear to be accurate for all three cases except for the area directly behind the breakwater, where the wave direction in the SWASH model turns towards the breakwater. In section 4.3 this dip will be investigated further. The negative wave direction (waves towards the breakwater) close to the breakwater in SWAN can be explained by the sheltering of waves with a large directional spreading (see section 2.1). The only wave components that can reach this area are the wave components that are not sheltered coming in from the right.

This is mainly the case for the case with a direction of 15 degrees because the same directional spreading results in more wave components from the right.

The Kamphuis module without refraction (without refraction) does not give a very accurate lee-side direction near the shore. Behind the breakwater the effect of the refraction is smaller than in the equilibrium area.

For the cases of Kamphuis with refraction the results give a much better representation of the wave direction, especially for the cases with the direction of 30 and 45 degrees. For the case with an incoming wave of 15 degrees the wave direction in the area from the breakwater until 500 meters the is too high. It can be concluded that the refraction input plays an important role in the for accurate modeling.

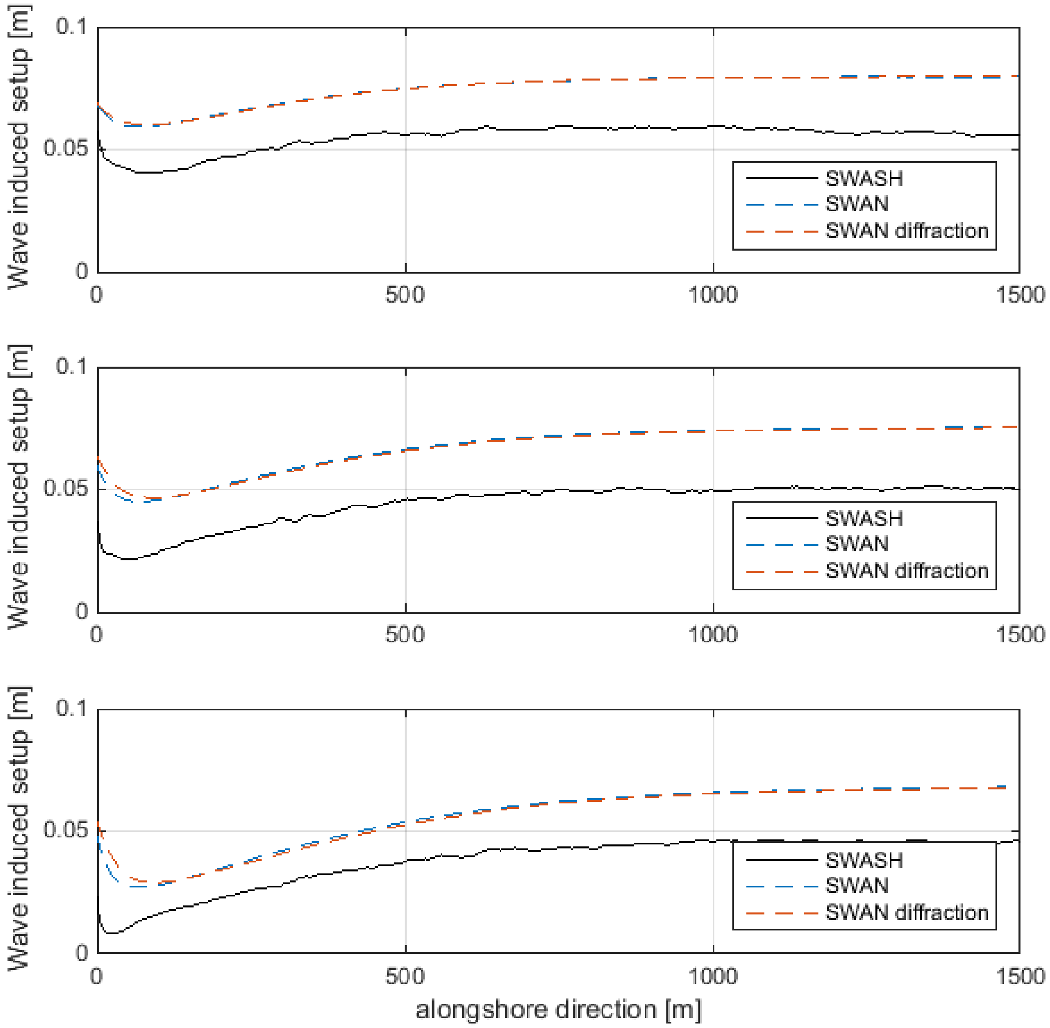

Figure 4.4: Wave-induced setup alongshore at y=4 m (at a depth of 25 cm) for three model approaches: SWASH, SWAN and SWAN with diffraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 2 (or 31.5 degrees).

In figure 4.4 the wave induced setup for the wave conditions as seen above is presented. It shows the wave setup at y = 4 meter. The wave setup is only shown for SWASH and SWAN because the Kamphuis module does not calculates wave induced setup. The wave setup itself does not generate sediment transport, but spatial variation in wave setup induces a (alongshore or cross-shore) current which transports sediment as explained in chapter 2.

The setup shows the same differences for all three cases. The SWASH model computes a lower setup, but the differences between the sheltered zone and the non-sheltered zone are equal. Interestingly, the setup is forced by the wave height, and the wave height differences between SWASH and SWAN are similar. Consequently, this has to do with the way the setup is calculated by the models, in which the SWAN model overestimates the setup compared to SWASH.

CONCLUSIONS SHORT CRESTED WAVES

The results for short crested waves (with the directional spreading of m=2) show that the SWAN model gives a good representation in these cases (for all three incoming wave types) for both the direction and the wave height. The models SWAN with diffraction and SWAN without diffraction yield little differences, and the SWAN with diffraction is not more accurate than SWAN without diffraction.

The Kamphuis with and without refraction approaches show a wave height which has a lower alongshore gradient compared to SWASH and for cases with larger incoming waves it gives a less accurate representation of the wave height directly behind the breakwater. The wave height from the Kamphuis module is however usable for fast computations. The Kamphuis models are not very accurate for wave directions in the sheltered area. In the non-sheltered zone, the Kamphuis model with refraction is accurate while the Kamphuis model without refraction is not. This emphasizes the importance of refraction in the computations.

RESULTS LONG CRESTED WAVES

Long crested waves have a little directional spreading. When long crested waves dominate the wave climate, this section will show how well the different model approaches do. Figure 4.5 illustrates the nearshore wave height, figure 4.6 shows the nearshore wave direction and figure 4.7 the setup along the coast for long crested waves.

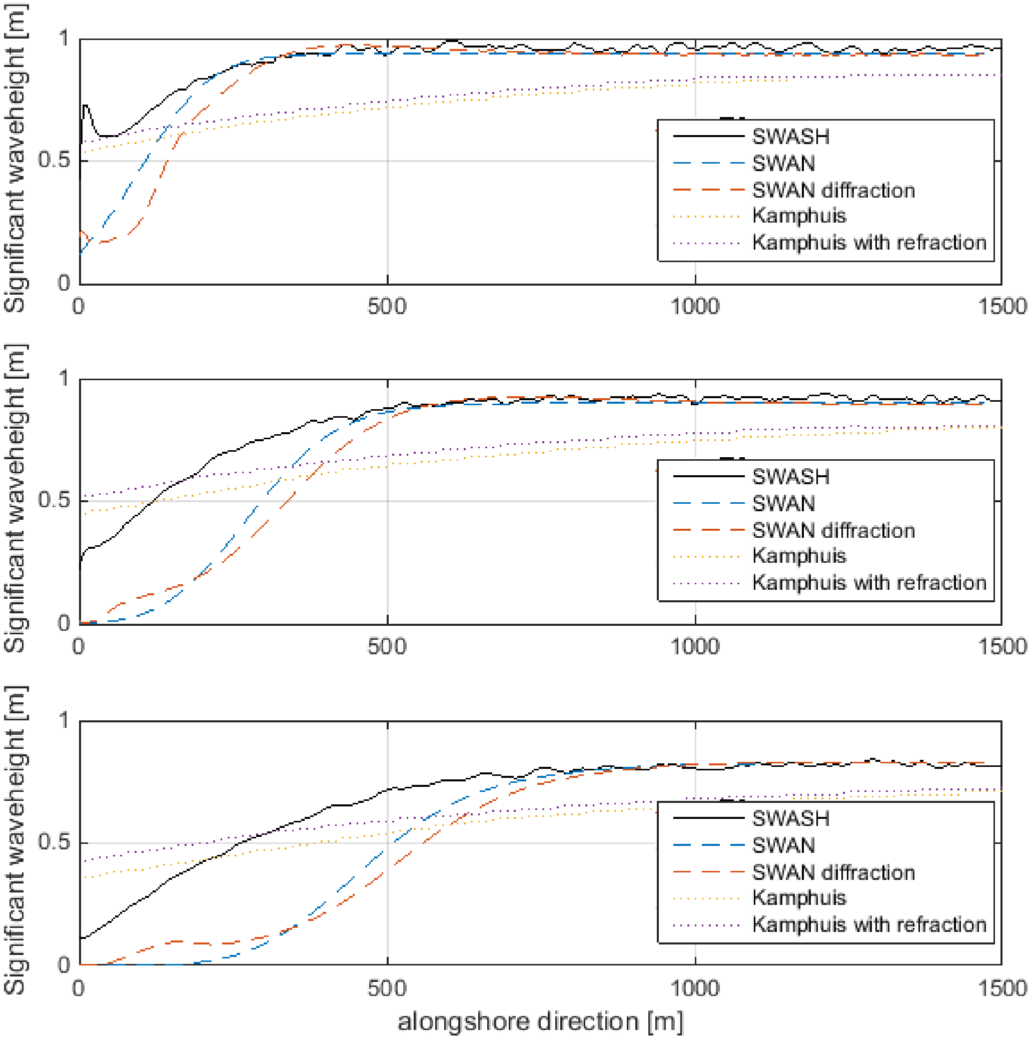

Figure 4.5: Significant wave height alongshore at y=100 m for the five model approaches: SWASH, SWAN, SWAN with diffraction, Kamphuis and Kamphuis with Refraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 10 (or 17.1 degrees).

Figure 4.5 shows the wave height nearshore for 3 different wave directions with a directional spreading of m=10 (or 17.1 degrees). The goal is to investigate how well the models compute the wave transformation behind the breakwater for long crested waves. Note that the directional spreading cannot be altered in the Kamphuis module and the same offshore directional spreading is used as for the cases with short crested waves.

The small directional spreading results in smaller waves behind the breakwater: there are no wave components that come in at an angle that can reach this area. When analysing the SWAN model approaches it can be seen that the wave height computed by the SWAN model directly behind the breakwater is smaller for the SWAN cases. Diffraction is more important for these cases because the energy differences in the shadowed zone and outside the shadowed zone are greater than in cases with large directional spreading. The difference between SWAN with diffraction and SWAN without diffraction is larger than for short crested waves. The SWAN model with diffraction turns wave energy towards the shadowed zone. However, it seems that the diffraction module does not turn enough energy towards the sheltered zone. In section 4.3 the influence of diffraction is analysed.

In figure 4.5 the Kamphuis module yields the same results as in figure 4.2 because the directional spreading cannot be changed. Because of the small directional spreading the significant wave height is more bundled, resulting in steeper alongshore gradient and for waves the Kamphuis module preforms worse than for the short crested waves.

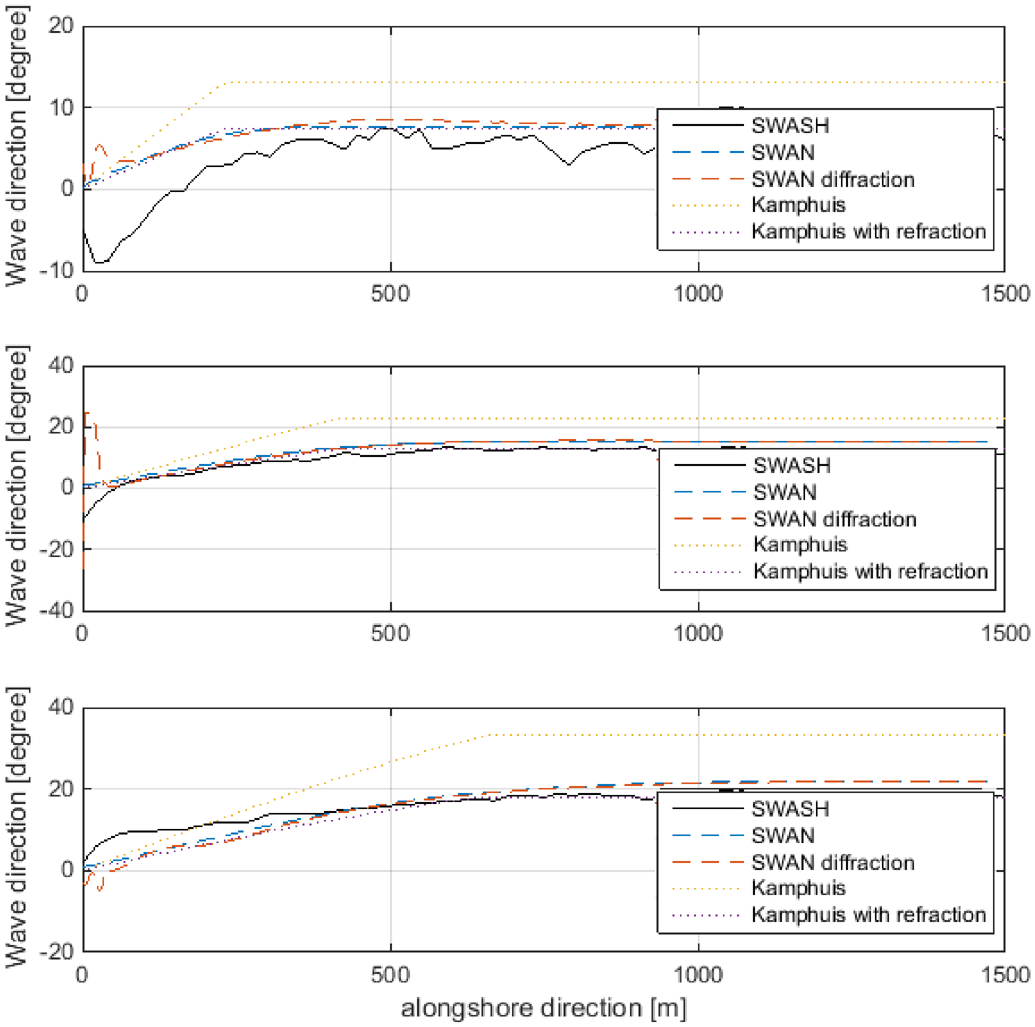

Figure 4.6: Wave direction alongshore at y=100 m for the five model approaches: SWASH, SWAN, SWAN with diffraction, Kamphuis and Kamphuis with Refraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 10 (or 17.1 degrees).

In figure 4.6 the nearshore wave direction for long crested waves is shown. The ground truth model

(SWASH) shows wobbles alongshore, especially for the case with an incoming wave direction of 15 degrees. For the cases with an incoming wave direction of 30 and 45 degrees the SWASH model gives a sharp turn of the wave angle towards the breakwater close to the breakwater. In section 4.3 the it is investigated what process forces the sudden change in wave direction.

The nearshore wave direction modelled by SWAN shows less accuracy than for the cases with short crested waves. For waves incoming at 15 degrees the SWAN model with diffraction shows an effect opposite to the ground truth model. The diffraction module does not make the computations in SWAN better for these cases.

The Kamphuis module with refraction preforms very well for all three conditions. The difference between SWAN and the Kamphuis module with refraction is also negligible. This is not what should be expected because it models the short crested waves.

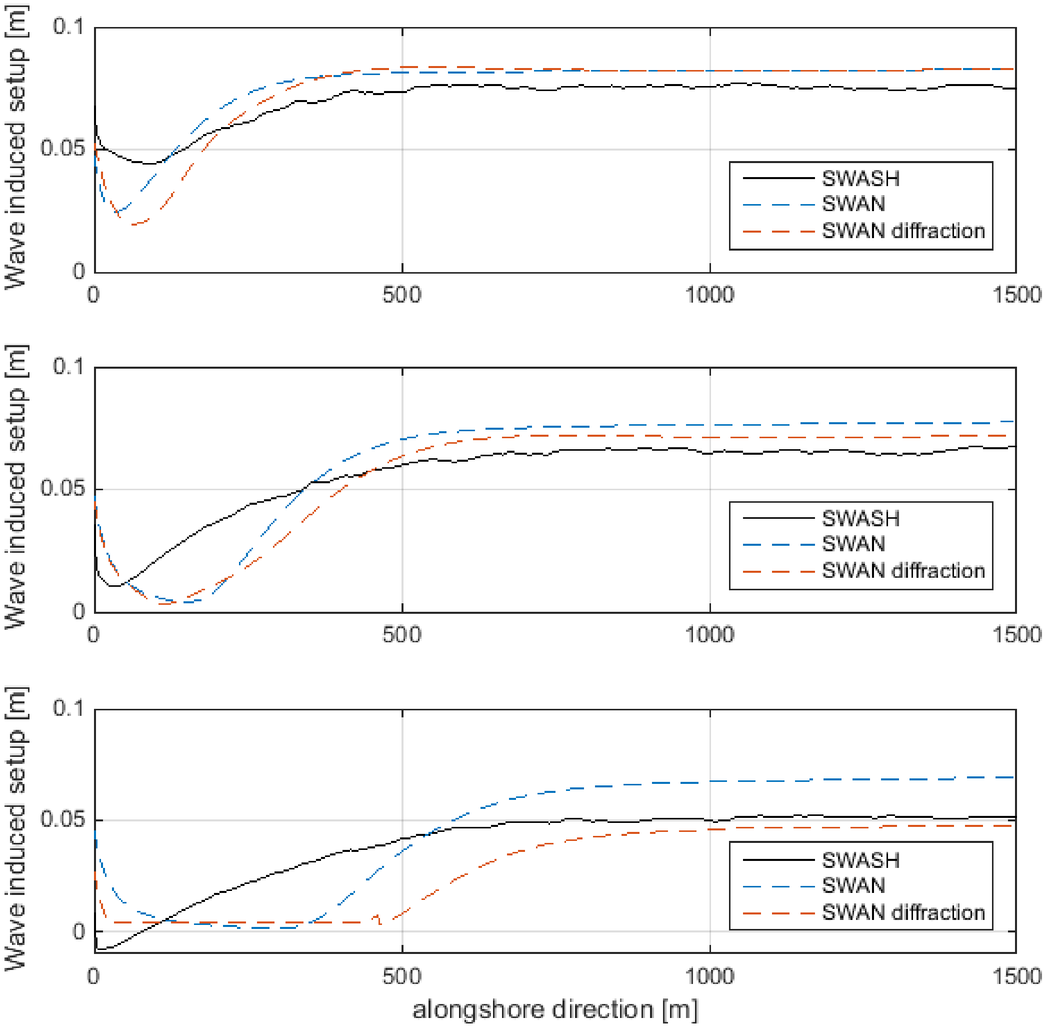

Figure 4.7: Wave induced setup alongshore at y=4 m (at a depth of 25 cm) for three model approaches: SWASH, SWAN and SWAN with diffraction for offshore waves with characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds and directional spreading m = 10 (or 17.1 degrees).

Figure 4.7 shows the wave induced setup for the cases with long crested waves with a small directional spreading. The trend for the top and middle cases is that the SWASH models show similarity to the SWAN model. The wave setup in the non-sheltered area is a little smaller for the SWASH model and the lowest setup is smaller in SWAN. This results in a larger setup difference in the SWAN models (about a factor 2). This does not mean that the setup drive flow is 2 times larger but there is a big difference between the two models. The SWAN with diffraction does not show a better setup than the SWAN model without diffraction, but over the whole length this does not have a big influence.

CONCLUSIONS LONG CRESTED WAVES

The results for the cases with long crested waves with a directional spreading of m=10 show that the SWAN models (both with and without diffraction) do not model this diffraction well. The wave energy in the sheltered zone in the ground truth model is much larger.

Comparing the model approaches SWAN with diffraction and SWAN without diffraction shows little differences, but the SWAN with diffraction a little is closer to SWASH than the SWAN without diffraction.

For mild incoming waves of dir = 15 degrees the Kamphuis module models the wave height very well but for sharper incoming waves this is not the case. The results for wave direction show that the SWAN model approaches are quite accurate. The models Kamphuis with and Kamphuis without Snell's law show a wave height that is comparable to the ground truth model for incoming waves of 15 degrees but not for incoming waves of 30 and 45 degrees. Although these models in general are less accurate the computation times are a lot faster. However, when Snell's law is applied the wave directions are accurate. These tests show the importance of the refraction in the computations.

DISCUSSION AND CONCLUSION MODEL APPROACHES

The last section shows the usability for the five model approaches for the given wave conditions. Next to these conclusions there are also three other conclusions that can be drawn from these tests; (1) The importance of the directional spreading in wave modelling is very large (2) the refraction, that is not incorporated in the kamphuis modul,e is of significance. For this simple case using Snell's law seems to be very effective and (3) The diffraction option added to SWAN does, for these cases except the long crested wave height, not make a difference.

Table 4.1 shows the relative performance of the model approaches compared to the SWASH model. The cases with a larger directional spreading show that the transition area from shelterd to non-sheltered is much larger. Especially the wave height along the coast is very different for long crested waves compared to shot crested waves, where the wave direction does not differ that much.

Table 4.1: Relative performance of the five model approaches

	Hs m=2			Dir m=2			Hs m=10			Dir m=10		
{Offshore wave direction}	15	30	45	15	30	45	15	30	45	15	30	45
{SWAN}	+	+	+	+	+	+	-	-	-	+	+	+
{SWAN with diffraction}	+	+	+	+	+	+	-	-	-	+	+	+
{Kamphuis}	+/-	+/-	+/-	-	-	-	-	-	-	+/-	+/-	+/-
{Kamphuis with refraction}	+/-	+/-	+/-	+/-	+	+	-	-	-	+	+	+

The Kamphuis module is for shot crested waves with a directional spreading of m=2, this results in poor usability for long crested waves. Figure 4.5 shows that the wave height for the long crested waves directly behind the breakwater are much smaller in the Kamphuis formula than in the SWASH model.

$$Kd = 0,68 + 0,008 * \theta \qquad \text{for} \qquad 0 \geqslant \theta > -90 \tag{4.1}$$

The formula for the the wave height in the Kamphuis module is given in equation 4.1. When fitting a better equation for waves with different directional spreadings three factors play a role: (1) the formula gives a coefficient for the wave height directly behind the breakwater of 0.71, for long crested waves this is however smaller. (2) Also the alongshore length to the equilibrium state is much smaller for long crested waves. (3) Because of the small directional spreading of these long crested waves diffraction could play an much more important role. It can be derived that the wave height for waves with a different directional spreading is more in the form of:

$$Kd = 0,68 * function(dir, dirspr) + 0,008 * function(dirspr) * \theta \qquad \text{for} \qquad 0 \geqslant \theta > -90 \tag{4.2}$$

The next section will analyze the influence of the directional spreading, the diffraction and some secondary effect on the wave processes modelling.

4.3. INFLUENCE OF THE WAVE PROCESSES

This section will investigate the wave processes involved in the transformation from offshore to nearshore. First the influence of the directional spreading is investigated, then the influence of the diffraction and lastly some secondary wave processes like rip-current induced refraction and energy dissipation.

SHELTERING

The model results for SWASH and SWAN for two different directional spreadings is shown in figure 4.8 for the wave height. The black lines are the SWASH model results and the red lines the SWAN model results (without diffraction). The solid lines give the results of the short crested waves with a directional spreading of m=2 and the dashed lines give the long crested waves with a directional spreading of m=10.

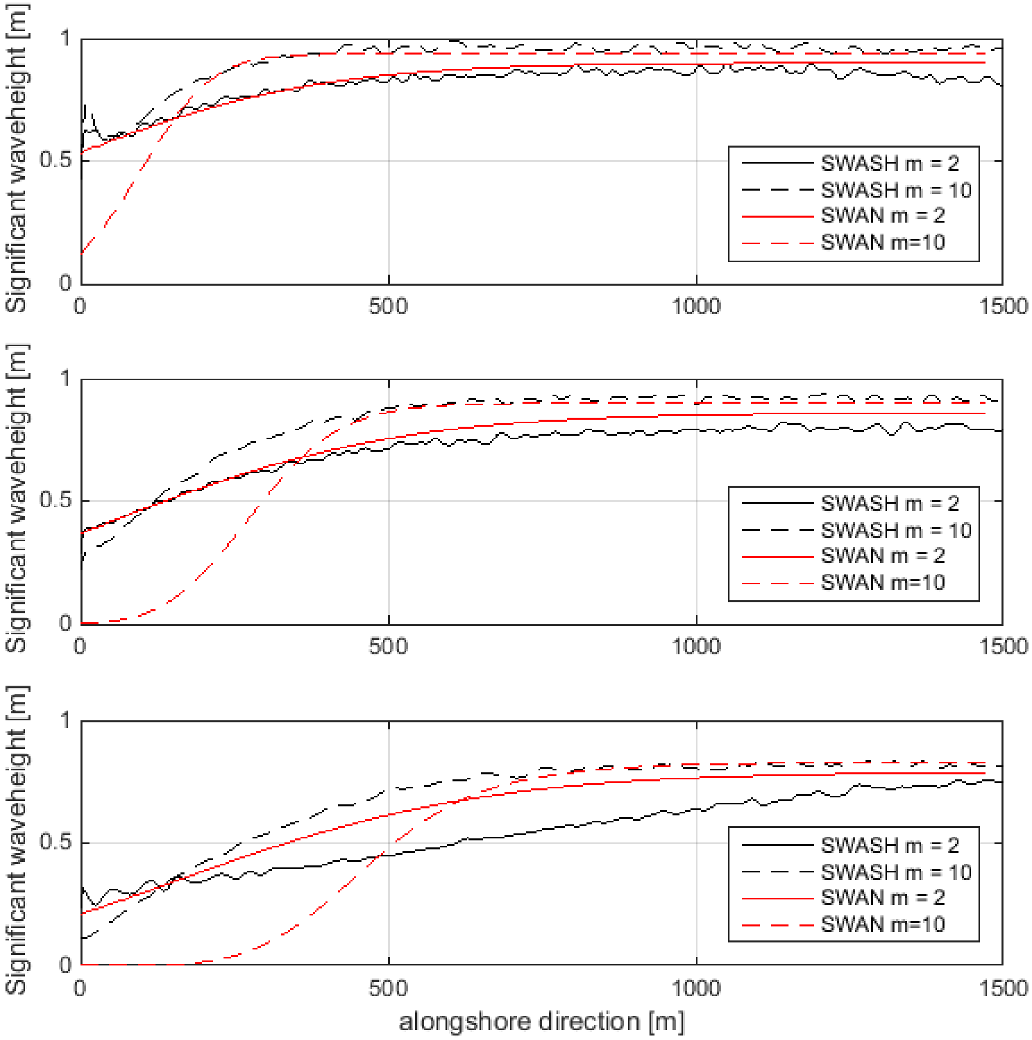

Figure 4.8: Significant wave height alongshore at y=100 m (at a depth of 2 m) modelled by SWASH, SWAN for short crested waves (m=2) and long crested waves (m=10). Other waves characteristics: dir = 15 (top), dir = 30 (middle) and dir =45 and for all three Hs = 1 m, Tp = 6 seconds.

The difference between the two SWAN model results per wave direction is completely due to the difference in directional spreading because the SWAN model does not include diffraction. The SWAN model does also perform according to the expectations. Figure 4.9 and figure 4.10 give a sketch of the expected wave height at the lee of a breakwater without diffraction. The short crested waves with large directional spreading get partially blocked by the breakwater, this results in higher wave heights directly behind the breakwater than for waves with a more narrow directional spreading; in the latter case the waves get completely blocked by the breakwater.

Also the alongshore length of the influence zone of the breakwater in the SWAN model corresponds with the sketch made in figure 4.9 and 4.10. For the case with a narrow directional spreading of a long crested wave this also results in a narrow and small influence zone. For SWASH, the comparison between the sketch with the expected wave height (without diffraction) and the results (fig 4.8) is only good for the cases with a large directional spreading. For these cases the influence length is long and the wave height directly behind the breakwater strongly reduced but not zero.

The model results for short crested waves (with a small directional spreading) show a large difference with the expected sketch. This can be explained by the diffraction.

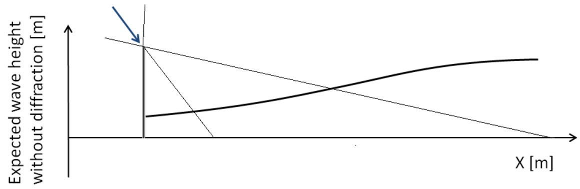

Figure 4.9: Expected wave height for short crested waves

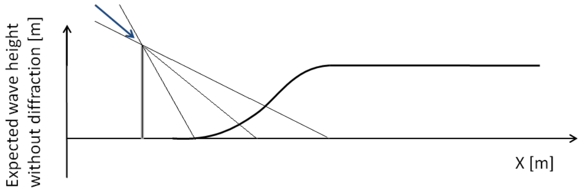

Figure 4.10: Expected wave height for long crested waves

DIFFRACTION

Diffraction is the wave energy transport along a wave crest due to abrupt changes in bottom profile or obstructions. as explained in section 2.1. When the energy differences between the sheltered and the nonsheltered area are small the diffraction is also small. But when the energy differences are larger more refraction will occur. This can be seen in figure 4.8. For the cases with long crested waves, and higher wave height differences between de sheltered and the non-sheltered area, the wave energy does turn towards the sheltered area. This results in much higher waves directly behind the breakwater than expected solely by the directional spreading.

From this analysis it can be concluded that the difference in the wave height between the SWASH model and the SWAN model is due to the diffraction of the waves. The SWAN modelling approaches for long crested waves shown in section 4.2 (figure 4.5) just miss this important process. The SWAN modelling approach with the diffraction apparently does not diffract enough.

CURRENT INDUCED REFRACTION

Current induced refraction is where the current forces the waves to turn toward the opposite flowing current. The opposite flowing current works as a friction on one side of the wave crest turning it towards this current. When tides create a current it is often more homogeneous and thus results in less refraction. These rip currents, forced by the waves, are more local and thus the wave direction changes locally. In these cases only the SWASH model incorporates these currents because it is a phase resolving model that computes the movement of the water (and thus the waves). Figure 4.11 to 4.16show the average currents in SWASH for 6 wave conditions. The figures show a domain 1000 meters in the x direction and 200 meters in the y direction. Because the nearshore wave characteristics where analysed at y=100, this is halfway these figures.

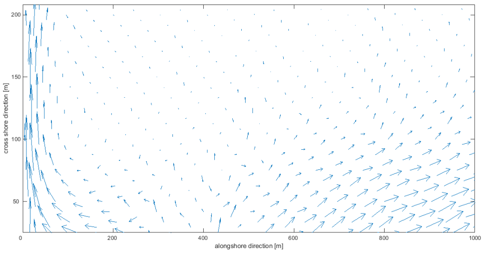

Figure 4.11: Rip currents for direction = 15 deg, m=2

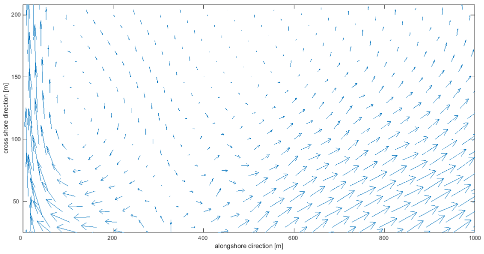

Figure 4.12: Rip currents for direction = 15 deg, m=10

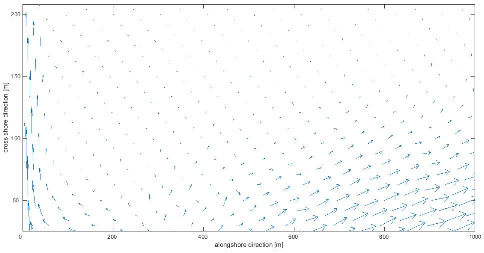

Figure 4.13: Rip currents for direction = 30 deg, m=2

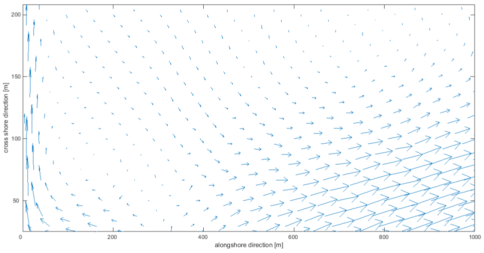

Figure 4.14: Rip currents for direction = 30 deg, m=10

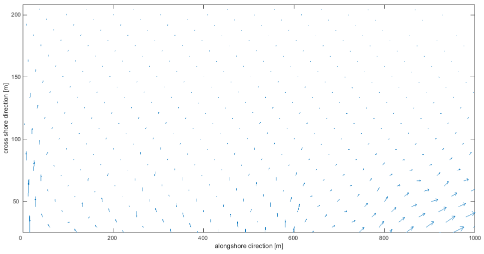

Figure 4.15: Rip currents for direction = 45 deg, m=2

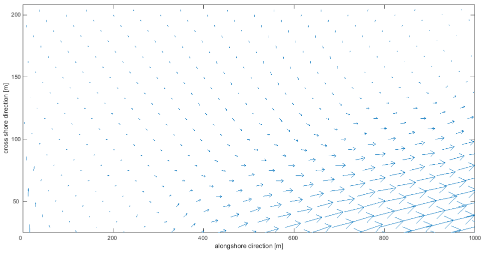

Figure 4.16: Rip currents for direction = 45 deg, m=10

In section 4.2 the wave direction in the SWASH modelling approach sometimes changed a lot locally. These abrupt changes can be explained by looking at the wave current. For the cases with an offshore wave direction of 15 degrees (both short crested waves and long crested waves) there is a large rip-current flowing along the breakwater to the top of the breakwater. In figure 4.3 and figure 4.6 it can be seen that these the waves make an abrupt turn towards the breakwater. This is due to the current induced refraction.

Interestingly, the directional spreading does not influence the currents that much, while the directional spreading did result in a major difference in wave height and direction. The main factor that seems to influence the rip currents is the incoming wave direction. It can be concluded that for cases with incoming wave directions of 0 to 30 degrees this a process that is of influence on the direction of the waves.

ADVISE MODEL IMPROVEMENTS

Because the Kamphuis formula is made for cases with a large directional spreading, for which it works fine, it is not so easy to find a solution for the cases with small directional spreading. It might be a better solution to use a different formula for cases with long crested waves. Equation 4.3 gives again the Kamphuis formula for the wave height with the added factors and table 4.2 gives the wave heights of the cases for different locations.

$$Kd = 0,68 * function(dir, dirspr) + 0,008 * function(dirspr) * \theta \qquad \text{for} \qquad 0 \geqslant \theta > -90 \tag{4.3}$$

.

Table 4.2: Nearshore wave height directly behind the breakwater for all six cases

Dir. spr. [-]	**Dir. [deg.]**	**SWAH**	**SWAN**	**Kamphuis**
2	**15**	0.60	0.58	0.54
2	**30**	0.37	0.42	0.45
2	**45**	0.31	0.28	0.36
10	**15**	0.62	0.19	-
10	**15**	0.27	0.007	-
10	**15**	0.11	0	-

4.4. ANALYSIS OF RELATIVE TRANSPORT RATES

Figure 4.17 and 4.20 show a proxy for the alongshore sediment transport as explained in section 3.2. This proxy shows the relative sediment transport rates without the constants that are present in the sediment transport formula's. However, it is assumed to give a good representation of the sediment transport. Note that the values at the y axis don't give the total transport. The relative sediment transport is forced by the nearshore direction and the wave height squared.

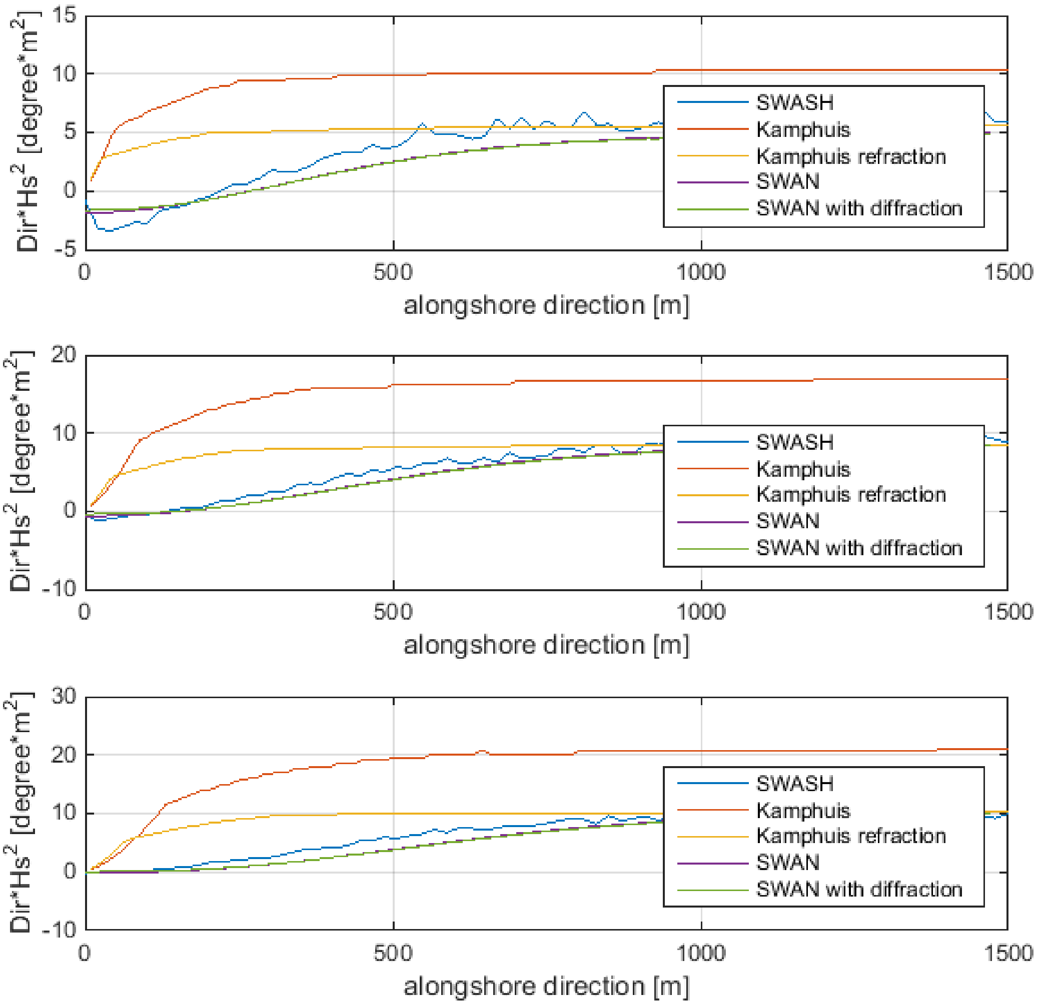

Figure 4.17: Sediment transport proxy that gives a relative sediment transport along the coast for short crested waves (m=2) with an offshore Hs =1 m and dir =15 (top), dir = 30 (middle) and dir = 45 (bottom). Proxy is calculated from the nearshore model results of SWASH, Kamphuis, Kamphuis with refraction, SWAN and SWAN with diffraction.

For the analysis of the transport two factors are important. The first is the derivative of the sediment transport, as this is the coastline change. The derivative of the sediment transport can therefore tell something about the shape of the erosion pit. The second is the length between the breakwater and where the sediment transport process is returned to the equilibrium state, this tells something about the length of the erosion pit.

Figure 4.17 shows the sediment transport for the short crested waves. Due to the current-wave interaction the ground truth model is not as smooth as the other four modelling approaches. The sediment proxy for the SWASH model is very however very similar to the SWAN model. This means that the SWAN model approaches give a good representation for the sediment transport. Both the influence length and de derivative of SWAN model are similar to the SWASH model. The Kamphuis computations do show a different sediment transport. The wave height directly behind the breakwater is higher and the waves come in at a higher angle, resulting in higher sediment transport rates. The influence length (and therefore the length of the erosion) is much smaller in the Kamphuis module. The derivative of the Kamphuis module is also differs from the other two models, resulting in a completely different coastline change as shown in figure 4.18 and 4.19.

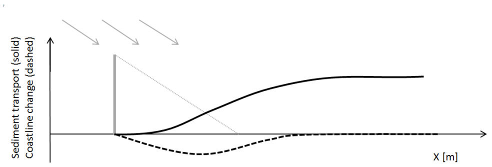

Figure 4.18: Schematized coastline change (dashed line) forced by the SWAN and SWASH model results sediment transport (solid line).

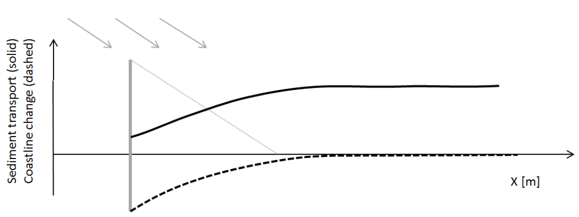

Figure 4.19: Schematized coastline change (dashed line) forced by the Kamphuis model results sediment transport (solid line).

Figure 4.20 shows the sediment transport proxy for the long crested waves. For the case with an offshore wave direction of 15 degrees both the SWASH modelling approach and the...... show a sediment transport towards the breakwater near the breakwater. This is mainly because of the current induced refraction because this forced the waves to turn further towards the breakwater. Because of the diffraction there is wave energy directly behind the breakwater to force this sediment transport. As expected after the analysis of the wave components the SWAN model approaches do not predict the coastline change very well for these cases. Because the SWAN model does not model diffraction the wave energy in the sheltered zone is too small, resulting in less sediment transport. The Kamphuis module shows the same results as in figure 4.17 because it cannot cope with long crested waves; it shows clearly that this results in unclear results for sediment transport rates and thus for coastline change.

Then there is something remarkable: At $x = 500$ a bulb in the sediment transport occurs in both the SWASH and the SWAN model, this will result in a bulb in the coastline ass-well. For cases in Florida, USA (with a long crested wave climate) there have been many of these bumps spotted (Bruun, 1995, 2001). The papers do not give a clear explanation why these bumps occur, but for long crested wave climates it is very well possible.

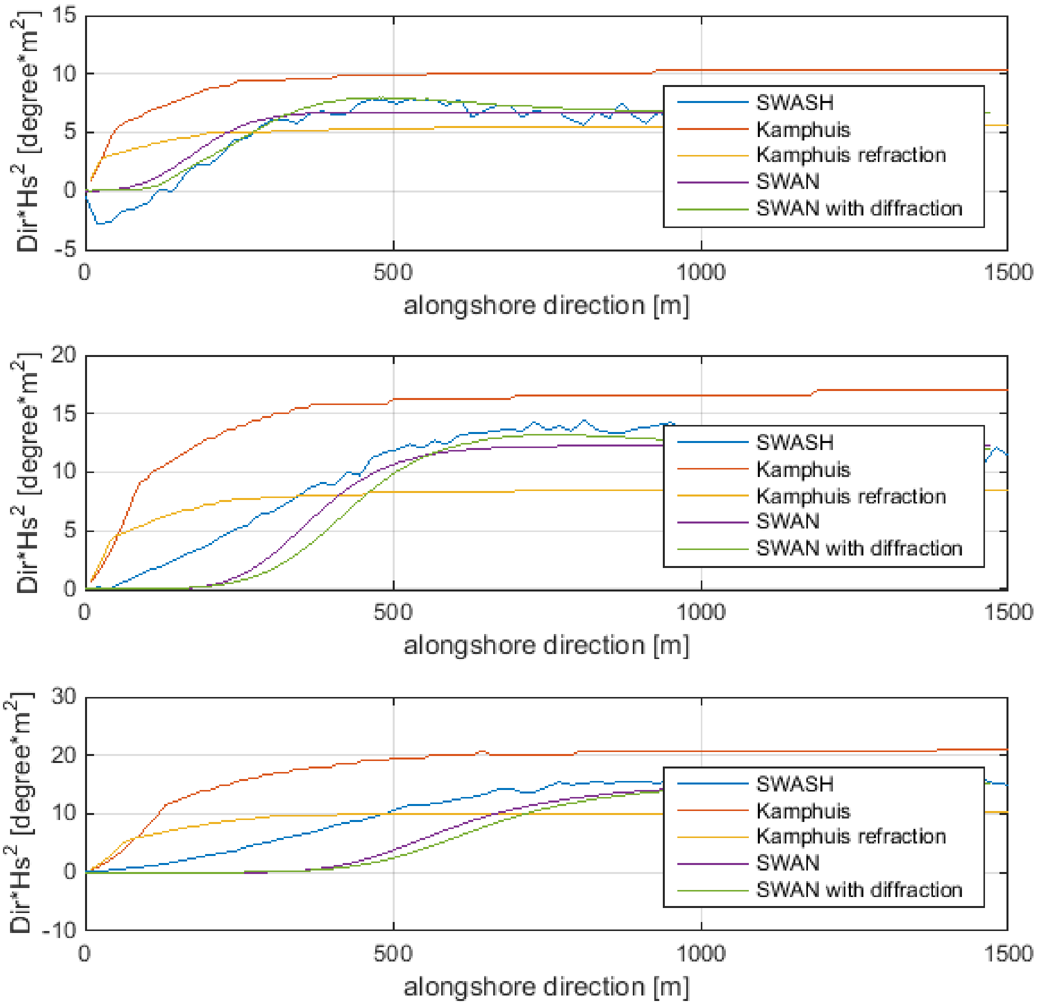

Figure 4.20: Sediment transport proxy that gives a relative sediment transport along the coast for long crested waves (m=10) with an offshore Hs =1 m and dir =15 (top), dir = 30 (middle) and dir = 45 (bottom). Proxy is calculated from the nearshore model results of SWASH, Kamphuis, Kamphuis with refraction, SWAN and SWAN with diffraction.

5

CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The objective of the thesis is to improve the coastline model predictions at the lee-side of a shore-normal breakwater at decadal scale. This was done by reviewing different wave model approaches. This research focused on (1) understanding of what wave processes are important for the coastline change and (2) an advice on what models to use for which conditions and how to the improve model predictions.

From the theoretical study which wave processes are relevant for the decadal coastline evolution at the lee-side of a shore normal construction (Research question 1) it is concluded that the following wave processes are relevant for the decadal coastline evolution at the lee-side of a shore normal construction. Refraction, sheltering, diffraction and second order processes (most important is the current induced refraction). It is also concluded that for different wave directions and directional spreading these processes have a different influence.

With three models the influence of these four wave processes is studied (research question 3). The three models that are used are SWASH (Simulating Waves till Shore) model (Zijlema et al., 2011), SWAN (Simulating WAves Nearshore) model (Booij et al., 1999) with and without the diffraction module and the Unibest-CL+ model with the Kamphuis module for diffraction (Huisman, 2014; Kamphuis, 1992; WL | Delft hydraulics, 1994) without and with refraction (refraction is added with the Snell's law for refraction). The processes are studied for a case with a long breakwater on a coast with parallel contour lines with offshore wave angles of 15, 30 and 45 degrees and for waves with a small directional spreading (m=10) and a large directional spreading (m=2). From this study it can be concluded that:

- The influence of refraction is larger for cases with a larger wave angle with the coast for both cases with a small directional spreading as well as a large directional spreading. The influence is largest outside the sheltered area. Close to the breakwater refraction has no influence. It is investigated by comparing the Kamphuis module (which does not incorporate refraction) with the ground truth model, also when Snell's law was applied to the Kamphuis module the model results did show good results.

- The influence of the sheltering on the wave height and wave direction is different for long crested waves with a small directional spreading and short crested waves with a large directional spreading. For cases with long crested waves all wave components get sheltered. This results in very little wave energy behind the breakwater. For short crested waves (especially with a small angle to the coast) the breakwater blocks not all wave components. This gives much more wave energy behind the breakwater. The direction of the waves directly behind the breakwater is towards the breakwater because those wave components don't get blocked.

- The influence of diffraction is strongly correlated with the difference in wave energy in and outside the sheltered area. Diffraction does not play an important role for short crested waves. As explained the large directional spreading results in more wave energy in the sheltered zone resulting in smaller energy differences between the sheltered and the non-sheltered zone. Even SWAN without diffraction gives a good representation for short crested waves. For long crested waves the influence of diffraction is large. There is a much larger difference in wave energy between the sheltered and the non-sheltered zone.

- The influence of current induced refraction is largest for cases with waves coming in at a small angle. For waves with an incoming agle 0 to 30 degrees rip currents along the breakwater will appear. The current induced refraction turn the waves (locally, close to the breakwater) up to an extra 10 to 15 degrees. The directional spreading has no effect on these rip currents and therefore no effect on the current induced refraction.

By comparing the four modelling approaches (the same as in the last paragraph) to SWASH it is studied what the best modelling approach is for the different wave conditions (research question 2)? The wave conditions that are studied are the same as in the last paragraph: waves with an incoming angle of 15, 30 and 45 degrees, with a significant wave height of 1 meter and a wave period of 6 second for both short crested waves as well as long crested waves. This is studied by comparing and analysing the computed wave height and wave direction of the four modelling approaches just outside the breaking zone (where the waves force the alongshore transport). The wave induced setup is compared on the coastline (where the wave induced setup is largest and force the current). It can be concluded that:

- SWAN model approach (with and without diffraction) is for cases with short crested waves a good model approach: the wave height, wave direction and the sediment transport are well modelled. Also the setup differences are very similar to the ground truth model. For cases with a small directional spreading SWAN (with and without diffraction) is not very accurate. For these cases the diffraction is more important this is not well modelled by the SWAN model, also with the diffraction module turned on. There is not enough wave energy in the sheltered area nor is the wave direction well represented.

- Kamphuis without refraction does give a good estimation of the wave height for cases with a large directional spreading. The refraction is (especially outside the sheltered zone) not modelled very well.

- Kamphuis with refraction models the wave height for the case with a large directional spreading reasonable good. For the cases with a small directional spreading the wave height is not accurate. Weirdly this is the opposite for the wave direction: For cases with a small directional spreading the wave direction is well modelled but for cases with large directional spreading the influence of wave sheltering is not modelled very well resulting in poorly modelled directions in the sheltered zone. With a modification for the directional spreading in the wave direction the Kamphuis module can be used very well for cases with large directional spreading.

At the end of this thesis the implications of the different wave model approaches for decadal scale coastline evolution modelling is studied (research question 4). This is studied by comparing the sediment transport proxy for the five modelling approaches. The sediment transport proxy gives the relative alongshore sediment transport. From the alongshore sediment transport the length of the erosion pit, the surface size of the erosion pit and the shape of the erosion pit can be concluded.

- The sediment transport proxy for the SWAN model approaches (with and without diffraction) showed well represented results for the cases with a large directional spreading. This could be expected after the well modelled nearshore waves.
- The sediment transportation proxy for the Kamphuis module with Snell's law was expected to be good for short crested waves, because the wave height is well represented. However the length of the erosion pit was much smaller and also the shape of the erosion pit is very different from the other two models. This is due to the poorly modelled wave direction in the sheltered area.

5.2. RECOMMENDATIONS

In conclusion there are few recommendations:

For cases where the directional spreading is of high importance the SWAN model without diffraction gives a good representation for all three investigated directions.

For cases with long crested waves the diffraction plays a much more important role and the SWAN model would not be a good model to use for the wave modelling. The Kamphuis model is however not made for these conditions either, and does not give a good representation either. For these cases SWASH can be used, but because of the large computation times other models that can include diffraction should be looked at too.

To improve the Kamphuis module refraction should be included in the formula, or prescribed to use together with the kamphuis formula. Also the wave direction change due to the partly sheltering of the waves should be included. Off-course there is no current-induced refraction, this can play a role for waves coming in between 0 to 30 degrees.

For improvements of the one dimensional wave computation the constants should be multiplied by a factor of the directional spreading and the direction. It is would furthermore be interesting to use a formula for long crested waves. For short crested waves a number of these small directional spreading bands can be (weighted) added together for computations for short crested waves. Transforming the current Kamphuis module for Swell wave is not possible.

There are also some recommendations for further research:

- Look at more conditions
- Look at wave climates
- Derive diffraction from SWASH for long crested waves (emperical)

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