Wave-focusing surfing reefs
a new concept

April 2002 MSc thesis Andrew West

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This thesis was submitted in partial fulfilment of the requirements for the degree of Master of Science (Ir.) in Civil Engineering (Faculty of Civil Engineering and Geosciences, Delft University of Technology).

April 2002

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Photo above from Waves (Australia), June 2001, vol.21 - no.6

Acknowledgements

This thesis has been written in partial fulfilment for the requirements for the degree of Master of Science in Civil Engineering from the Division of Hydromechanics, Faculty of Civil Engineering and Geosciences, Delft University of Technology (the Netherlands).

The work reported in this thesis was planned and carried out under the supervision of Professor Marcel Stive of Delft Hydraulics and Dr Peter Cowell of the Coastal Studies Unit, Sydney University (Australia). Their close cooperation over the years made it possible for me to carry out my research in Sydney. Peter, the scientist and surfer, developed the concept of the wave-focusing surfing reef. I hope one day we will be able to surf 'our' reef together.

Wave concepts and theories brought this research work into the domain of Professor Jurjen Battjes, who became the supervising professor of my final research project. His critical comments have been crucial in bringing the science of wave theory to bear on the sport of surfing.

During my time in the Coastal Studies Unit, I shared an office with PhD student, Aaron Coutts-Smith. It was great to share ideas and to discuss our work, sometimes over a cup of coffee and often over a beer. I would like to thank Professor Andrew Short and everyone at the Coastal Studies Unit who welcomed me warmly and allowed me to participate in coastal field trips and fieldwork. It not only provided excellent experience but was also a lot of fun.

On my return to the Netherlands, WL|Delft Hydraulics hosted me during the last months of completing my thesis. I would like to thank Ir Neelke Doorn for her help and support, particularly with the numerical modeling. I would also like to thank Dr Dano Roelvink for agreeing to co-supervise my work.

Throughout my studies, I have had the unconditional support of my family. My father has always been a source of inspiration and encouragement to me, while my mother and my sister Rachel helped me regain a sense of perspective whenever the light at the end of the tunnel became dim. Finally, I would like to thank my surfing and housemates for their friendship and the great times we have had during my time in Delft.

Abstract

Submerged artificial reefs have been built for many different purposes, including coastal protection and improving surfing conditions. In recent years, two such reefs have been built in Australia and there are numerous proposals for artificial surfing reefs in other countries.

The conventional approach to constructing an artificial surfing reef is to create an irregular seabed topography that causes the waves to break in the desired way. As waves travel towards the shore, they start to shoal as they enter shallower water. When waves reach a conventional artificial reef, they are forced to break because of the sudden change in water depth.

Another approach to constructing an artificial surfing reef is to create a structure over which the waves do not break, but which induces a surf break landward of the reef. This can be achieved by constructing a reef that creates a topographic 'lens' seaward of the breaker zone. In principle, such a structure acts as a magnifying lens by making the waves refract. Wave energy is focused to a point thus creating a peak in the wave crest as it passes over the reef. The purpose of the reef is to make part of the wave break sooner in one place ('the peak') and to delay breaking on other sections of the same wave crest. This process is referred to as 'wave focusing' and hence reefs based on this principle are referred to as wave-focusing reefs. The aim of such reefs is to influence otherwise closing out waves (waves breaking simultaneously along the wave crest) by delaying wave breaking, so that surfers can take-off earlier and ride such waves successfully.

Conventional reefs are based on wave breaking controlled by alongshore variations in water depth and seabed gradients over the reef. Waves actually break on such conventional reefs, which provide a suitable topography while with wave-focusing reefs the waves break after passing the reef. Wave breaking is then controlled by alongshore variation in wave height along the wave crest.

Wave-focusing reefs are designed to focus incoming waves in order to increase wave height locally and to induce waves to break further offshore. Thus, the aim of the study was to determine the dimensions required for such a reef, which include height, width, length, optimum position of the reef offshore, and the profile of the reef relative to the seabed. Simulation studies were carried out to establish the required dimensions of a wave-focusing reef and to assess the effect of varying reef dimensions on wave breaking patterns. For this purpose, the combined wave refraction and diffraction computer model Ref/Dif was used.

Different shaped reefs were superimposed on a constant seaward sloping beach with a bed slope of 1:20. For most simulations, the hydrodynamic conditions were kept constant at a wave height of 1 m and a wave period of 8 s. The Iribarren number for this is 0.5, which characterises the transition between spilling and plunging breakers: such waves are preferred for surfing.

In order to establish the effect of reef height and width on waves, simulations were conducted with reefs of infinite length but varying in width and crest height. An infinite length was chosen initially so that changes in the wave field attributable to differences in cross section could be examined in the absence of effects of reef length. To establish the effect of reef length on waves, simulations were done with reefs of various lengths but with a fixed height and width. Simulations were also carried out with finite length reefs placed at different distances from shore in order to establish the role of reef position. For comparison simulations for a representative case were also conducted with Triton, a non-linear Boussinesq-type model, in order to account for non-linear effects such as wave shape.

A reef can be characterised by its cross section, length and position from the shore. Wave focusing, which is a function of breaker height and breaker distance, increases with increasing reef height at constant reef width, and similarly with increasing reef width at constant reef height. The combined influence of reef height and width on wave focusing is described by a factor developed in this research: the West-Cowell surfing reef factor, which is related to wave focusing in an almost linear way.

The reef should be longer than the reef height and longer than the reef width. Such a reef would be positioned just beyond the surf zone and could have a height of 1.5 m, width of 10 m and length of 40 m. Because wave-focusing surfing reefs can be a lot smaller than conventional reefs, they could be constructed more cheaply and be designed in such a way that they would be removable and tuneable.

Further studies will need to examine additional parameters such as wave direction, period and height. Numerical simulations could be done with models that account for non-linear effects and experiments would need to be conducted in a wave basin. Because wave-focusing surfing reefs are relatively small, it may be attractive to field test them. Consideration will also need to be given to possible designs; to constructing the designs developed; and to performance, price, tuneablity, removeablity, durability and various environmental issues.

In conclusion, the concept of wave-focusing surfing reefs was found to be viable and the required dimensions of such reefs have been established. A parameter has been derived, referred to as the West-Cowell surfing reef factor, which relates reef cross-section to wave focusing. Wave-focusing surfing reefs have a number of advantages over conventional reefs. The work carried out provides sufficient basis for conducting field trials. However, more attention will need to be given to construction methods and to refining the relationships of reef dimensions to wave-breaking patterns.

List of symbols

Roman letters

Symbol	Description	Units
A	Wave amplitude	m
A_{focus}	Relative augmented breaker distance (wave focusing)	[-]
C	Wave celerity	m/s
C_g	Wave group speed	m/s
D	Reef height	m
D_{nl}	Coefficient for non-linearity	[-]
D_{rel}	Relative reef height	[-]
g	Acceleration due to gravity	m/s^2
G_0	Inshore parameter by Galvin, breaker type index	[-]
G_b	Offshore parameter by Galvin, breaker type index	[-]
h	Water depth	m
h_b	Water depth at breakpoint	m
h_{beach}	Water depth at breakpoint without a reef	m
h_{in}	Water depth at boundary of grid	m
h_{min}	Minimum water depth over the reef	m
h_{reef}	Water depth at breakpoint with a reef	m
H	Wave height	m
H_{axis}	Wave height along reef's axis	m
H_b	Breaker height	m
H_{beach}	Breaker height on beach (without reef)	m
H_0	Offshore wave height	m
H_{reef}	Breaker height with a reef	m
i	Complex number	[-]
k	Wave number	[-]
$\bar{k}$	Average wave number along y axis	[-]
K	Empirical constant for wave breaking from Dally	[-]
K_{axis}	Wave factor along reef's axis	[-]
K_{beach}	Beach wave amplification factor	[-]
K_{focus}	Wave-focusing factor	[-]
K_S	Shoaling coefficient	[-]
L	Wave length	m
L_{in}	Wave length at offshore boundary of grid	m
L_0	Deep water wave length	m
L_{reef}	Wave length at breakpoint with reef	m
S_{RF}	West-Cowell surfing reef factor	[-]
T	Wave period	s
U_r	Ursell number	[-]

Symbol	Description	Units
W	Reef width at the crest	m
W_{base}	Reef width at the base	m
W_{rel}	Relative reef width	[-]
x	Distance from shore	m
X_{beach}	Breaker distance without a reef	m
X_{focus}	Augmented breaker distance due to wave-focusing	m
X_{OP}	Offshore position of the reef	m
X_{reef}	Breaker distance with a reef	m
X_{γ}	Gamma-effect (bed offset distance due to reef)	m
y	Alongshore distance	m
Y	Alongshore distance from the centre of the reef	m

Greek letters

Symbol	Description	Units
α	Angle of beach slope	$(^0)$
ΔH	Difference breaker height with and without reef	m
ΔX	Difference breaker distance with and without reef	m
γ	Ratio of breaker height to breaker depth	[-]
Λ	Reef length	m
Λ_{rel}	Relative reef length	[-]
θ	Wave direction	$(^0)$
σ	Angular frequency of waves	rad/s
ω	Energy dissipation factor	s^{-1}
ξ	Iribarren number	[-]
ψ	Empirical constant for wave breaking from Dally	[-]

Contents

1 Introduction

1.1 Background

Submerged artificial reefs have been built for many different purposes, including coastal protection and improving surfing conditions. In recent years, two such reefs have been built in Australia. One was built in Perth solely for the purpose of improving local surfing conditions. The other reef was constructed on the Gold Coast for the dual purposes of controlling coastal erosion and enhancing surfing conditions. There are numerous proposals for the construction of artificial surfing reefs in other countries including New Zealand, the United States, United Kingdom and the Netherlands. The main reason for building submerged artificial reefs on the ocean floor close to shore is to enhance the wave conditions for surfing. In addition, such reefs have been shown to be effective in coastal protection and thus have an additional ecological value.

The conventional approach to constructing an artificial surfing reef is to create an irregular seabed topography that causes the waves to break in the desired way. As waves travel towards the shore, they start to shoal as they enter shallower water. When waves reach a conventional artificial reef, they are forced to break because of the sudden change in water depth. Such a reef structure is a topographic irregularity in the vicinity of the breaker zone that causes the waves to break at a certain depth. In this thesis, this type of artificial reef is referred to as a conventional reef.

Another approach to constructing an artificial surfing reef is to create a structure over which the waves do not break, but which induces a surf break landward of the reef. This can be achieved by constructing a reef that creates a topographic 'lens' seaward of the breaker zone. In principle, such a structure acts as a magnifying lens by making the waves refract. Wave energy is focused to a point thus creating a peak in the wave crest as it passes over the reef. Thus, when a wave enters shallower water, it will start to break where it is highest, that is at the peak. The purpose of an artificial reef is to make part of the wave break sooner in one place ('the peak') and to delay breaking on other sections of the same wave crest. This process is referred to as 'wave focusing' and hence the term wave-focusing reef is used in this thesis.

By initiating breaking at one point of the wave crest, the breakpoint should move along the wave crest with time. The rate at which the breaking point moves along the wave crest is called the peel rate (see Section 2.2.4). The higher the peel rate, the more difficult the wave is for the surfer to ride.

Wave-focusing reefs could be constructed immediately seaward of the point at which waves would normally break and may be smaller structures than conventional reefs. If these reefs were to be comparatively smaller and more compact, wave-focusing reefs may be modified to respond to changing conditions. Wave-focusing reefs could then even be adjustable or removable, which would be advantageous in storm-prone areas and prevent undesirable environmental impacts.

The work described in this thesis aims to establish whether wave-focusing reefs have the potential to influence wave behaviour and thus to enhance surfing conditions. Simulation studies were carried out to establish the required dimensions of a wave-focusing reef and to assess the effect of varying reef dimensions on wave breaking patterns. For this purpose, use was made of the combined wave refraction and diffraction computer program Ref/Dif [Kirby and Dalrymple 1994]. The program, which has also been used to model large-scale natural surfing sites, predicts wave behaviour over irregular bottom bathymetries.

1.2 Benefits of artificial surfing reefs

Artificial reefs placed in the near-shore zone have a great potential for water sports, in particular surfing. Currently, there is a steadily increasing number of surfers while there are comparably few suitable sites exposed to the ocean with the appropriate wave and wind conditions. Such sites are coming under increasing pressure with the growing popularity of the sport and furthermore many natural surfing beaches are no longer suitable because of construction projects. Good surfing sites are becoming more overcrowded which increases the risk of injury. There is an increasing demand for new locations and such a demand could be met by artificial surfing reefs.

Artificial surfing reefs could also provide sheltered swimming areas on the leeward side. In addition, such reefs could become a marine habitat supporting coral growth and a variety of fish [Mead and Black 1999]. Development of marine life would also support recreational fishing and diving.

Storms associated with large waves remove much beach sand seaward resulting in beach narrowing. While beaches are restored in periods of calmer weather with smaller waves, beach nourishment is often required after storms and this can be very costly [Liverpool/Thessaloniki network 1996]. Nowadays, wider beaches are needed to provide more public space not only for recreation, but also to protect against flooding to the land beyond. Such arguments were used to justify the construction of the artificial surfing reef at Narrowneck on the Gold Coast of Australia [Jackson et al. 1997].

Other measures to stabilise beaches and to protect valuable property and infrastructure such as houses and roads, include the construction of structures such as groynes and breakwaters along the coast [Black 1999]. Artificial reefs have a potential application as coastal protection measures. Placed at a short distance from shore, an artificial reef could dissipate incoming waves before they reach the beach, thus reducing wave impact on the coast. Such a reef could also trap sand and thus contribute to preventing down-drift erosion and could well be a more cost-effective solution than annual beach supplementation.

Reefs form a coastal control point in the same way as breakwaters do but they are softer and more versatile. As artificial reefs are submerged, they do not contribute to visual pollution and therefore may be more acceptable.

1.3 Outline of thesis

This thesis begins with a description of the mechanics of surfing, the type of waves required for this sport, the theory of breaking waves and the ideas and concepts of artificial surfing reefs (Chapter 2). Chapter 3 sets out the problem definition and theoretical approach, the concept of a wave-focusing reef and its parameters. In Chapter 4, Methods, the two models used in this study – Ref/Dif and Triton (Boussinesq-type model) – are described and the simulations carried out with the models are presented. Chapter 5 sets out the results obtained from simulations with regard to the reef parameters described in the previous chapter. Finally, Chapter 6 discusses these results, makes recommendations and draws conclusions with regard to the concept of artificial wave-focusing reefs.

2. Surfing and waves

2.1. Surfing

2.1.1 What is surfing?
Surfing is the sport of riding broken waves whereby a surfer rides on a wave towards the beach ahead of the broken part of the wave. Generally a surfer rides across the wave in front of the point at which the wave is breaking (see Figure 2.1). Waves can be ridden using various sorts of equipment such as surfboards, body boards, wave skis or sailboards. Often waves are ridden with no equipment at all and, when this is done, it is called body surfing. For surfing, generally beginners ride waves from 0.5 m high, whereas waves up to 8 m high and sometimes even greater are surfed by experts. The wave height is measured from the trough to the crest of the wave face, where the waves are ridden. Surfability also depends on the way waves break. The characteristics of surfing waves, such as breaker type and peel angle, will be explained in detail in Section 2.2. The seabed, particularly close to where waves start to break, transforms incident waves. Thus the locations suitable for surfing (i.e., 'surfing sites') usually have a particular bed form, which will be discussed in Section 2.1.3.

Figure 2.1: Surfer riding across the wave under the curl of the wave (Source www.baliwaves.com)

2.1.2 Mechanics of surfing
In order to ride a wave, the surfer first needs to attain a position beyond the surf zone (i.e., just beyond the point where the waves start breaking). For board riding, this means that the surfer has to paddle on his board to the position to where waves have not yet broken. There the surfer waits until a suitable wave for surfing (see Section 2.2) approaches. The surfer can catch a wave at the 'peak', which would likely be the case with a wave-focusing reef, or along the shoulder of a wave (i.e., a section of the wave crest adjacent to the broken section, see Appendix A.1). Once the surfer has selected a wave he wishes to surf, he must paddle in front of the wave in the direction of wave advance and then match the speed at which the wave is moving in order to 'catch the wave'. The surfer will

catch the wave by sliding down the face of the wave (‘take the drop’) using the force of gravity, before the wave has broken completely. Board riders will stand up on their board or take a crouching position as soon as their speed matches that of the wave, before sliding down the face of the wave from near the crest towards the trough. On taking the drop, the surfer accelerates in front of the wave and the wave begins to break. The duration of ‘the drop’ depends greatly on the size of the wave and can take from 2 s for a 1 m wave up to 5 s for a 5 m wave (for example, in locations in Hawaii studied by Walker 1972). As the wave travels forward, it will break along the crest. When reaching the bottom of the wave, after the acceleration experienced during the drop, the surfer will turn in the direction at which the wave is breaking (‘bottom turn’) to gain position on the curl or on the wall (see Appendix A.1).

After the bottom turn, the surfer can ride up and down the face of the wave thereby trying to remain in front of the broken section of the wave, by travelling at a speed greater than that of the wave. The wave should also propagate fast enough for the surfer to maintain his balance. Depending on the type of wave, the surfer can have a high speed ride and ride under the curl of the wave, which is called ‘tube riding’ or riding in the ‘barrel’ of the wave. Or the surfer can carry out manoeuvres on the wave such as aerials or cutting back and riding back towards the breaking section when the surfer comes too far in front of the breaking section. When the surfer falls or the ride is ended because the wave closes out (see Section 2.2) or is no longer high enough, the surfer ‘kicks out’ back over the wave crest and then recovers his board and paddles back to the take-off zone in order to catch another wave.

2.1.3 Surfing sites

‘Surfing sites’ are locations with the right wave and wind conditions where waves break regularly in the form desirable for surfing. In order to accommodate waves, a surfing site must be open to swell from the ocean and be oriented in the right direction. It is also preferable to have the wind offshore or to have no wind at all, at least not onshore as that causes the waves to be blown down and the quality of the waves to be degraded. At surfing sites, waves are generally amplified by processes such as shoaling and refraction due to the local bed topography. Waves can break on sandy beaches, such as on the Dutch coast and in Australia, for example where the Narrowneck reef has been built. When waves break in a favourable way for surfing along beaches, they are called ‘beach breaks’. However waves can also break on outcropping natural reefs resulting in ‘reef breaks’ and after being wrapped around coastal promontories or headlands, resulting in what are referred to as ‘point breaks’. At point breaks, waves generally break in one direction. When waves break to the left of the direction of wave advance, these are called ‘left handers’ or ‘lefts’, and waves breaking in the opposite direction are called ‘right handers’ or rights. When creating a surfing reef where waves break both to the left and to the right, the capacity with respect to number of surfers of the site would be greater than when waves break in only one direction.

Easy access to the site is not necessary but makes the site accessible for more people. However for selecting a suitable site for an artificial surfing reef, aspects such as proximity to populated areas, access, parking areas and other amenities are important in order for such a reef to be more acceptable and beneficial to many people. Thus when creating an artificial surfing reef, the selection of an appropriate site is important.

2.2 Breaker characteristics of waves

2.2.1 General

As waves move into shallower water they interact with the seabed or feel the bottom. In shallow water the wave velocity is depth dependent and decreases shoreward. As the water becomes increasingly shallow, waves increase in height and decrease in length, this process is known as shoaling. The height of the waves increases as they approach the beach to within a certain distance offshore. At this distance, waves reach a height that causes them to become unstable such that they start to break (see Section 2.2.2).

For conventional surfing reefs, waves propagating over the sloping seabed are shoaled as the water depth over the bottom decreases rapidly. The combination of rapid shoaling and shallower water creates a definite breaking region [Walker 1974b]. Thus surfing waves result from an interaction of the wave and the bottom configuration. Waves are not only influenced by shoaling but also by processes such as refraction, diffraction, reflection, dissipation and other non linear transformations of energy to higher and lower wave periods.

Variations in wave velocity along a wave crest caused by variable water depth produces wave refraction. This causes a wave crest to bend as part of the wave moving in deeper water travels faster than that part moving in shallower water. By altering the direction of wave propagation, refraction tends to align wave crests with the bottom contours and shoreline. Thus refraction causes a redirection of wave approach and redistribution of wave energy along the crest, with energy increasing as crests are compressed onto points, or decreasing as crests radiate and expand into bays [Short 1999]. Wave energy can also be transmitted along the wave crest by diffraction.

The breaker line is defined as the locus of the break points along the wave crest. If a wave breaks along its entire length at the same distance from shore, the breaker line generally is straight, which for example occurs on beaches with parallel and straight depth contours. However, when waves wrap around a headland, the breaker line is generally neither straight nor equidistant from the shore.

Alongshore differences in water depth over a reef are responsible for the spatial and temporal pattern of topographically controlled wave breaking. A wave will break further offshore and thus earlier in temporal terms, due to localised areas of shallower water, than elsewhere along the wave crest where the water is deeper. For example, the breaking distance from the shoreline varies along the coast when the depth contours are not equally spaced or parallel. It is most likely that wave breaking on an outcropping reef will occur at a greater distance offshore and thus earlier than further away from the reef. Variations in the spatial pattern of wave breaking result when waves break at different times along different sections of the wave crest. This is the case with a peeling wave where the breakpoint moves along the wave crest in time (see Section 2.2.4 describing peeling waves).

2.2.2 Conditions for wave breaking

Waves break when they become too steep, that is when the ratio of wave height to wave length is too high, when wind topples a wave crest, or when waves reach a water depth about equal to their height. The earliest criterion for wave breaking was that described by McCowan [1894], who determined that theoretical 'solitary' waves travelling over a horizontal bottom, break when their height becomes equal to a given fraction of the water depth. Thus the breaker height (H_b) is a fraction of the water depth at which the wave breaks (h_b):

$$H_b = \kappa \cdot h_b \tag{2.1}$$

Where, the subscript 'b' denotes values at breakpoint. According to McCowan, the breaker index (κ) has a value of 0.78. However, other investigators have different theories and criteria for wave breaking which give values of κ ranging from 0.73 [Laitone 1963] to 1.0 [Dean 1968].

The reliability of the above criteria is questionable, because wave theories are generally not valid near the breaker zone and the criteria have been derived for a horizontal bottom. Based on a review of several wave flume experiments, Galvin [1969] developed breaking criteria including bottom slope. Weggel [1972] also found a dependency of breaker height on beach slope, by reinterpreting many laboratory results. For Weggel's relationship for bed slopes approaching horizontal, κ approaches 0.78 (i.e., the value of κ according to McCowan). However other investigators have defined breaker criteria based on parameters such as wave steepness.

2.2.3 Classification of breaking waves

Iribarren derived a parameter for waves breaking on a slope, which determines whether or not breaking occurs [Iribarren and Nogales 1949]:

$$\xi \equiv \frac{\tan\alpha}{\sqrt{H/L_0}} \tag{2.2}$$

Where, α is the angle of the bed slope and H/L_0 is the wave steepness in which $L_0 = gT^2/2\pi$, and g is the acceleration due to gravity and T is the wave period.

Waves will break on the slope when ξ is lower than a critical value of $\xi_c = 4/\sqrt{\pi} \cong 2.3$ [Battjes 1974]. Thus waves break when $\xi < \xi_c$ and do not when $\xi > \xi_c$. The Iribarren parameter also provides an indication of how waves will break. A wave will not break on a very steep slope because it will be reflected back to sea. If the slope of the bed (tan α) decreases below a threshold, the waves will become unstable and break. The bed slope and the wave steepness need to be compared to ascertain whether and in what way the waves will break. Cases for a constant slope and increasing values of the wave steepness (H/L_0) are comparable to those of decreasing values of α and a fixed value of H/L_0.

Breaker type is a means of classifying wave profiles during breaking, which is of great importance for surfing. Waves where the crest curls over the wall of the wave thus creating a 'tube' are most desirable for surfing, especially for experienced surfers. The breaker type depends on the extent to which the crest is thrown over the wave face. The following breaker types have been identified:

- Surging breakers, which occur on very steep beaches and are characterised by high reflection with a very narrow or no surf zone at all.
- Plunging breakers, the most spectacular breaker type, which occur on comparatively steep beaches. They are characterised by a curling wave crest that is thrown forward thus forming a 'tube' after the crest falls onto part of the wave trough. When air gets trapped in the tube, it escapes by bursting through the back of the wave or blowing out at a non-breaking section of the wave crest.
- Collapsing breakers, a transition form between plunging and surging breakers, which were identified by Galvin [1968].
- Spilling breakers, which occur on mildly sloping beaches where there are many waves present in the surfzone.

On the coast of the Netherlands where there are generally mildly sloping beaches and steep wind waves, spilling breakers occur most often. On the NSW coast in Australia, where there are waves with higher periods and also steeper beaches than generally found in the Netherlands, breakers are of the spilling (see Figure 2.2) and plunging types.

Figure 2.2: Surfers riding a spilling breaker at Bondi Beach, Sydney (Photo taken by the author, June 2002).

Galvin [1968] derived the 'inshore parameter' and the 'offshore parameter' for establishing a breaker type index by studying motion pictures of flume waves. Based on the inshore parameter.

$$G_b = \frac{H_b}{gT^2 \tan\alpha} \qquad (2.3)$$

Thus, G_b is the ratio of wave steepness to bed slope where the subscript 'b' denotes the wave at breaking. The suggested limits for breaker types are: surging when $G_b < 0.003$; plunging when $0.003 < G_b < 0.068$; and spilling when $G_b > 0.068$ [Walker 1972].

Galvin's criterion regarding breaker types in terms of an 'offshore parameter' is:

$$G_0 = \frac{H_0}{L_0 \tan^2 \alpha} \qquad (2.4)$$

Where H_0 and L_0 are the offshore wave height and offshore wave length respectively. This offshore parameter can be written as ξ_0^{-2}, where the subscript '0' denotes offshore waves [Battjes 1972]. The limits for breaker types with ξ_0 are shown in Table 2.1.

G_b is not equivalent to ξ_b (i.e., H_b is used for calculating ξ_b) presented here, which was determined with Galvin's data. However, the classification of breakers as plunging or spilling can be done equally well with ξ_b as with G_b [Battjes 1972]. The approximate transition values for wave description with ξ_b are also shown in Table 2.1.

Table 2.1: Breaker types for given surf similarity parameters, where ξ_0 and ξ_b denote wave characteristics offshore and at breaking. Wave shape in surfing terminology is also given.

Surf similarity parameter	Breaker type	Surfing terminology
$\xi_0 > 3.0$ $\xi_b > 2.0$	Surging or collapsing	'Unsurfable' wave
$0.5 < \xi_0 < 3.0$ $0.4 < \xi_b < 2.0$	Plunging	'Tubing' or 'hollow' wave
$\xi_0 < 0.5$ $\xi_b < 0.4$	Spilling	'Full', 'fat' or 'mushy' wave

Thus, spilling and mildly plunging breakers are preferred for surfing [Walker 1972]. Experienced surfers also ride stronger plunging breaking waves. But collapsing breakers should be avoided because they can be dangerous. Because the type of breaking desired may vary along the riding zone (i.e., in surfing terminology 'down the line'), different sections along the reef could be designed to induce spilling or plunging breakers [Couriel and Cox 1996], which is often attempted in conventional reef design. Spilling breakers allow the surfer to make the drop more easily (i.e., to 'take off' or initiate a ride on the wave) and provide high manoeuvrability for the rider along the wave. Plunging breakers provide an opportunity for high-speed rides and tube riding. Different modes of breaking may also be preferred for different wave heights; for example, spilling breakers (lower ξ) are generally preferred for larger waves ($H_b > 3$ m approximately), which with conventional reef design could be accommodated by gradually milder seaward slopes [Couriel and Cox 1996].

Very big waves, especially those that are also plunging, are only ridden by very experienced surfers. These waves are difficult to catch and to make the take off successfully because of the high speed at which they travel and because they are often very steep and have a high wave face that has to be descended. It is almost impossible for surfers to paddle into waves higher than 8 m, although the limit of surfability depends on breaker type and the skill of the surfer. Therefore some big wave surfers are towed in front of approaching waves by a jet ski or wave runner in order to take off on such waves. Once the surfer is riding down the face of the wave at a speed greater than that of wave advance, he releases the towrope and continues the ride down the big wave. This form of surfing called 'tow-in' surfing originated in Hawaii about 10 years ago.

As a background to designing artificial surfing reefs, research was conducted on the breaking form of waves on natural surfing reefs [Sayce 1999, Mead 2001]. Studies related breaking wave characteristics such as breaking intensity and 'wave hollowness' (shape of plunging breaker) to the bathymetry. A geometrical measurement of the plunging wave's vortex ('tube') was found to provide a quantitative description of the breaking wave form in relation to the seabed gradient [Sayce 1999]. This was a refinement of the surf similarity parameter for describing surfing waves. Longuet-Higgins [1982] showed that a cubic curve could describe the forward face of a plunging wave. By fitting such a curve to the forward face of the breaking wave, dimensions of breaking vortex (tube) were quantified such as width, length, angle of the vortex to the horizontal, area of the tube and non-dimensional measurements of the vortex. This allowed wave shapes and sizes to be compared. Intense breaking occurs for waves that project their crest forward, from the wave face, and land in the forward trough of the wave. Thus, the action of projection can be estimated from measurements of the breaking vortex angle and the size (width and length) of the vortex in relation to wave height. The wave intensity increases with the area of the vortex [Sayce 1999]. Mead [2001] found relationships of vortex parameters of plunging surfing waves and local seabed gradients. The vortex length to width ratio is an indicator of plunging wave breaking intensity. This ratio can be calculated from the orthogonal seabed gradient [Mead 2001].

The wind also influences wave breaking. Winds opposing the direction of wave advance (offshore winds) postpone wave breaking, resulting in a shallower breaker depth. This results in an increased wave height, due to the increased distance over which the wave shoals and increased wave steepness. Therefore the surfer will have more time to negotiate the take off. However offshore winds exceeding approximately 20 knots [Walker 1974] may reduce paddling speeds making it more difficult to catch a wave, and cause the water surface to be choppy resulting in a bumpy ride.

Onshore winds cause the sea to be choppy by generating local sea conditions and therefore are not advantageous for surfing. Also, onshore winds cause waves to break earlier and at a greater depth, resulting in lower wave height and steepness. Thus offshore winds cause waves to break in a more plunging manner and onshore winds in a more spilling manner.

2.2.4 Peeling waves

In order to understand what surfable waves are, peeling waves will be described in this section. As a wave moves into shallower water approaching the shore, it begins to break at a water depth approximately equal to the wave height. For surfable waves, the point of incipient breaking must move along the wave crest. When this occurs these waves are referred to as peeling waves where the point of incipient breaking is the interface between the part of the wave that is broken and that which is not broken.

The *peel angle*, first defined by Walker [1974], is the angle between the wave crest and the trail of broken water caused by the breaking of the wave (i.e. the air-entraining turbulent wake). This can be seen from a photograph in Figures 2.3 and 2.6 and schematically in Appendix A.2. Generally waves with peel angles between 30 and 60 degrees are sought most by surfers. World-class surfing breaks (locations where surfing waves break consistently) with the most challenging rides suited for experienced surfers have a peel angle between 30 and 40 degrees whereas peel angles around 60 degrees are more suited for beginners [Walker 1974]. Generally, peel angles above 60 degrees are not suitable for surfing because the surfer travels too slowly to maintain balance. When the peel angle is 90 degrees, the surfer will ride straight to shore. This is because the wave does not continue to break further along the wave crest and thus the water surface is not steep enough to allow surfing.

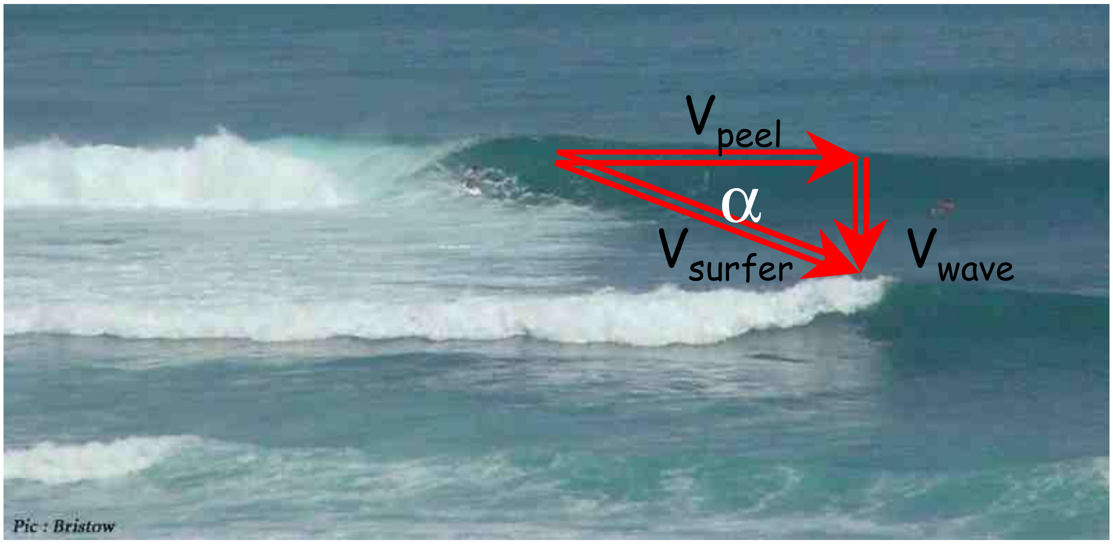

Figure 2.3: Photograph of a peeling wave where the peel angle is illustrated. The vectors V_{surfer}, V_{peel} and V_{wave} represent velocity of the surfer, peeling of the wave and wave advance, respectively (source: www.baliwaves.com).

Waves that break simultaneously along the whole wave crest do not peel, and thus have a peel angle of 0 degrees. In surfing terminology these are termed 'close-out' waves (see Figure 2.4). Whether a wave closes out or not depends on the angle at which the wave approaches the beach and the alignment of the wave crest with the depth contours. If the wave crests entering shallower water become aligned parallel to the depth contours they tend to close out. This occurs often when the angle of progression of the wave crests relative to the depth contours (isolines of water depth) is small. This means that the wave will start breaking simultaneously along the whole wave crest. Although close-out waves are very common, close outs may be prevented by a number of conditions that cause alongshore irregularity in water depth relative to the line of the wave crest. These conditions include irregular sandbars on beaches, which depend upon dynamic conditions associated with beach state [Wright et al 1979: Wright and Short 1983]; embayments caused by coastal promontories; and rocky coasts with bottom contours that are not straight or parallel to the beach. At natural surfing sites (see Section 2.1.3) and on artificial surfing reefs waves are affected by the bottom configuration and the surfing waves consequently break in a given form.

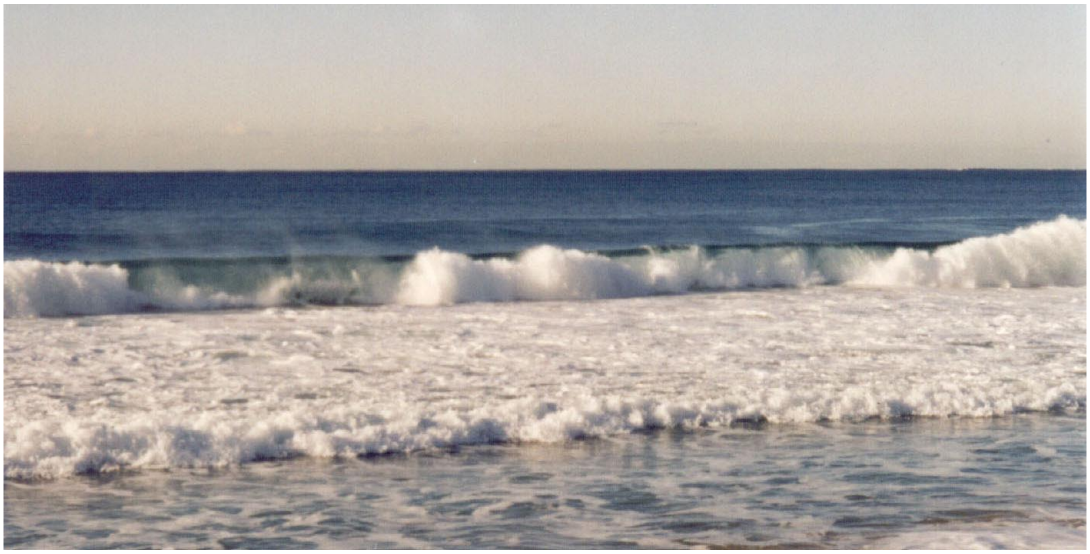

Figure 2.4: Wave ‘closing out’ at Narrabeen NSW, Australia (Photo taken by the author, May 2001)

Although the peel angle has proved to be a good parameter to classify waves as suitable for beginners, intermediate or expert surfers, the height at which waves break, referred to as the breaker height (H_b), is also important. Thus, Walker has plotted the peel angle against H_b (see Figure 2.5). In the figure, isolines of surfer velocity and limits of surfability for beginning, intermediate and expert surfers are given. The maximum speed that a surfer can maintain on a surfboard is about 12 m s^{-1}.

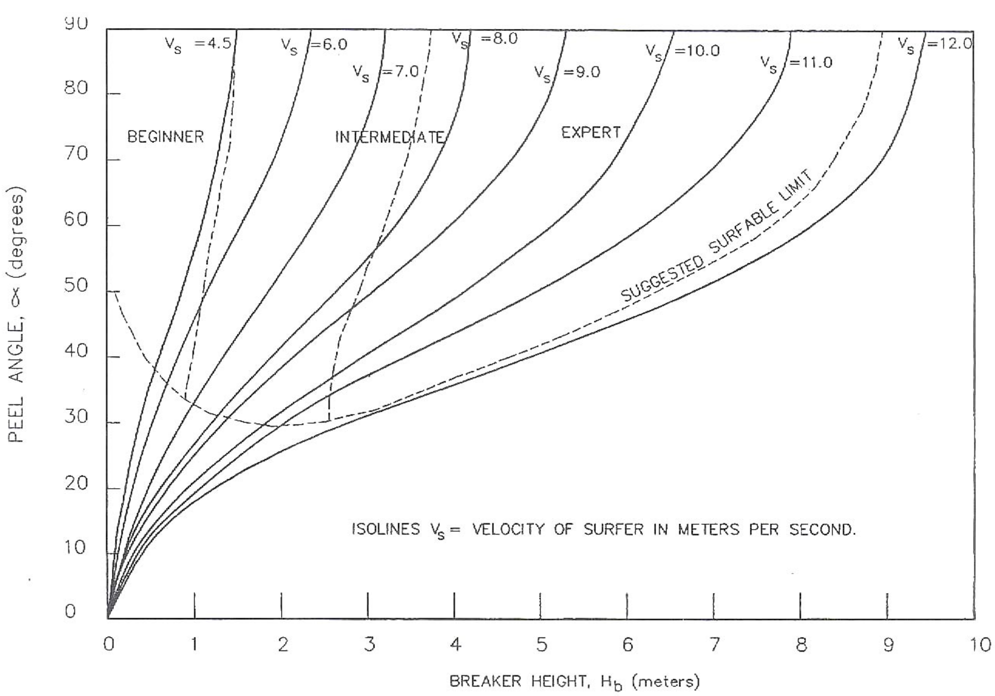

Figure 2.5: Isolines of surfer velocity at various peel angles and breaker heights. The broken lines represent limits of surfability for beginning, intermediate and expert surfers [Walker, 1974].

In designing surfing reefs, it would be desirable to have sections of waves with different peel rates as well as different modes of breaking as discussed in Section 2.2.3. Larger peel angles (i.e., waves with slower peel rates) with spilling breakers in the take-off area could be followed by a fast (hollow) plunging section, the peel rate of which would for a short time exceed the surfer velocity, thus putting the surfer progressively further back on the wall, and deeper in the tube. When the section would be followed by a slower spilling section, this would allow the surfer to emerge from within the curl, and continue down the line, or cut back as required [Couriel and Cox 1996]. A variety of sections would make waves less monotonous, and would provide an opportunity for other surfers to take-off further down the line, should the rider from the seaward take-off area fail in the attempt to catch the wave. In Section 3.2.2, the way in which a wave-focusing reef is able to influence ‘close-out’ waves to make them more surfable, which particularly concerns the take-off, is explained.

Figure 2.6: Wave peeling to the left and right, forming a ‘V’, during a large swell at McMasters Beach, NSW, Australia (photo taken by author, April 2001)

2.4 Surfing reefs

In this section, a brief history of artificial surfing reefs is given. Particular attention will be given to the two artificial surfing reefs that have been built in Australia and a prototype surfing reef that has been built in California.

2.4.1 Brief history

The idea of artificial surfing reefs originated in the early 1970s. In Hawaii and California, surfing sites were being lost due to construction projects and the interest arose to regenerate these sites, improve surfing conditions at other sites and to make new sites for surfing. Because popularity of surfing was also increasing in other parts of the world, surfing sites especially those close to populated areas were becoming overcrowded. This impaired enjoyment of the sport and increased the frequency of injuries. This lead to the concern that good natural surfing sites should be preserved and enhanced, and that it was necessary to investigate the feasibility of constructing artificial surfing reefs. Walker [1974b] conducted a detailed study from 1970 to 1974 on the characteristics of existing surfing reefs in Hawaii. With Moffatt & Nichol Engineers of Long Beach (California), Walker also prepared preliminary designs and carried out feasibility studies for artificial surfing reefs in Hawaii and California.

Since the beginning of the 1970's many sporting organisations in Western Australia such as the West Australian Surfrider Association have been raising interest in artificial surfing reefs (see Section 2.4.2), which led to the construction of Cables Station Reef. While in Sydney, a committee was formed, including members of the Coastal Studies Unit of the University of Sydney, with the aim of enhancing a natural surfing reef at Freshwater Beach in Sydney. Unfortunately, the project could not be pursued due to opposition from the community. The first international symposium on artificial surfing reefs was held in Sydney in 1997, organised by the Recreational Surfing Reef Committee and the Coastal Studies Unit of the University of Sydney.

In New Zealand, Black and his company ASR, have carried out much research on the characteristics of natural surfing reefs (see Section 2.4.6) and surfing waves. Many designs, some of them preliminary, have been made for artificial surfing reefs including Narrowneck Reef (see Section 2.4.3). Proposals for artificial surfing reefs throughout the world are discussed briefly in Section 2.4.5.

2.4.2 Perth's recreational surfing reef – Cable Station

In 1999 the world's first reef with the sole purpose of enhancing the surfing conditions was constructed at Cable Station in Perth, Western Australia. The Government of Western Australia has funded the reef and the Centre for Water Research of the University of Western Australia undertook the design studies for the reef. Surfing in Perth is very popular but the area lacks good surfing beaches because the swell is partially blocked by a chain of offshore reefs and Rottnest Island [Pattiaratchi 1999]. The competition between surfers, swimmers and fisherman for beach use had increased, resulting in injuries to swimmers and surfers. Fishhooks are the main source of injury to surfers and injuries to swimmers come mainly from surfboards. Over a period of three years there were 110 injuries including one death [Pattiaratchi 1999]. The aim of the reef design was to enhance the existing surfing site that did not produce good waves very often, thus allowing board riders to surf only about 5 to 7 times per year.

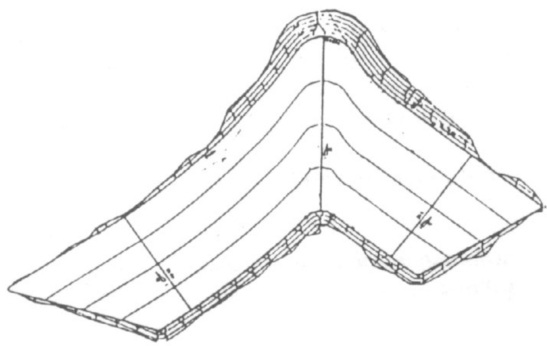

Figure 2.7: Final design of the Cable Station artificial surfing reef, the apex of the 'V' is the seaward end of the reef [Pattiaratchi 1999]

The reef design was such that the existing 3 m depth contour was extended offshore and a 1:20 slope was constructed up to the 1 m contour of the existing reef by placing boulders on the existing reef 300 m from shore. The reef was designed in such a way that waves would break to the left and right over the reef whenever incident waves were larger than 0.5 m. The length of the ride for the left handed segment was 30 to 40 m and for the right handed segment was 50 to 80 m [Pattiaratchi 1999]. Since completion of the reef, the number of surfable days has increased and there has been no damage to the coast [Pattiaratchi and Bancroft 2000].

2.4.3 Goldcoast's multipurpose reef - Narrowneck reef

At Narrowneck beach on the Australian Gold Coast, construction of the first multifunctional artificial surfing reef was completed in 2000. The Gold Coast attracts many visitors to the beaches. The Gold Coast beaches experience a northward littoral drift of 500.000 m^3 of sand per year and regularly experience episodic storm erosion [Turner et al. 2000]. In 1997 the Gold Coast City Council initiated the 'Northern Gold Coast Beach Protection Strategy' to maintain and widen the beaches at Surfers Paradise. The project comprised an initial 1.3 million m^3 of sand nourishment, annual nourishment of approximately 800.000 m^3 and the construction of an artificial surfing reef. The purposes of the reef were to improve the surfing conditions and to stabilise and enhance the beach by promoting beach widening through the maintenance of a shoreline salient [Turner et al. 2000].

The reef was made from approximately 500 very large geotextile sandbags filled with 150-300 tonnes of sand. The reef structure extends approximately 350 m alongshore and to 600 m offshore from the natural 2 m depth contour to the reef toe in 11 m depth. The reef is oriented shore normal and consists of two arms, forming an underwater headland, providing left and right hand surfing waves. The northern arm, which is longer than the southern arm extends to 400 m offshore and has a beginner's surfing segment at the inshore end. In order to increase the breaker height at the take off, the reef arms have a large focusing segment at the offshore tip [Black 1999]. The length of the ride is 200 m for 1 m wave, occurring most often and 120 m long for the largest design wave height of 4 m. The two reef arms are separated to provide a paddling channel to give surfers access in large swells. Shoreward of the reef, a lagoon provides sheltered paddling and at low tide sheltered swimming [Black 1999].

Sand nourishment started in February 1999 and construction of the reef started in August 1999. The reef has proven to be a successful alternative to maintain the beach, which is very important for tourism in the area.

2.4.4 Pratte's surfing reef in California

A prototype surfing reef has been constructed at Ventura in California where a surfing site had disappeared due to the construction of a pier for the oil industry. The Surfrider Foundation El Segundo surf enhancement project was experimental and intended to test whether a surfing reef would produce more surfable waves. The project was the result of co-operation among the California Coastal Commission, Chevron USA El Segundo and the Surfrider Foundation El Segundo. During the El Nino winter of 1982-83, large waves eroded the beach in front of the Chevron oil refinery. This was repaired by beach nourishment and by building a 270 m groin to stabilise the beach [Skelly]. However, a condition for granting permission for the groin and for the beach nourishment was that mitigation would be required if the surfing conditions were adversely affected. This condition was placed due to the efforts of Tom Pratte, former Executive Director of the Surfrider Foundation after whom the reef was named. The surfing conditions were affected and therefore Chevron granted $US 300.000 for the surf reef.

During 2000 and 2001, a reef was constructed of geotextile sandbags with a total volume of 5000 m^3 sand and a size of about 800 m^2. Both the plan and the cross-section of the reef were triangular [Skelly]. The top of the reef was below lowest sea level, in order not to be exposed during low tide. This was to avoid liability if someone were to be injured by crashing against the bare reef. The reef will not be a permanent structure and can be removed by cutting and removing the bags and allowing the sand to be dispersed.

2.4.5 Proposed reefs

Plans are ready to build a surfing reef at Ventura in California to compensate for the loss of good surfing conditions because of the construction of an overpass for a highway in 1970 [Ross 1997]. This removable reef has been designed by Gary Ross and will be constructed of pipes. It will be a Y-shaped reef focusing waves at the bottom end of the Y, which points seaward and wave breaking is controlled by the two ends of the Y, thus creating a left and right surfing break. The angled legs of the reef and therefore the length of the ride could have a length of 40 m to 60 m. The reef could be constructed on land, and then towed into position where it could be sunk and anchored to the seafloor. The structure can be refloated and repositioned and removed for modification if necessary. The concept of a wave-focusing reef was inspired by this design.

Around the world there are many propositions for artificial surfing reefs. In New Zealand many designs for multipurpose artificial surfing reefs have been made such as at Mount Maunganui [Mead 2001]. In Newquay in the United Kingdom, a feasibility study and a preliminary design for a reef has been conducted. There are also other proposals for surfing reefs in the United Kingdom and in the Netherlands.

2.4.6 Study on natural surfing reefs

Mead [1999] conducted a study on natural surfing reefs that classified large-scale reef components. Certain combinations of these components were found to produce high quality surfing waves. The reef component most resembling the concept of a wave-focusing surfing reef was named the ‘Focus’ [Mead 1999]. Focus forms a wave peak, where the wave will break earlier than on any other part of the wave and so defines the start of the surfing ride, or the take-off zone [Mead 2001]. The benefit of the Focus is the decrease of the effective seabed gradient, which is defined along the orientation of the wave travel path. Therefore, the effective seabed gradient is milder, caused by the angle between the isobaths of the Focus and the wave orthogonal. Resulting in a decreased breaking intensity at the breakpoint, which makes it easier for the surfer to take off successfully.

2.4.7 Criteria for reef design

Although the aim of the work described in this thesis was to establish whether wave-focusing reefs have the potential to influence wave behaviour and thus enhance surfing conditions, other criteria need to be taken into account when designing and constructing a reef. Firstly, it should be noted that the studies were carried out for a model reef situation and not for a specific site. Thus site-specific conditions, such as wave climate, beach bathymetry and tidal range, would need to be taken into account when designing a reef.

Reefs are built to improve surfing conditions, the site selection is therefore crucial in order to be successful. Environmental factors such a changing seabed, tidal range and waves from different directions add to the complexity of the design. Access to the surfing site is an important factor in selecting a location for an artificial surfing reef, so that many people can benefit from it.

Reefs should be designed to meet the skill of surfers. In general reefs are designed to produce waves for competent surfers. Reefs should be designed to increase the number of surfable days per year and cater for a wide range of surf ability, rather than producing surfing waves that can only be ridden by expert surfers a few times a year.

For the design of conventional reefs, criteria such as breaker type and peel rates are usually defined for the take off and along the ride (see Sections 2.2.3 and 2.2.4). The desired form of wave breaking is controlled by designing the reef with certain water depth over the reef and seabed gradients. The length of the ride is generally determined by the size of the reef. Left and right breaking waves should be provided on the reef in order to allow natural and goofy foot surfers to surf the wave 'frontside' (facing the wave) or 'backside' (with their back to the wave). Natural and goofy-foot surfers ride surfboards with their left or right foot at the front of the board, respectively.

The desired water depths over the reef will depend on the range of design breaking wave heights for the particular location [Couriel and Cox 1996]. Therefore the water depth over the reef should be shallow enough to induce breaking at high tide and deep enough at low tide to prevent injury should a surfer come off the wave. However before entering the water, surfers should assess the dangers and decide whether they are competent enough to surf there.

For all surfing reefs it is necessary to take into account the possible impact on the environment, such as changes that may be produced in the seabed and currents, and the degree of protection provided to the coast. In fact, one of the consequences of building an artificial surfing reef may be to improve coast protection and such improvement may be a design criterion. In the design for the Narrowneck reef criteria were developed for the beach stabilisation, such as changing the alongshore sediment transport rate and sand trapping capacity.

Beach safety is an important issue. Due to the presence of the reef, sandbars may be formed inducing rip currents (see Chapter 6), which may be hazardous for swimmers.

2.4.8 Wave-focusing surfing reef

The concept being researched in this thesis is a wave-focusing reef, which is based on an approach different from conventional surf reefs designed up until now. More specifically in relation to this study, the initial objective relates to the design of a minimal structure. The existing artificial surfing reefs and those proposed are based on wave breaking controlled by alongshore variations in water depth and seabed gradients over the reef. Waves actually break on such conventional reefs, which provide a suitable topography while with wave-focusing reefs the waves break after passing the reef. Wave breaking is then controlled by alongshore variation in wave height along the wave crest.

3. Problem definition and outline of research

3.1 Introduction

This chapter sets out the concept of an artificial wave-focusing reef and a definition of the parameters that describe wave focusing. The approach taken in this first study on wave-focusing reefs was to determine whether a wave-focusing surfing reef can be created to initiate early wave breaking so that closing-out waves are made more surfable. The study aimed to determine the optimal dimensions for such a reef structure.

3.2 Concept of wave-focusing reefs

3.2.1 The principle

The conventional approach to the design of an artificial reef is to control wave breaking by means of underwater topographic irregularities in the vicinity of the breaker zone. Waves are forced to break at a certain depth on top of the reef. However with a wave-focusing reef, waves break first where they are highest. Thus, a complicated topography for a surfing site will not have to be created because waves will break on an unaltered beach.

In the concept of a wave-focusing reef, wave breaking is controlled by means of alongshore variation in wave height, i.e. the gradient in the wave height along the wave crest on either sides of the peak. A wave-focusing reef located seaward of the surf zone would cause a peak in the wave crest and then cause waves to break on the unaltered beach after passing the reef.

The reef is designed to act as a lens that converges the wave rays to cause a peak in the wave crest. This is similar to the lens effect that occurs but on a larger scale, at the end of a headland or at the tip of a breakwater where the waves wrap around and cause focusing of the wave energy (see Figure 3.1).

A wave-focusing reef acts as a magnifying lens by making the wave refract and to focus to a point (see Figure 3.2), creating a peak in the wave crest. Refraction is caused by differences in water depth over the seabed resulting from the presence of the submerged reef (see Figure 3.3 and also Section 2.2.1). The reef causes a section of the wave crest to break sooner in one place (the peak) and later in other sections of the same wave crest. This is achieved by focusing wave energy to form a peak in the wave crest, preferably seaward of the break point, so that this peak can break on an otherwise plane beach.

The concept is based on wave focusing rather than on causing waves to break on a topographic ridge that results in a sudden change in water depth as in the design of conventional surfing reefs. Thus, a particularly interesting aspect concerns reefs that are placed seaward of where waves will break. The question is: how long does the peak persist after the wave passes the landward end of the reef? This is important with respect to reef deployment, as working inside the surfzone is difficult. If the reef could be located entirely outside the surfzone, it could be towed into place.

Figure 3.1: Waves focusing on a headland and refracting into the bay at Bells Beach, Australia (source: www.aspworldtour.com)

3.2.2 Effect of wave focusing

A wave that breaks simultaneously along its entire crest is not surfable and is called a 'close out' in the sport of surfing (see Section 2.2.4). Preventing waves from closing out is one of the primary purposes of a wave-focusing reef. Due to the focusing effect, waves passing over the reef are amplified and wrap around the reef. This means that the crests of waves curve as they approach the reef (refraction, see Section 2.2.1) and slow down above the reef, where the water is shallower than on either side of reef. Also, due to the focusing effect of the reef, the wave height is greater in this section of the wave crest.

When the wave has passed over the structure, the whole length of the wave crest resumes travelling further over the plane sloping beach. If a wave's approach to the shore is uninterrupted, it will break along its entire crest equidistant from shore. Because the reef can slow down a section of a wave and also amplify the wave height, it is expected that the wave will start to break at the peak (Figure 3.4). After the initial breaking of the wave at the highest point along the wave crest, the wave on either side of the peak will break causing the wave to peel to both sides of the peak. The overall mechanism can be regarded as inducing added instability in the wave crest in the region of the peak.

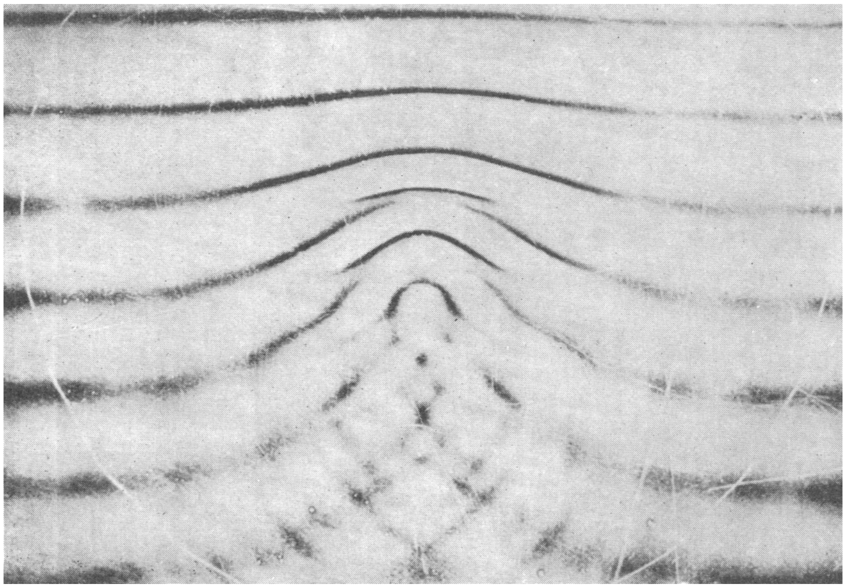
Figure 3.2: Shadow graph of waves focusing as they travel over a shoal, [Stoker 1957]

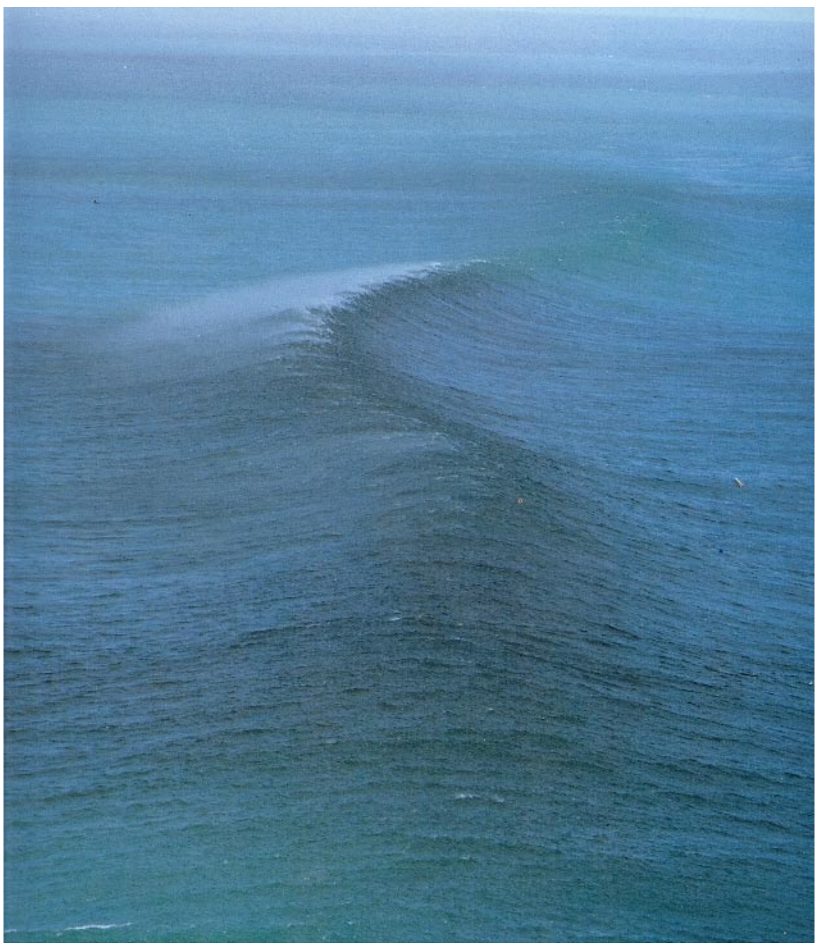
Figure 3.3: Wave crest bends as the wave travels to shore over a natural reef in deep water, waves are approximately 10 m high, at outside Pipeline, North Shore Oahu, Hawaii (The Book of Waves: form and beauty on the ocean, Roberts Rinehart publishers, 1997)

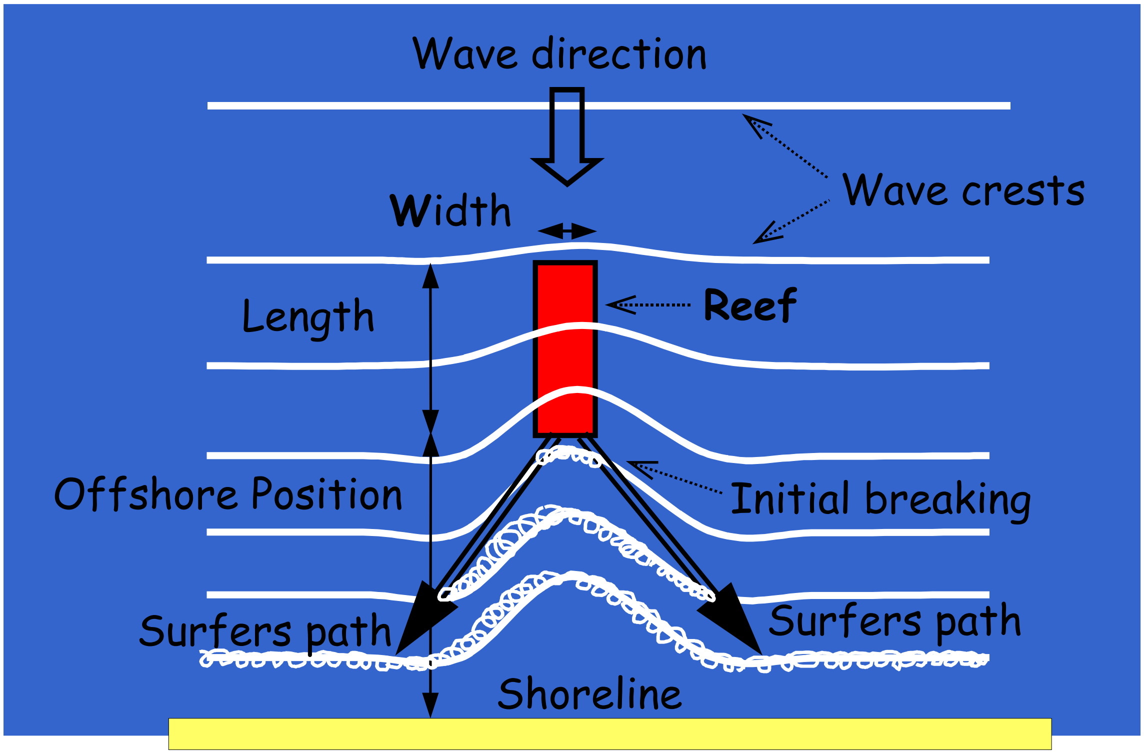

Figure 3.4: Concept of a wave-focusing reef

Thus in effect, a small-scale submerged artificial reef can convert a close-out wave to a peeling wave. However, the purpose of this type of reef is not only to create a peeling wave but also to allow a surfer to "take off" earlier than would otherwise be possible, this is analogous to tow-in assistance (see Section 2.2.3). By taking off earlier, a wave with a high peel rate can be ridden successfully. The project is aimed at influencing waves with a spilling to plunging character (see Section 2.2.3) which would be otherwise suitable for surfing if they did not close out. Thus, by delaying wave breaking at the take off zone with a reef, these waves would be made more surfable.

3.3 Definition of parameters

In defining the parameters of a wave-focusing reef, waves breaking on such a reef were compared with waves breaking without a reef. These parameters were defined in order to quantify the degree of wave focusing on the reef and include amplification of wave height and increase in breaker distance.

3.3.1 Parameters describing amplification of wave height

Wave transformation at the centre of the reef crest and induced breaker patterns were compared with the same situation without a reef. This is referred to as the plane case. For normally incident waves on a plane sloping beach, only shoaling will effect the offshore wave height (H_0). Thus, breaker height on the beach (H_{beach}) is:

$$H_{beach} = K_s H_0 \tag{3.1}$$

Where K_s is the shoaling coefficient at the breakpoint. In the case of oblique waves or irregular bed topography, wave refraction and diffraction also influence the offshore wave height. The ratio of the breaker height on a beach (no reef) to the offshore wave height is the beach wave amplification factor (K_{beach}):

$$K_{beach} = \frac{H_{beach}}{H_0} \tag{3.2}$$

Thus, for normally incident waves on a plane sloping beach where only shoaling influences the waves, K_{beach} would be equal to K_s.

The relatively shallow water over the reef causes a wave to shoal earlier. Therefore the wave height will be expected to reach its maximum further away from the coast than in the plane case. In addition, the alongshore variations in water depth will cause the wave to focus. The wave on the reef will reach its maximum height earlier and subsequently break further away from the coast. Thus due to wave focusing, the breaker height with the reef is expected to be greater than the breaker height without the reef. The difference between breaker height with and without the reef (ΔH) is:

$$\Delta H = H_{reef} - H_{beach} \tag{3.3}$$

Where H_{reef} is the breaker height with a reef and H_{beach} is the breaker height without a reef (see Figure 3.6). The relative wave-focusing effect caused by the reef (K_{focus}) is determined by the ratio of H_{reef} to H_{beach}:

$$K_{focus} = \frac{H_{reef}}{H_{beach}} \tag{3.4}$$

Where K_{focus} is the wave-focusing factor. Thus, a value of 1 for K_{focus} means that the reef has not had any focusing effect and that the breaker height would be equal to that without the reef. A value of K_{focus} larger than unity means that there is a focusing effect.

When comparing the plane case with normally incident waves where only shoaling has effected H_{beach} to the case with reef, the relative wave-focusing effect (K_{focus}) can be written as:

$$K_{focus} = \frac{H_{reef}}{K_S H_0} \tag{3.5}$$

Thus, a wave travelling towards the shore is affected by the seabed and also focused by the reef. Therefore, the breaker height on the reef (H_{reef}) will be:

$$H_{reef} = K_{focus}\ K_{beach}\ H_0 \tag{3.6}$$

The change in wave height as waves travel to shore along the reef's axis (K_{axis}), is defined by:

$$K_{axis} = \frac{H}{K_S H_0} \tag{3.7}$$

Where, K_{axis} is the wave factor along the reef's axis, at a given distance from shore (x). When $K_{axis} > 1$, the waves have been focused due to the reef.

3.3.2 Parameters describing increase in breaker distance

As was done for wave height, breaker distance on the reef was also compared to the plane case. In the plane case, waves approach a coastline with straight and parallel depth contours normally. Wave crests are therefore parallel to the straight depth contours and the breakerline is straight and parallel to shore. In this case, the distance to the breakerline from shore is the same along the breakerline (see Figure 3.5). For the plane case, the distance from the shoreline at which the wave breaks (X_{beach}) is the ratio of the breaker depth (h_{beach}) and the tangent of the angle (α) of the beach slope (see Figure 3.6).

$$X_{beach} = \frac{h_{beach}}{\tan\alpha} \tag{3.8}$$

For normally incident waves X_{beach} can be expressed as:

$$X_{beach} = \frac{K_s H_0}{\gamma \tan\alpha} \tag{3.9}$$

Where γ is the ratio of H_{beach} to h_{beach}.

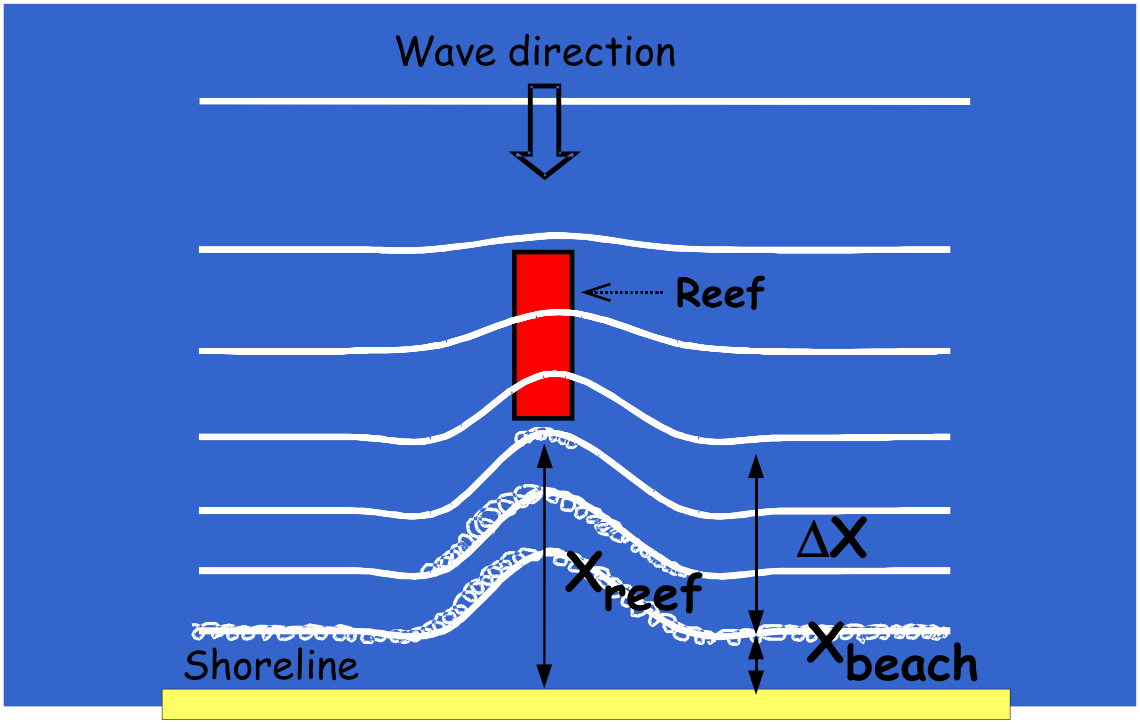

Figure 3.5: The increase in breaker distance due to the presence of the reef

The breakpoint with the reef where the wave will first start to break is X_{reef}, which generally will be larger than X_{beach} because reefs cause waves to break. The difference between the breaker distance with the reef (X_{reef}) and the breaker distance on the beach without a reef (X_{beach}) is the increase in breaker distance (ΔX, see Figure 3.5).

$$\Delta X = X_{reef} - X_{beach} \quad (3.10)$$

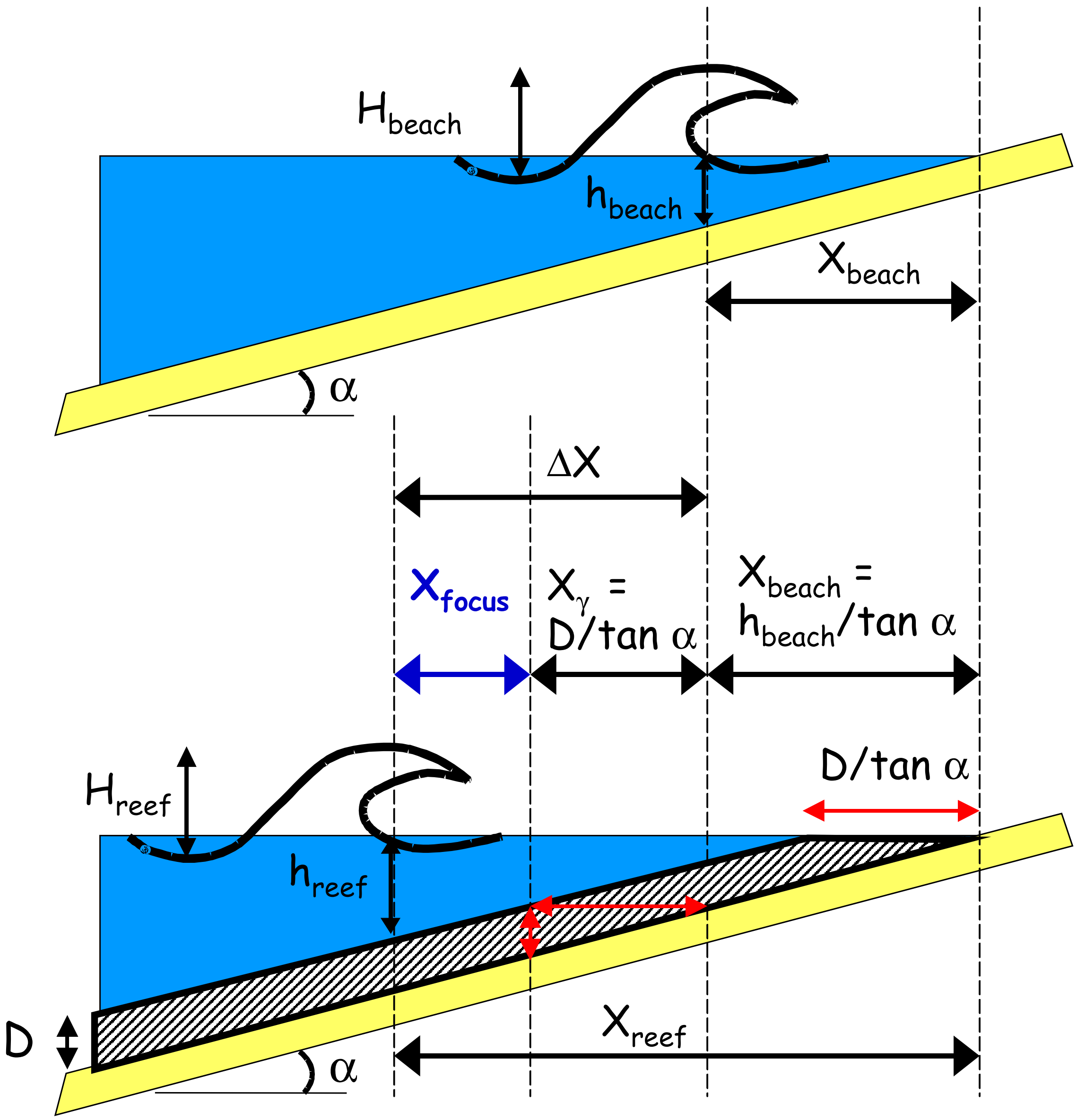

Figure 3.6: Breaker distance on the reef compared to the breaker distance for the plane case.

In order to determine the relative contribution to earlier wave breaking of the forced effect of the shallower water over the reef and of wave focusing, these two effects need to be separated. Because the water depth over the reef is the same as that at a point further onshore, it therefore would be expected that the waves would break at a distance further offshore. This distance (X_γ) defined as the gamma effect, which is the effect of a shallower water depth over the reef, is the ratio of the reef height (D) to the tangent of the angle (α) of the beach slope (see Figure 3.6).

$$X_\gamma = \frac{D}{\tan\alpha} \tag{3.11}$$

For example, for a reef of uniform height on a bed slope of 1:20, X_{reef} is expected to be at least 20 times the reef height further offshore than for the plane case (as would be expected from topographic forcing at constant ratio of $H_b/h_b = \gamma$). For D = 1 m, the gamma effect would be 20 m.

As the contribution to earlier wave breaking of the forced effect of shallow water can be described by X_γ, earlier wave breaking (ΔX) is as follows:

$$\Delta X = X_\gamma + X_{focus} \tag{3.12}$$

Where X_{focus} is the distance that can be attributed to wave focusing (see Figure 3.6) and is the augmented breaker distance:

$$X_{focus} = X_{reef} - \frac{D + h_{beach}}{\tan\alpha} \tag{3.13}$$

Where h_{beach} is the waterdepth at breakpoint for the plane case. The relative wave-focusing effect (A_{focus}) causing the wave to break earlier is:

$$A_{focus} = \frac{X_{reef}}{X_{beach} + X_\gamma} = \frac{X_{reef}}{(D + h_{beach})/\tan\alpha} = \frac{X_{reef}\tan\alpha}{\left(D + \dfrac{K_S H_0}{\gamma}\right)} \tag{3.14}$$

Where A_{focus} is the relative augmented breaker distance. Thus, a value of A_{focus} of 1 means that the reef has had no focusing effect. When $K_{focus} > 1$, the surf zone width is augmented due to wave focusing, ignoring the gamma effect.

3.3.3 Other reef parameters

The optimal dimensions of the reef, given a set of design criteria, will depend on the wave parameters. Waves start to break when they reach a certain water depth (h_{reef}) which is expected to depend on the reef height (D). For higher reefs, the wave breaking height would be greater because the wave would be more affected. Thus, the ratio of the reef height (D) to the water depth at breakpoint with a reef (h_{reef}) is defined as the relative reef height (D_{rel}):

$$D_{rel} = \frac{D}{h_{reef}} \tag{3.15}$$

Wave height and breaker distance are influenced not only by reef height but also by reef width. A very narrow reef, such as a paling fence (a fence made from stakes) or a vertical sheet placed perpendicular to the shoreline, will have practically no effect. Examples of such narrow reefs are the groynes comprising a row of poles as seen on the coast of Zeeland in the Netherlands. These very long narrow structures have very little effect on the waves passing over them. The question is how much wider than a paling fence does a reef need to be in order to have sufficient influence on waves, i.e. what is the minimum reef width required to focus waves.

In contrast, there is also possibly a maximum reef width beyond which no further effect on wave focusing would occur. A very wide reef would not produce a wave peak but rather would result in an extended section along the wave crest with a maximum wave height.

The optimum reef width would be a trade off between the minimum possible (for economic reasons) and as effective as possible for wave focusing. The minimum and maximum widths of the reef are most likely to depend on the wave length. Wider reefs that focus waves more than do narrow reefs would cause waves to break at a greater distance from shore where the wave length is also greater. The ratio of reef width (W) to wave length at breakpoint (L_{reef}) is the relative reef width (W_{rel}):

$$W_{rel} = \frac{W}{L_{reef}} \tag{3.16}$$

As waves propagate to shore, they start feeling the seabed at a certain water depth, depending on the wave period and thus the wave length. The longer the reef is the earlier the waves will be influenced by the reef. A reef that extends further offshore is expected to influence waves more than a shorter reef of the same height and width. The ratio of the reef length (Λ) to the wave length at breakpoint (L_{reef}) is the relative reef length (Λ_{rel}):

$$\Lambda_{rel} = \frac{\Lambda}{L_{reef}} \tag{3.17}$$

As will be explained in chapter 4, reef height and reef width could be combined into one dimensionless parameter, which is the product of relative reef height and relative reef width. This is the West-Cowell surfing reef factor (S_{RF}):

$$S_{RF} = \frac{D}{h_{reef}} \frac{W}{L_{reef}} \tag{3.18}$$

S_{RF} consists of the product of D and W, which approximates the cross-section of the reef. It is expected that K_{focus} and A_{focus} will increase with increasing S_{RF}.

3.4 Outline of research

The study reported in this thesis was carried out in order to address the following questions about wave-focusing artificial surfing reefs, which have not been studied up until now:

- Can a wave-focusing surfing reef be created that will initiate early wave breaking in such a way that waves otherwise closing out can be made more surfable?
- If this can be done, what are the optimal dimensions of such a structure?
- How does varying the dimensions of the reef influence the wave-breaking pattern and what are the effective minimum and maximum dimensions of the reef?

The main focus of this study is on how wave-focusing reefs of various dimensions affect wave behaviour. However, a reef placed close to the surf zone will alter wave pattern and currents, which in turn are likely to affect the seabed, sandbars and other aspects of coastal morphology, especially on sandy coasts. Such effects with regard to placing of wave-focusing reefs are discussed in relation to the main results of the study. In addition, design features of the reef other than shape are discussed briefly.

A series of numerical experiments were conducted with the computer model Ref/Dif [Kirby and Dalrymple 1994]. Preliminary tests were carried out with reefs of different dimensions to determine whether a wave-focusing artificial surfing reef is a workable concept. In order to establish the dimensions of a wave-focusing reef, simulations were conducted with different reef dimensions and wave conditions. Primarily, waves approaching the shore normally where the reef is aligned perpendicular to shore were simulated. A dimensional analysis was also conducted in order to generalise for different reef shapes and wave parameters. Finally case simulations were conducted with the Triton Boussinesq-type model [Borsboom 2000] using a representative reef in order to examine non-linear effects. Triton is a non-linear model of a higher order than Ref/Dif and may provide a better approximation of waves particularly with respect to wave shape.

4. Methods

4.1 Introduction

Numerical simulations using the combined refraction and diffraction model Ref/Dif [Kirby and Dalrymple 1994] were carried out in order to determine the specifications for a wave-focusing reef. A number of reefs with varying width, height and length were modelled. Initially, the reefs were subjected to the same regular waves in order to compare wave transformation over reefs of different shapes. Then, wave conditions were varied to study the performance of a few reefs. Finally, the output data was used to find the relationships, in dimensionless parameters, between reef dimensions and wave breaking patterns.

In this chapter the approach is outlined and the numerical model used and simulations carried out are described.

4.2 Modelling approach

4.2.1 Specifications for a wave-focusing reef
Wave-focusing reefs are designed to focus incoming waves in order to increase wave height locally and to induce waves to break further offshore. Thus, the aim of the study was to determine the dimensions required for such a reef (Figure 4.1), which include height, width, length, and the optimum position of the reef offshore and the profile of the reef relative to the seabed. The concept of a wave-focusing reef and the parameters used here have been discussed in Chapter 3. Preliminary studies were also carried out on the role of wave period of in determining reef parameters, especially relative to reef dimensions. From a practical and economic point of view, a reef should be as small as possible.

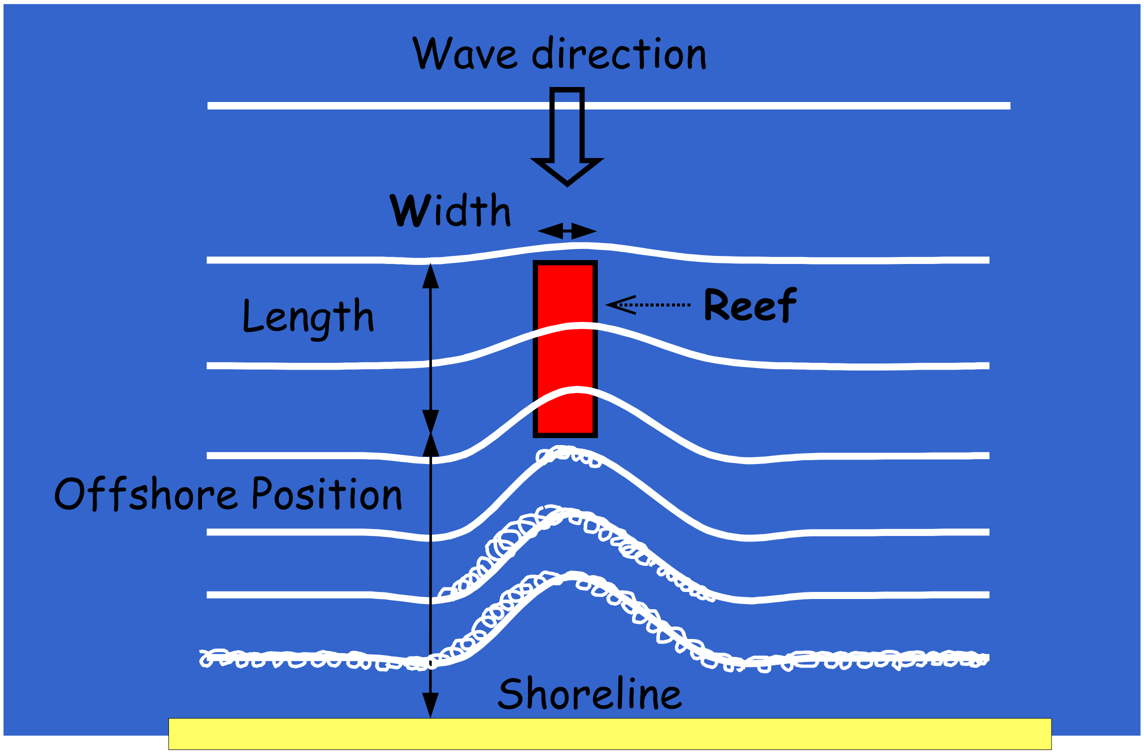

Figure 4.1: Reef dimensions of wave-focusing reef

4.2.2 Approach to designing reef with numerical model

The main aim of the research was to determine the minimum dimensions of an effective reef. In other words, how small can a reef be while still inducing a wave peak at which an early initiation of breaking can be successful in making a wave peel instead of closing out? Another aim was to determine the dimensions above which there is only a marginal influence of a reef on wave height and consequently on breaker distance. That is, the overall aim is to evaluate the range of reef dimensions that produce a significant effect on wave focusing.

Submerged reefs differing in dimensions were compared in order to determine the dimensions required to make waves break in the desired way. Topographic models were developed for reefs with various heights, widths and lengths on a plane beach (no alongshore variations in the bathymetry). The reason for this is that differences in the wave field can be attributed to the reef dimensions. Apart from the reef, the only other parameter of the bathymetry was the beach slope.

In order to establish the role of reef height and width on waves, simulations were conducted with reefs of infinite length but with various width and crest heights. An infinite length was chosen initially (i.e., constant reef dimensions relative to the seabed out to the seaward limit of the computational grid) so that changes in the wave field attributable to the different cross-sections could be examined in the absence of effects of reef length. To establish the role of reef length on influencing waves, simulations were done by changing the length of reefs of a certain height and width. Simulations were also carried out with finite length reefs placed at different distances from shore in order to establish the role of reef position.

For the simulations establishing the role of reef dimensions on influencing waves, regular waves were used with constant height, period and direction. However simulations were also conducted varying wave period for an infinitely long reef, in order to find out the effect of wave period for a certain reef. Trapezoidal cross-sections were chosen for the test reefs because Ref/Dif interpolates the water depth linearly between adjacent grid points. Therefore, the sides of the reefs were inclined making the cross-section trapezoidal instead of rectangular. In reality, such a relatively simple shape probably would be chosen because it would be practical to construct and to deploy in the surf zone.

Because it is expected that non-linear effects may be better described by Triton, a Boussinesq-type model developed at WL|Delft Hydraulics in the Netherlands [Borsboom 2000], simulations were also conducted for a limited sub set of cases [Appendix D].

4.3 Description of numerical model Ref/Dif

4.3.1 Wave theory in Ref/Dif

The wave breaking on the reefs was simulated with Ref/Dif, which is a combined refraction and diffraction numerical model that predicts wave behaviour over an irregular seabed. Ref/Dif is a phase resolving model, which predicts wave patterns when waves are affected by refraction, diffraction, shoaling and energy dissipation.

Combined wave refraction and diffraction models include both effects explicitly and therefore waves can be modelled in regions where the bathymetry is irregular and where diffraction is important. Ref/Dif treats areas where wave rays converge strongly due to focusing effects or where caustics are caused by other means, correctly and thus no infinite wave heights are predicted. However, wave reflection is not included in the model and therefore in general, wave reflection phenomena are not reproduced correctly. Thus Ref/Dif can be applied for the calculation of wave heights and directions in areas where one or both of these effects are present. For example, to determine wave heights in a bay given the offshore wave heights, periods and directions, or to determine the amount of wave energy penetrating an island chain and for waves propagating over submerged shoals such as surfing reefs (see Section 4.3.5).

The basic equation in absence of the wave-current interaction is [Kirby and Dalrymple 1983]:

$$\frac{\partial A}{\partial y} i(\bar{k}-k)C_g A + \frac{\sigma}{2} A \frac{\partial}{\partial x}\left(\frac{C_g}{\sigma}\right) - \frac{i}{2\sigma}\frac{\partial}{\partial y}\left(CC_g \frac{\partial A}{\partial y}\right) - \sigma \frac{k^2}{2} D_{nl} |A|^2 A = 0 \qquad (4.1)$$

Linear dispersion relationship:

$$\sigma^2 = gk \tanh kh \qquad (4.2)$$

4.3.2 Assumptions in Ref/Dif

The Ref/Dif model has been typically used with monochromatic wave trains propagating in one direction. Waves can be described by Stokes' theory but this is not valid when the Ursell parameter (i.e., $U_r = HL^2 / h^3$, where H, L and h are wave height, wave length and water depth, respectively) is greater than 40, which occurs in shallow water. Thus, Ref/Dif can be used with Stokes' theory but the option using a dispersion relationship developed by Hedges provides a better approximation in shallow water than does Stokes' theory. In shallow water, the wave celerity according to Hedges' model approaches that of a solitary wave and in deep water, it approaches that of a linear wave. Thus, for shallow water the Hedges' model is preferred while for deep water, the Stokes' model is preferred. Therefore in Ref/Dif, a combination of Stokes and Hedges model can be used for deep and shallow water respectively.

Thus of the three options in Ref/Dif for wave modelling (linear model, Stokes-to-Hedges non-linear model and the Stokes model) the combined

Stokes-to-Hedges model was used. Compared with other options, it covers a broader range of water depths and wave heights and it provides a good description of wave propagation before wave breaking.

4.3.3 Wave breaking

The Ref/Dif model uses the McCowan breaking criterion (see Section 2.3.1) for the onset of wave breaking which occurs when the ratio of wave height to water depth reaches 0.78. After breaking has initiated, energy dissipation due to wave breaking is given as [Kirby and Dalrymple 1986]:

$$\omega = \frac{KC_g\left(1 - (\psi h / H)^2\right)}{h} \tag{4.3}$$

Where, K = 0.17 and ψ = 0.4, which are empirical constants [Dally et al. 1985]. By using the dissipation model and the breaking index relation for the onset of breaking, Ref/Dif is able to represent waves both inside and outside the surf zone.

4.3.4 Grid specifications

The maximum grid dimensions of the bathymetry are 200 by 200 grid points. It is necessary to specify the wave parameters on the seaward boundary, which is the first grid row. The program subdivides the grid in order to ensure that there are at least 5 grid points per wave length.

Subdivisions can be made both in the x and y directions in order to make the computational grid finer than the bathymetric grid. However, output such as wave height, can be only given for the grid points specified in the bathymetric grid.

4.3.5 Application of Ref/Dif

In relation to surfing reefs, it is important that both refraction and diffraction are represented well in the numerical model as this allows small-scale effects to be examined.

Ref/Dif has been used to model various natural surfing sites in the world including reefs where extraordinarily large waves break such as those in the northern Pacific Ocean:

- Maverick’s on the centre of California’s coastline [Raichle 1998];
- Jaws on the northern shore of Maui, Hawaii [Fearing and Dalrymple, 2000];
- Cortes Bank situated about 300 km off the coast of California, modelled by Dalrymple [O’Hanlon 2001].

These large wave breaking surfing sites have been modelled with Ref/Dif to study the specific conditions (i.e., wave height, period, and angle of wave approach and tide), which most influence waves. Under such conditions, the biggest waves are produced.

Jaws is one of the sites that has been most studied [Achenbach 1998; Fearing and Dalrymple 2000]. Only large swells with long periods are affected by the submerged triangular ridge located at a water depth of about 10 m. The main effect of the ridge is to cause waves to refract, because the part of a wave that travels over the ridge moves slower than the rest of a wave in deeper water. The wave bends around the ridge and causes a peak in the wave crest [Fearing and Dalrymple 2000]. Such wave magnification at Jaws is similar to the wave-focusing reef concept presented in this thesis.

The modelling at Cortes Bank has assisted surfers willing to ride waves 18 m or larger that are breaking over a submerged mountain range. Because Cortes Bank is about 300 km from land, surfers need to be able to predict conditions before they make the long journey out to the surfing site.

4.4 Description of numerical simulations

4.4.1 Specifications of simulations

For the simulations with varying reef dimensions, the wave conditions were kept constant at a wave height of 1 m and a wave period of 8 s, such conditions occur often in Australia. Thus these are the type of waves that the project is aimed at with respect to initial practical applications. A wave with a height of 1 m is surfable if the peel angle is greater than 30 degrees (Figure 2.5). The wave direction was chosen so that waves approached the reefs normal to the shoreline and thus parallel to the reef cross-shore axis (Figure 4.1). This enabled comparison of the altered wave-breaking pattern caused by the reef with the plane case where the waves would otherwise close out. In reality wave conditions are irregular, however regular waves with one constant height, period and direction were chosen in order to study the focusing effect on the reef. Different shaped reefs were superimposed on a constant seaward sloping beach with a bed slope of 1:20. Surfing sites with a bed slope of 1:20 include Angourie (north coast, NSW), Kirra (Gold Coast, Queensland) and Cables Station (Perth, Western Australia). The Iribarren number (ξ, see Section 2.2.2) for this case (bottom slope = 1:20, H_0 = 1m, T = 8 s) is 0.5. This value of ξ characterises the transition between spilling and plunging breakers; such waves are preferred for surfing [Walker 1972].

4.4.2 Preliminary simulations

The purpose of these simulations was to determine the specifications of the bathymetric grid, such as the number of grid points and the grid spacing and also the range of reef heights and widths for further model simulations. The number of grid points (see Section 4.3.4) and the choice of grid spacing determine the total size of the area to be modelled. Because the bed slope was set at 1:20, the size of the grid also determines the water depth at the seaward boundary (h_{in}), which is 0.05 times the distance of the offshore boundary from the shoreline.

The area of the modelling grid should be chosen so that h_{in} is sufficient to model the process of wave shoaling due to the influence of the seabed. However, the resolution of the bathymetric grid should provide sufficient detail to specify the reef and to simulate waves. The accuracy of the calculated breaker distances also depends on the choice of the bathymetric grid resolution. A trade-off has therefore to be made between detail of the bathymetry (fine grid spacing) and the total area represented by the grid (coarse grid spacing).

One difficulty in selecting a suitable grid for simulating reefs is that the range of reef heights and reef widths that need to be modelled is not known *a priori*. However, the resolution of the bathymetric grid should also be chosen according to these reef dimensions.

Simulations were therefore carried out with five trapezoidal-shaped reefs with crest widths (W) in the range of 0 m to 20 m and heights (D) in the range of 0.5 m to 2 m, in order to determine whether reefs of these dimensions would influence the wave breaking pattern. The trapezoidal-shaped reefs (Figure 4.2) had a base width (W_{base}) 20 m wider than the crest width. For three 10 m-wide reefs, D = 0.5 m, 1.0 m and 2.0 m (side slopes were 1:20, 1:10, 1:5) while for two 1 m-high reefs, W = 0 m and 20 m (side slopes were 1:10). All the reefs were infinitely long extending from the shore to the offshore boundary. Reefs with a height of 1 m were chosen because this is equal to H_0. To extend the range, D = 0.5 m and 2 m were chosen which are half the height and double the height respectively. Because the main interest was to determine how narrow the reef can be, a reef was chosen with a triangular cross-section where W = 0 m (with W_{base} = 20 m). This is the minimum width of reef that can be modelled on this grid. In order to examine wider reefs, W = 10 m and 20 m were chosen. After this preliminary investigation, a better decision could be made concerning various reef dimensions to be simulated and grid specifications.

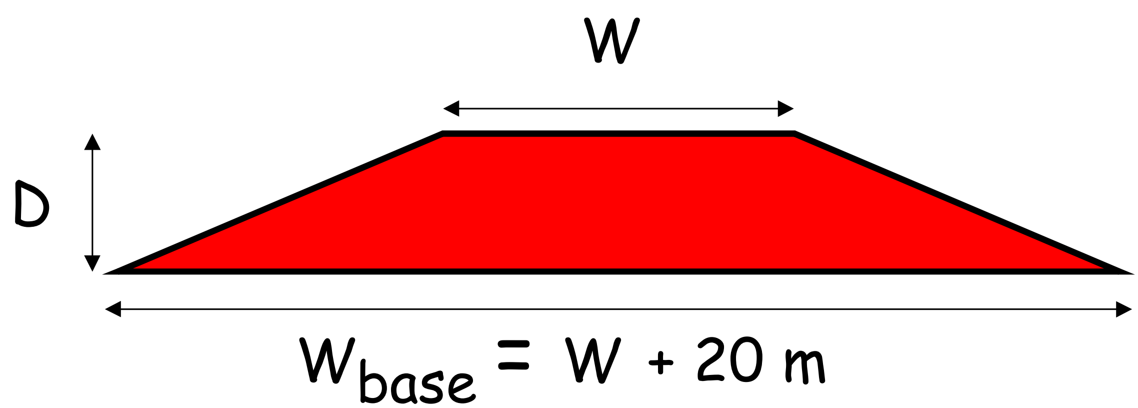

Figure 4.2: Cross-section of reefs for simulations on grid with 20 by 20 grid points

These simulations were conducted on a grid comprising 20 by 20 grid points with a grid spacing of 10 m by 10 m. The total bathymetric grid had a size of 190 m by 190 m. Thus, from the shoreline with a water depth of 0 m, the water depth increased linearly to h_{in} = 9.5 m. However a coarse grid was used, the results provided a basis for the simulations of the reefs.

4.4.3 Specification of bathymetric grid
As a result of the preliminary investigation (see Sections 4.4.2 and 5.2), the grid for further simulations could be specified. The grid size was chosen to satisfy criteria for waves in relatively deep water; i.e., $h_{in}/L_0 \geq 0.5$ [Komar 1976]. At the offshore boundary (h_{in}) of the grid, water depth had to be greater than 50 m for the chosen T = 8 s where L_0 = 99.9 m. Thus, h_{in} was chosen to be 50 m, and because bed slope was 1:20, the length of the grid was 1000 m.

Because the model's maximum number of grid points is 200 by 200, the minimum grid spacing was 5 m. This was sufficient to specify the extended and refined range of reef dimensions (see Section 4.4.4). Thus, the total area of the bathymetric grid was a square with sides of 995 m, comprising 199 by 199 grid blocks, each of 5 m by 5 m. The water depth at the offshore boundary was therefore 49.75 m and L_{in} = 99.1 m, which means that the waves were affected to a very limited extent by the seabed from the start.

4.4.4 Influence of reef height and width

Simulations were carried out to determine the influence of dimensions of the reef's cross-section, such as reef height and width, on the wave-breaking pattern. In order to study the effect of varying reef heights and widths, the crest height (D) and crest width (W) of the trapezoidal shaped reef were varied. All reefs were of 'infinite length', extending from the shoreline to the offshore boundary in the modelling grid.

As result of the preliminary simulations (see Sections 4.4.2 and 5.2), a refined and extended range of reef heights and widths was selected for these simulations. These were conducted on a bathymetric grid with 200 by 200 grid points with a spacing of 5 m by 5 m (see Section 4.4.3). In the range of reef widths of 0 m to 20 m, W = 5 m and W = 15 m were added. A reef height of 1.5 m was added in order to complete the range of D = 0.5 m to 2 m with a 0.5 m interval. To assess the effect of considerably higher reefs, reef heights of 4 m and 8 m were included. Thus, simulations were conducted with D = 0.5 m, 1 m, 1.5 m, 2 m, 4 m and 8 m and with W = 0 m, 5 m, 10 m, 15 m and 20 m. In total, 30 reefs with five different crest widths and six different heights were modelled.

The base width (W_{base}) of the reefs was 10 m wider than the crest width (Figure 4.3), and thus the side slopes of the reef were D:5 (1:10, 1:5, 1:3.3, 1:2.5, 1:1.25 and 1:0.63).

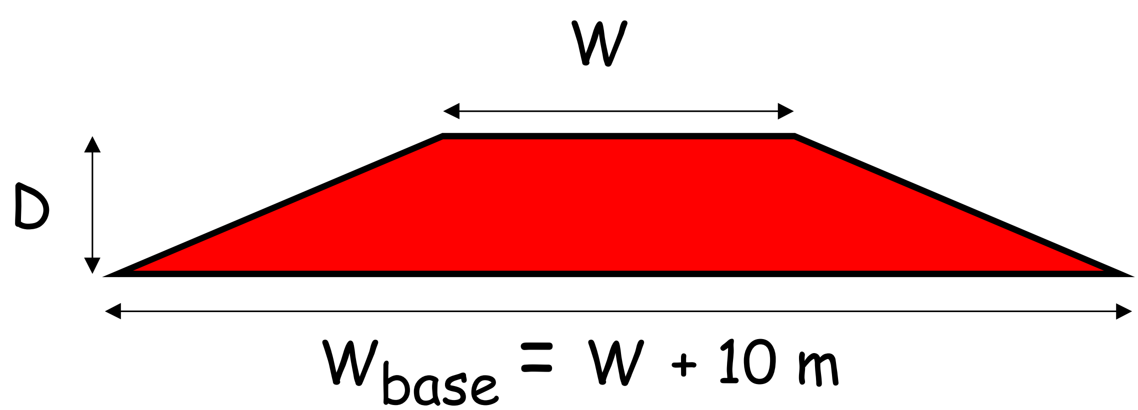

Figure 4.3: Cross-section of reefs

In addition for the 5 m-wide reefs, D = 0.25 m, 0.75 m, 3 m, 5 m, and 10 m were added to provide a better assessment of the effect of reef height (side slopes were 1:20, 1:6.7, 1:1 and 1:0.5).

4.4.5 Influence of reef length

These simulations were conducted to determine the influence of reef length (Λ, see Figure 4.4) on the wave-breaking pattern. In order to study the effect of different reef lengths of shore connected reefs, Λ was varied while the cross-section was kept constant. Simulations were conducted of shore-connected reefs with D = 1.5 m, W = 5 m and varying Λ from 35 to 100 m at 5 m intervals, from 100 to 150 m at 10 m intervals, and with Λ of 200, 250 400 and 995 m. The 995 m-long reef extended to the offshore boundary in the modelling grid, and thus represented an infinite length reef as simulated in the previous Section. For these simulations, the same specifications (H_0 = 1 m and T = 8 s, see Section 4.4.4) were used as used for the simulations with reefs of infinite length.

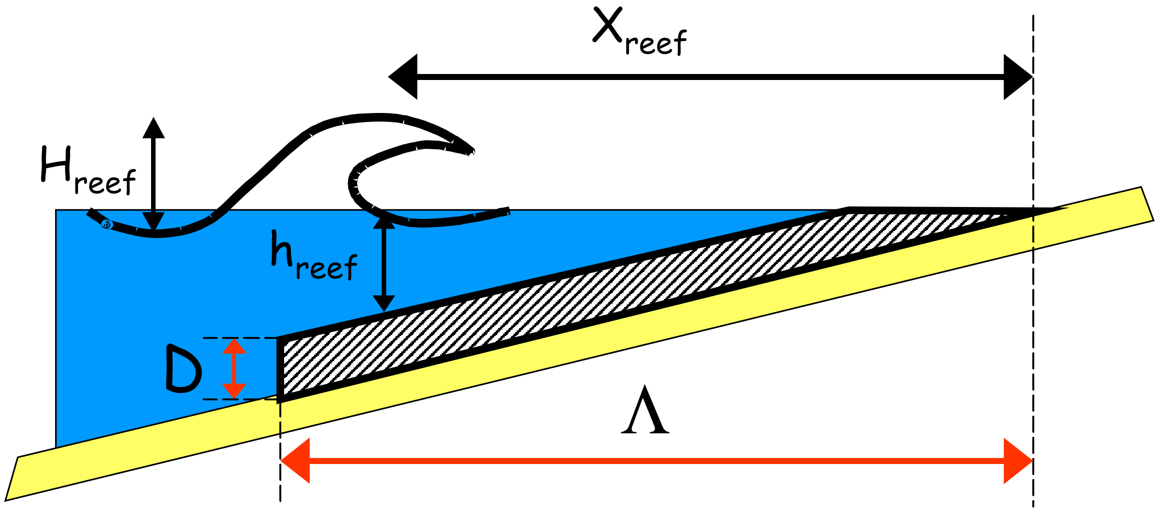

Figure 4.4: Illustration of reef length (Λ) and reef height (D) of shore-connected reefs

4.4.6 Influence of reef position

These simulations were conducted to determine the influence of the offshore position of the reef (X_{OP}, see Figure 4.5) on the wave-breaking pattern. In order to study the effect of reefs placed at different distances from shore; X_{OP} of reefs reaching from the offshore boundary of the grid was varied while the cross-section was kept constant.

Simulations were conducted of reefs with D = 1.5 m, W = 5 m and varying X_{OP} of 35 m to 55 m at 5 m intervals and of 60 m to 120 m at 10 m intervals and X_{OP} of 105 m. Because the grid reached to 995 m from the shoreline, the length of the reefs was, Λ = 995 m - X_{OP}. The horizontal section at the shoreward end of the reef (see Figure 4.5) had a length equal to X_γ, which is 30 m for reefs with D = 1.5 m. For a few simulations where the reefs were placed just beyond the surfzone, also the spatial pattern of wave breaking was examined, which was for X_{OP} = 35 m, 40 m and 45 m.

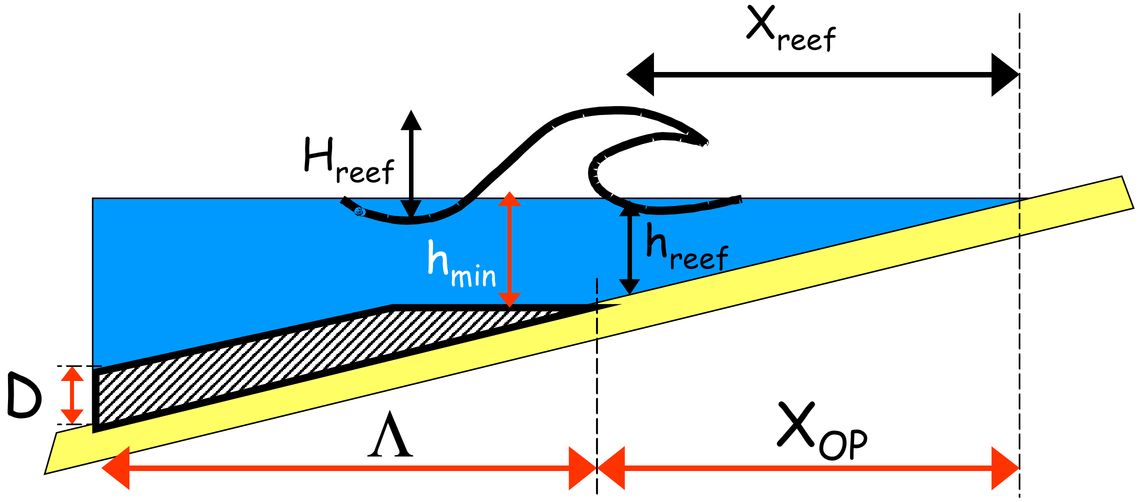

Figure 4.5: Illustration of reef length (Λ) and reef position (X_{OP}) of reefs which extend to the offshore boundary of the modelling grid, where h_{min} is the minimum water depth over the reef.

4.4.7 Examining influence of wave period

Simulations of a reef with different wave periods were conducted in order to compare wave-focusing effects along the reef's axis. For an infinitely long reef with W = 5 m and D =1.5 m, simulations were carried out of waves with H_0 = 1 m and varying T of 4 s, 8 s, 12 s and 16 s.

4.4.8 Generalising reef specifications

The results for the simulations with reefs of infinite length (see Sections 4.4.4 and 5.3) were used to establish relationships between reef dimensions and wave breaking patterns. Of particular interest were the influence of combinations of reef dimensions such as reef height and width on breaker height and distance. Therefore, relationships were investigated between wave-focusing parameters, such as the wave-focusing factor (K_{focus}, see Section 3.3.1) and the relative augmented breaker distance (A_{focus}, see Section 3.3.1) with dimensionless reef parameters, such as the West-Cowell surfing reef factor (S_{RF}, see Section 3.3.3). Also examined was, the relationships of K_{focus} and A_{focus}, respectively with the ratio of the relative reef height and relative reef width (see Section 3.3.3).

5. Results

5.1 Preliminary simulations

5.1.1 Reefs of varying cross-sectional dimensions

As outlined in Section 4.4.2, simulations were conducted in order to determine the specifications of the bathymetric grid and to determine the range of reef heights and widths for further simulations. These simulations were conducted of waves (H = 1 m, T = 8 s) propagating from an offshore boundary with a water depth (h_{in}) of 9.5 m to the shoreline which had a water depth of 0 m over a constant sloping seabed of 1:20. The bathymetric grid comprised 20 by 20 grid points with spacing 10 m by 10 m. The offshore wave length (L_0) of waves with a period of 8 s is 99.9 m and thus, $h_{in}/L_0 = 0.1$, which means that such waves are in water of intermediate depth from the start; i.e., for $0.05 < h/L_0 < 0.5$ [Komar 1976]. These waves would therefore have started shoaling in water deeper than that at the offshore boundary where L_0 is reduced to L = 67.4 m.

In simulations of the plane case (without reef), breaker height (H_{beach}, see Section 3.3.1) was 1.30 m and breaker distance (X_{beach}, see Section 3.3.2) was 40 m. For all simulations with infinitely long reefs with various size cross-sections (see Table 5.1), the breaker height (H_{reef}, see Section 3.3.1) and breaker distance (X_{reef}, see Section 3.3.2) were greater.

Because the model calculates wave height for all grid points, it was possible to establish the points at which the waves would start to break. Thus, breaker distances (X_{reef}) were a multiple of the grid spacing (i.e., 10 m). Because the bed slope was constant, the difference in water depth between grid points in the seaward direction was 0.5 m. Values for breaker depth (h_{reef}, see Section 3.3.2) were therefore multiples of 0.5 m. As shown in Table 5.1, values of the ratio of H_{reef} to h_{reef} (i.e. γ, see Section 4.3.3) for the simulations were less than 0.78, which is the breaker criterion for the model. This difference from 0.78 indicates that the grid resolution is too coarse.

Table 5.1: The effect of reef width and height on parameters of wave breaking

W (m)	D (m)	X_{reef} (m)	H_{reef} (m)	h_{reef} (m)	γ [-]
0	0	40	1.30	2	0.65
10	0.5	50	1.46	2	0.73
0	1	60	1.52	2	0.76
10	1	70	1.50	2.5	0.60
20	1	70	1.58	2.5	0.63
10	2	90	1.67	2.5	0.67

For the three W = 10 m reefs with D = 0.5 m, 1 m and 2 m, H_{reef} was 1.46 m, 1.50 m and 1.67 m, respectively (Table 5.1). Thus, H_{reef} increased with increasing D for constant W (Figure 5.1). As shown in Figure 5.1, there is a close relationship between H_{reef} and D. This suggests that reef width had very little effect on wave amplification compared to reef height for this range of D and W.

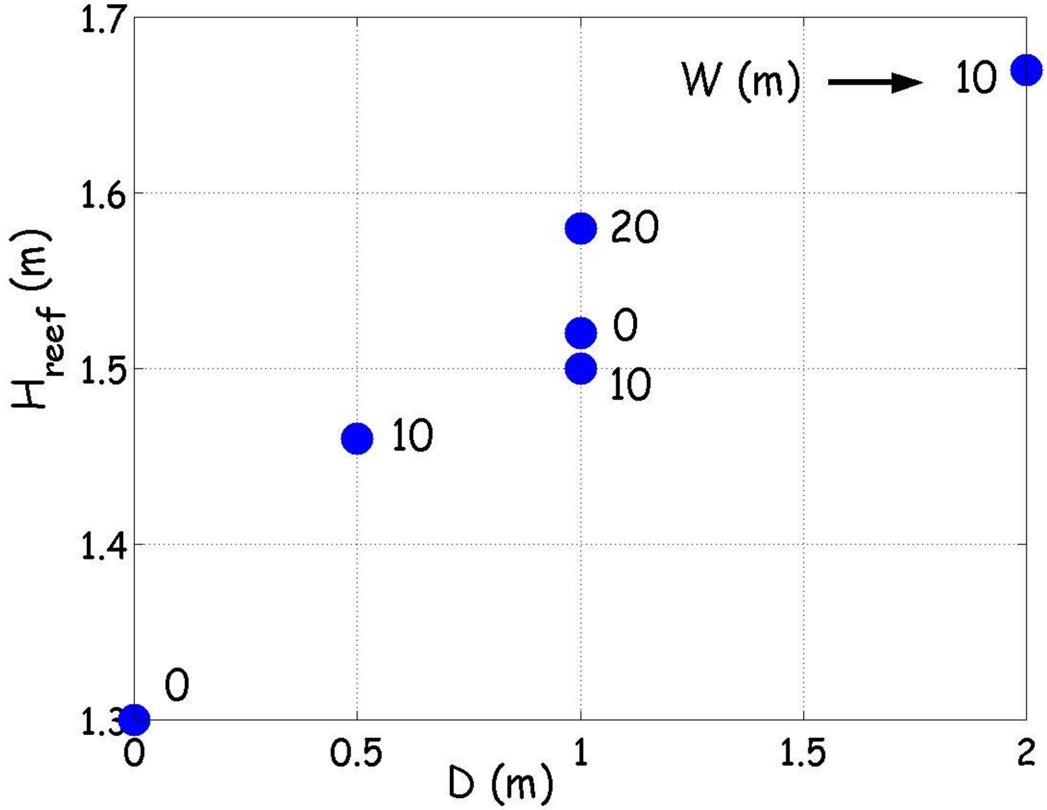

Figure 5.1: Breaker height with reef (H_{reef}) related to reef height (D). The numbers next to the points in the figure refer to reef width (W). Where D = 0 m, refers to the plane case without reef.

For the three reefs with D = 1m and with W = 0 m, 10 m and 20 m (Figure 5.2), H_{reef} was 1.52 m, 1.50 m and 1.58 m, respectively. Thus, an increase in W increased H_{reef} very little.

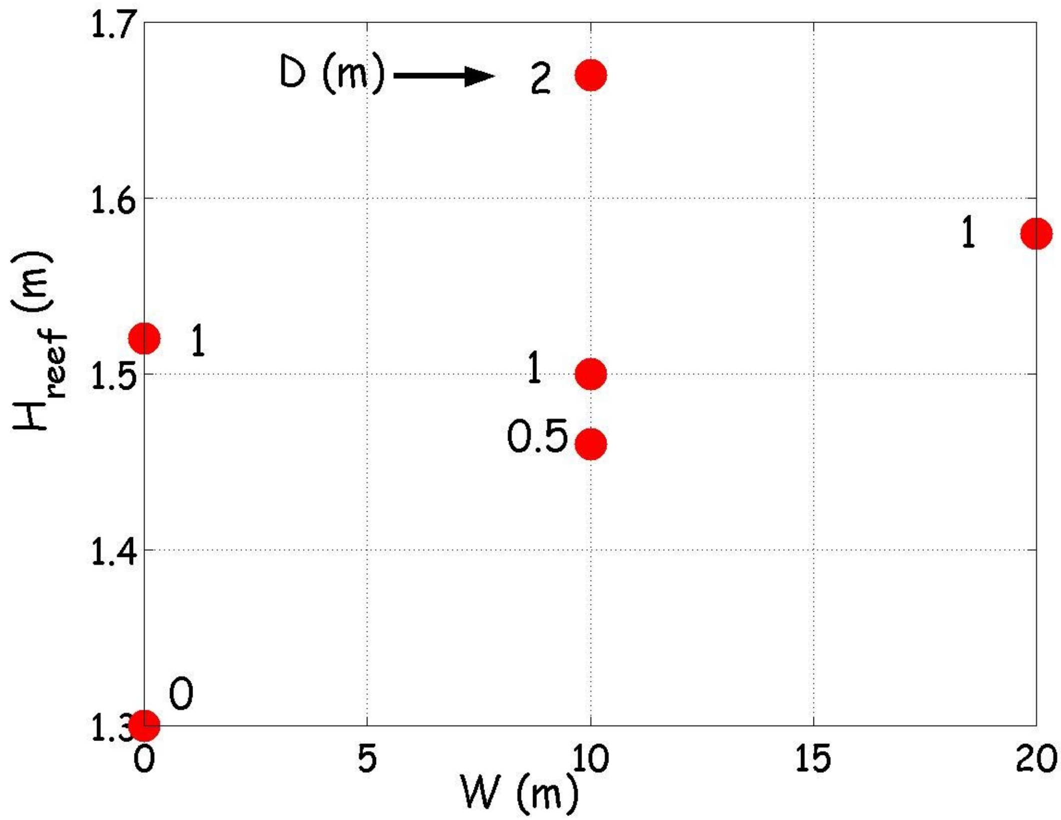

Figure 5.2: Breaker height with reef (H_{reef}) related to reef width (W). The numbers next to the points in the figure refer to reef height (D). Where W = 0 m and D = 0 m, refers to the plane case without reef.

For each of the three reefs with W = 10 m and with D = 0.5 m, 1.0 m and 2.0 m, X_{reef} was 50 m, 70 m and 90 m, respectively (see Table 5.1 and Figure 5.3). Thus for W = 10 m, X_{reef} increased with increasing D (see Figure 5.3). This increase would be expected due to the seaward topographic offset due to the presence of the reef. This compares to the offset of shallower water over the reef for depth-forced breaking ($\gamma = H/h$); i.e., the gamma effect ($X\gamma$, see Section 3.3.2) is included. For D = 0.5 m, 1 m and 2 m, $X\gamma$ is 10 m, 20 m and 40 m. In order to determine the distance that could be attributed to wave-focusing, i.e., the augmented breaker distance (X_{focus}, see Section 3.3.2), the distances $X\gamma$ and X_{beach} were subtracted from X_{reef}. Thus for the reefs with W = 10 m and D = 0.5 m, 1.0 m and 2.0 m, X_{focus} was 0 m, 10 m and 10 m, respectively. However the grid spacing of the model was 10 m, and therefore values of X_{focus} could be calculated only in multiples of 10 m.

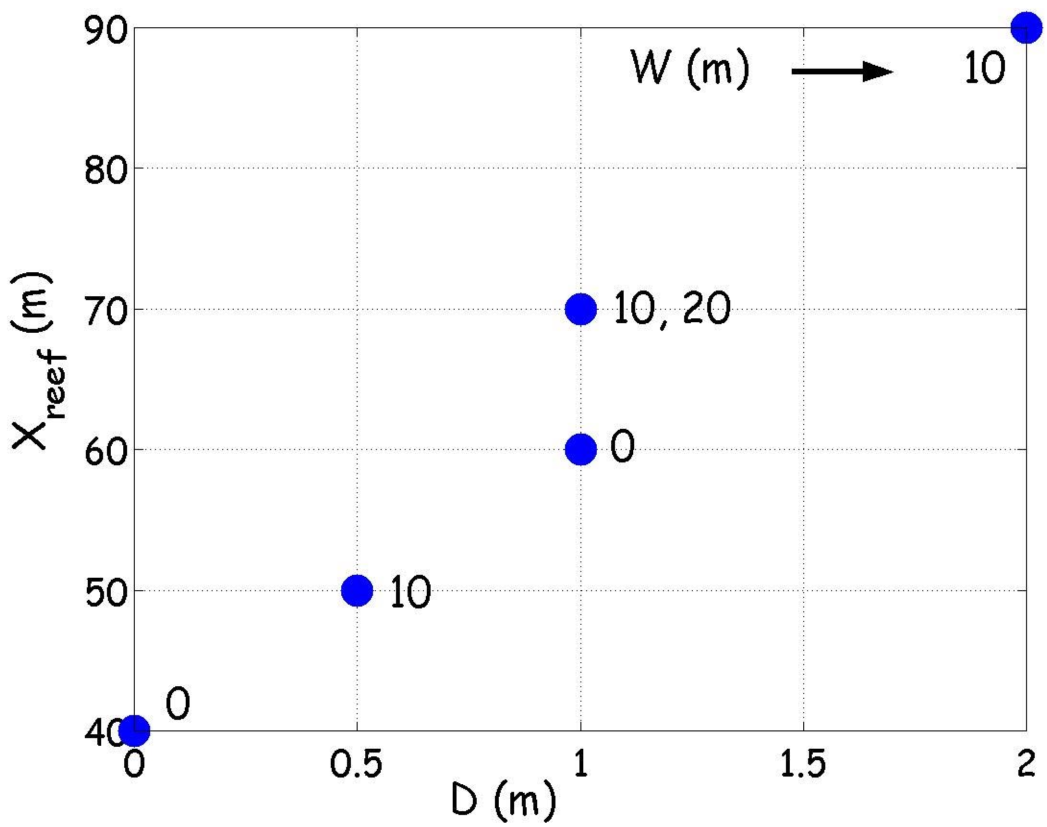

Figure 5.3: Breaker distance with reef (X_{reef}) related to reef height (D). The numbers next to the points in the figure refer to reef width (W).

For each of the three reefs with D = 1 m with W = 0 m, 10 m and 20 m, X_{reef} was 60 m, 70 m and 70 m respectively. Although the reefs with D = 1m and with W = 0 m and 10 m had approximately the same H_{reef} (1.5 m), X_{reef} for the wider reef was 10 m greater (Figure 5.4). The difference in X_{reef} cannot be attributed only to the seaward topographic offset due to the presence of the reef, but is attributable also to reef width. Thus, for the reefs with D = 1 m and with W = 0 m, 10 m and 20m, X_{focus} was 0 m, 10 m and 10 m, respectively.

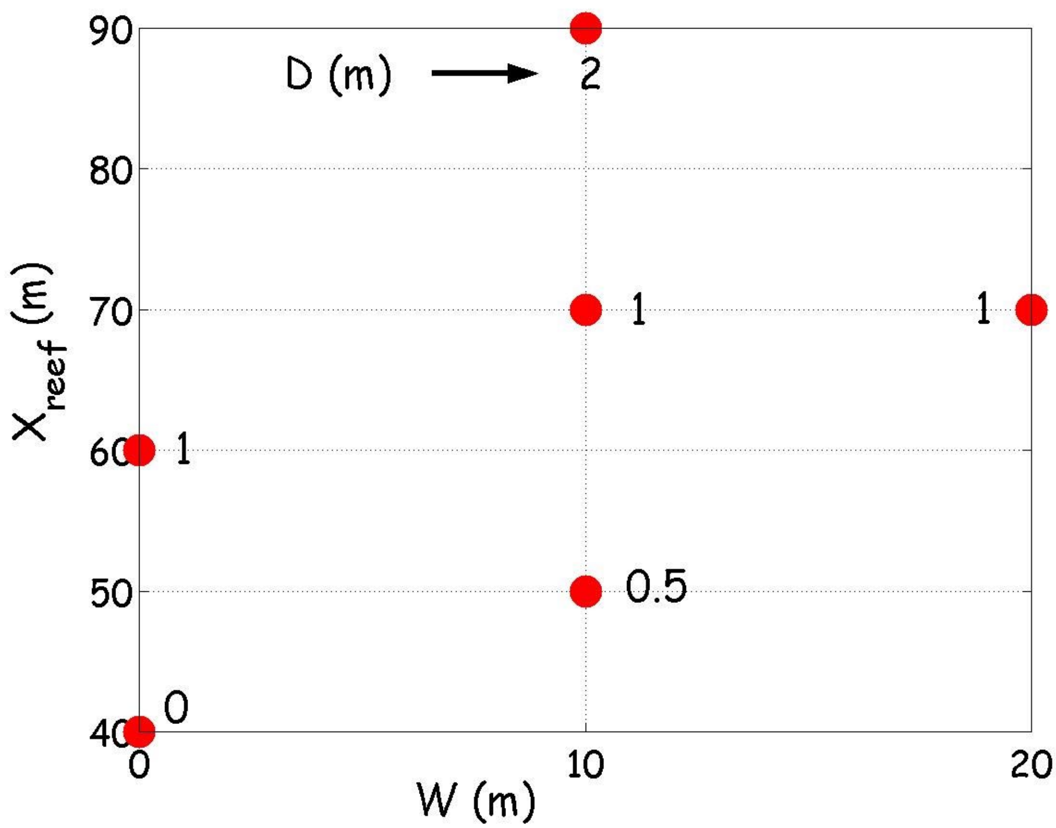

Figure 5.4: Breaker distance with reef (X_{reef}) related to reef width (W). The numbers next to the points in the figure refer to reef height (D).

5.1.2 Refinement of the simulations

As result of the preliminary simulations, a refined range of reef heights and widths was selected for simulations to examine the influence of reef height and width on wave breaking (see Section 4.4.4). These were conducted on a bathymetric grid with 200 by 200 grid points with a spacing of 5 m by 5 m (see Section 4.4.3). Thus, the total area of the bathymetric grid was a square with sides of 995 m, comprising 199 by 199 grid blocks, each of 5 m by 5 m, and h_{in} = 49.75 m.

5.2 Influence of reef height and width

5.2.1 Influence of reef height on breaker height

A plot of the water surface elevation for an infinitely long reef with reef width (W) of 10 m and reef height (D) of 1.5 m is given in Figure 5.5. As the wave travelled to shore over the reef, a peak in the wave crest formed that increased until the wave initially broke at 75 m from shore (i.e. X_{reef} = 75 m). On the reef where the wave first broke at the peak, the breaker height (H_{reef}) was greatest at 1.61 m. The gap in the wave crest nearest to shore, was due to the reef not being submerged from the shore to 30 m offshore (see Figure 3.4).

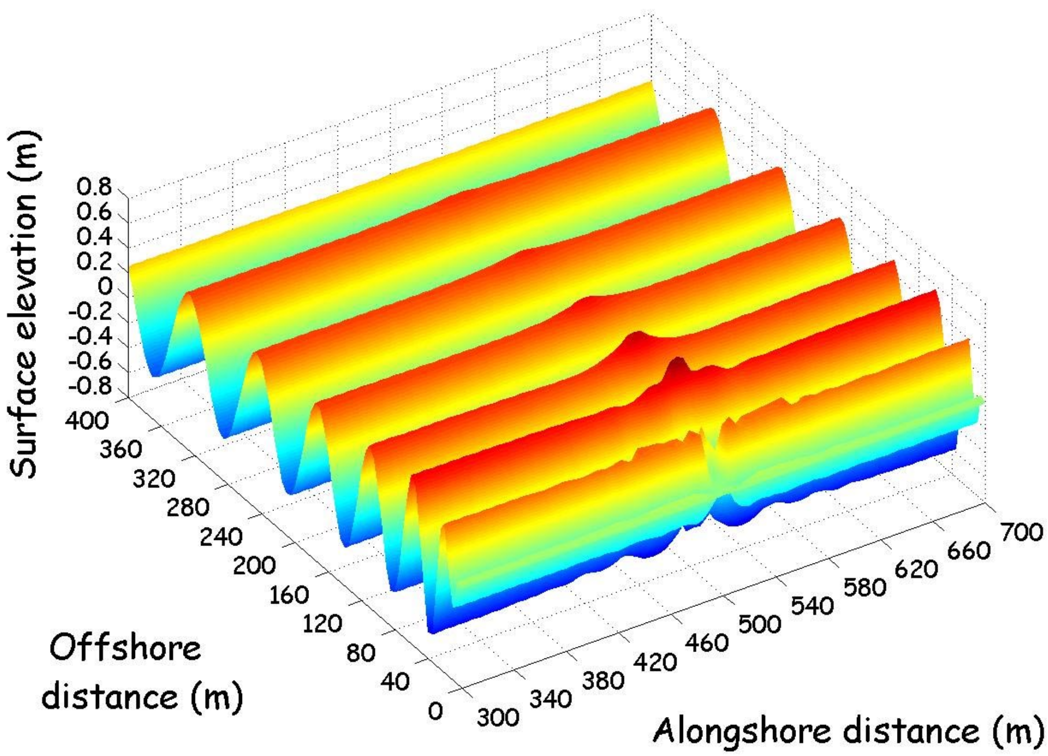

Figure 5.5: Water surface elevation for an infinitely long reef with width of 10 m and height of 1.5 m. As the wave travels to shore the peak in the wave crest increases until the wave breaks at 75 m from shore.

In Figure 5.6, a plot of the water surface elevation for an infinitely long reef with reef width (W) of 10 m and reef height (D) of 1.5 m is given. Because this 2-dimensional plot is of greater detail than Figure 5.5, there can be seen how the wave crests bend as the wave travels over the top of the reef. The white line in the figure shows where wave breaking occurs, which occurs first at the peak and subsequently further away from the peak closer to shore. Because waves approached the shore normally and the reef was perpendicular to shore the wave breaking pattern is symmetrical along the reef's axis.

The peel angle on either sides of the reef was approximately 60^0, which could be calculated at 5 m from the reef edge at an alongshore distance (y) of 490 m and 520 m.

At 20 m from the reef edge the effect of wave focusing on the reef was negligible, thus the breaker line was straight (i.e., X_{beach} = 35 m). However at y = 440 m and 570 m, there was an irregularity in the breaker line.

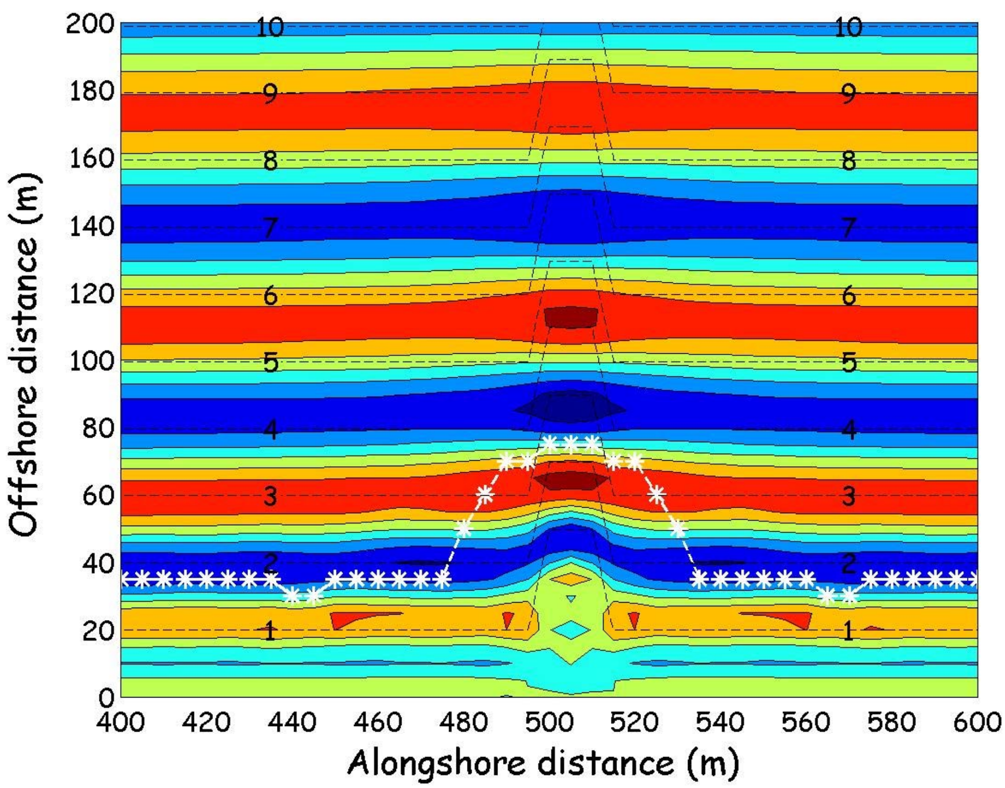

Figure 5.6: Instantaneous surface elevation for an infinitely long reef with width of 10 m and height of 1.5 m. As the wave travels to shore the wave crests bend above the reef. The black dashed lines are depth contours where the numbers denote the local water depths. The white dashed line is the breaker line, where the calculated breakpoints are given by a *.

In Figure 5.9, the effect of varying reef height (D) at constant reef width (W) on breaker height (H_{reef}) is presented. For all reef simulations, H_{reef} was greater than H_{beach} (1.27 m) for the plane case (no reef).

For constant D, H_{reef} was greater for wider reefs because dH/dD increased for wider reefs (Figure 5.7).

For reefs of constant W, H_{reef} increased with D, however the increase of H_{reef} with D (i.e., dH_{reef}/dD) was less for D > 2m. For reefs with W = 0 m, H_{reef} did increase with D up to 2 m, but where D > 2m there were diminishing marginal returns.

Thus, H_{reef} increased with D (Figure 5.7) for all reefs of constant W, but dH_{reef}/dD decreased as D increased.

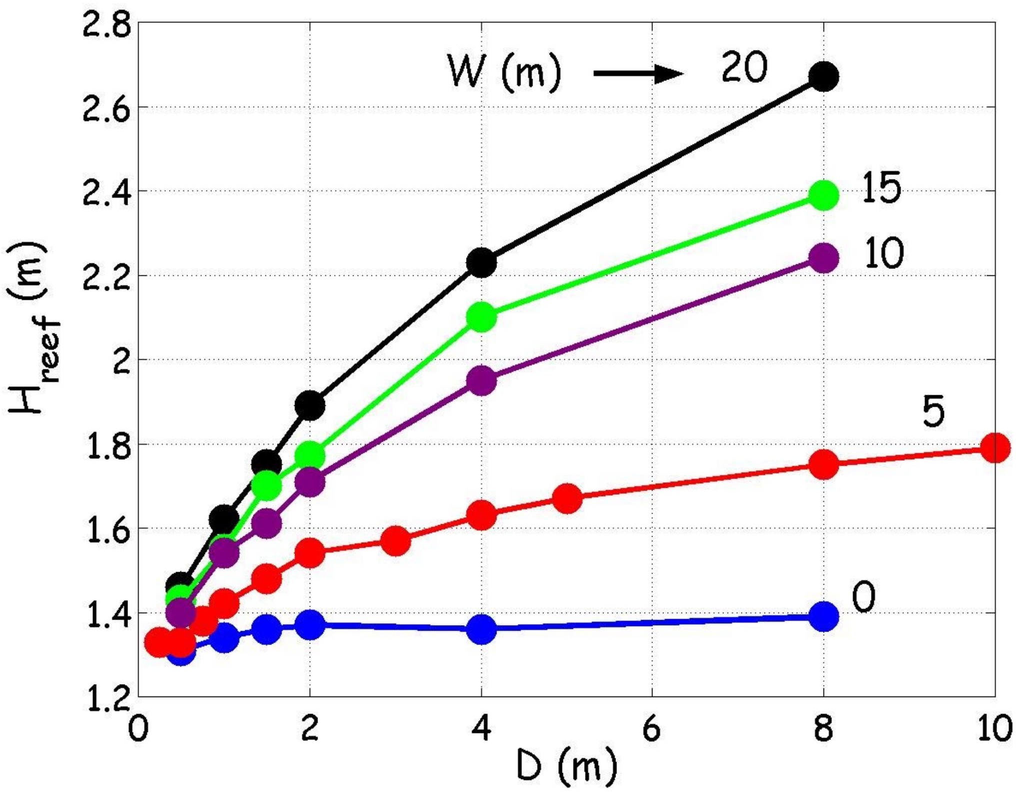

Figure 5.7: Breaker height with reef (H_{reef}) related to reef height (D) for infinitely long reefs. For the plane case (no reef) H_{beach} = 1.27 m. Each line represents reefs of constant width (W), which are given by the numbers at the end of the line.

As shown in Figure 5.8 for constant W, the wave-focusing factor (K_{focus}, see Section 3.3.1) increased with increasing relative reef height (D_{rel} = D/h_{reef}, Section 3.3.3).

For reefs with W = 0 m, K_{focus} increased for $D_{rel} \leq 1.14$, but where $D_{rel} >$ 1.14 there were diminishing marginal returns (Figure 5.8). For reefs with W > 5m, the increase of K_{focus} with D_{rel} (i.e., dK_{focus}/dD_{rel}) was less for D_{rel} > 1.

For reefs of constant W = 5 m, 10 m, 15 m and 20 m, K_{focus} increased linearly to 1.21, 1.35, 1.39 and 1.49 respectively with increasing D_{rel} up to 1.0, 0.9, 0.8 and 0.8 respectively (Figure 5.8). However for $D_{rel} > 1$, dK_{focus}/dD_{rel} decreased with D_{rel}. A value of $D_{rel} > 1$ means that a wave will break in a water depth that is less than the reef height. The points in Figure 5.8 with D_{rel} of 0.8 to 1.0 (for W > 0 m) were based on the D = 2 m simulations. Because D = 2m was at the end of the 0.5 m to 2 m-range with 0.5 m intervals of simulations, the change in dK_{focus}/dD_{rel} at D_{rel} = 1 is an approximation.

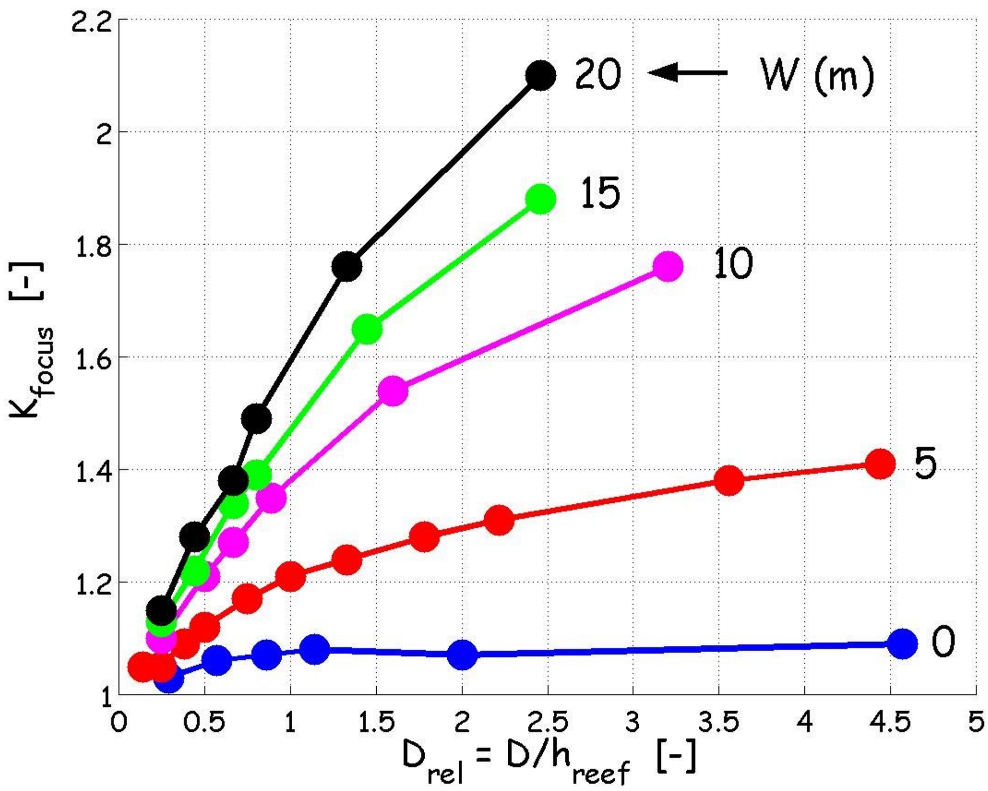

Figure 5.8: Wave-focusing factor on the reef (K_{focus}) related to relative reef height (D_{rel}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given by the numbers at the end of the line.

For wider reefs, dK_{focus}/dD_{rel} increased and there were smaller distances between the lines of constant W in Figure 5.8: i.e., diminishing marginal returns on W, which become pronounced for W > 10 m. The influence of W on H_{reef} is discussed in Section 5.2.2.

5.2.2 Influence of reef width on breaker height

When the effect of varying W, at constant D, on H_{reef} is plotted, not only did an increase in D but also an increase in W cause an increase in H_{reef} (Figure 5.9).

For reefs of constant D, H_{reef} increased proportionally for W ≤ 10 m, but thereafter the gains in H_{reef} were much less. The value of dH_{reef}/dW was greater for reefs with higher D (Figure 5.9).

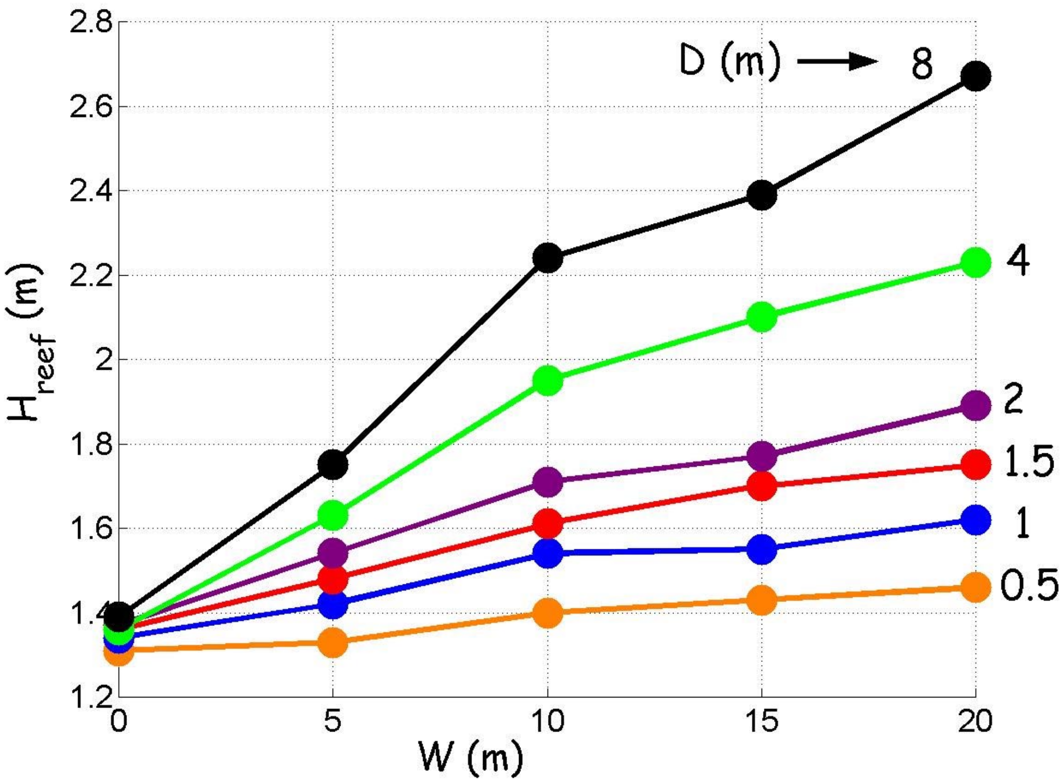

Figure 5.9: Breaker height with reef (H_{reef}) related to reef width (W) for infinitely long reefs. For the plane case (no reef) H_{beach} = 1.27 m. Each line represents reefs of constant height (D), which are given by the numbers at the end of the line.

K_{focus} increased linearly with increasing relative reef width (W_{rel} = W/L_{reef}, Section 3.3.3) for all reefs of constant D (Figure 5.10). The value of dK_{focus}/dW was greater for higher D (Figure 5.10).

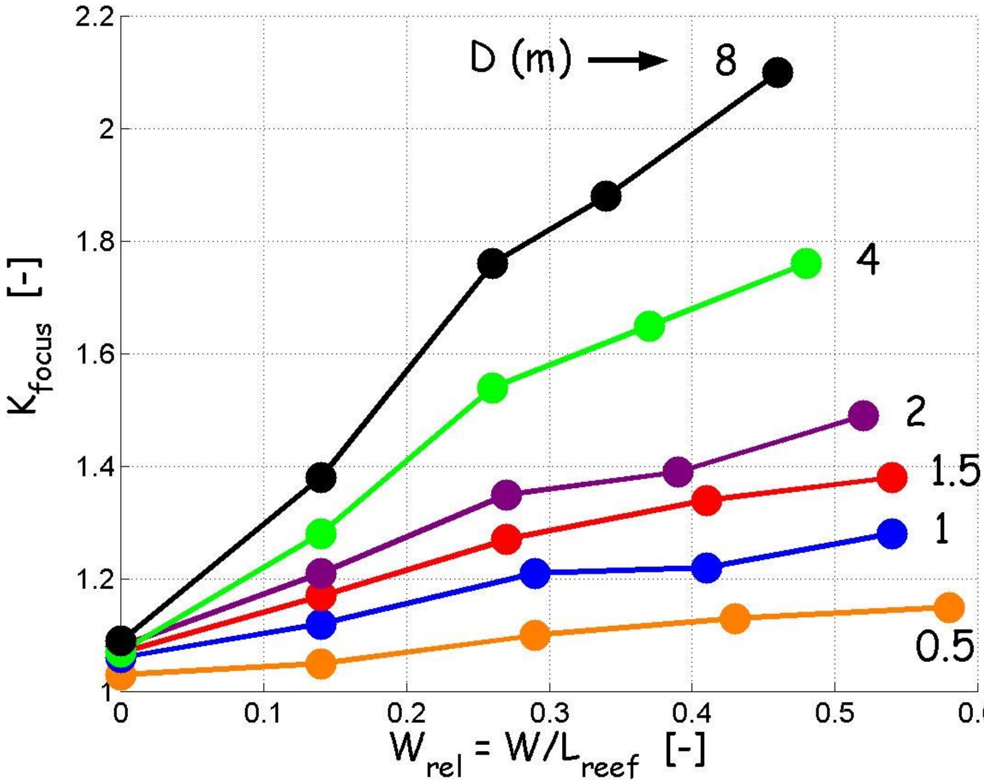

Figure 5.10: Wave-focusing factor (K_{focus}) related to relative reef width (W_{rel}) for infinitely long reefs. Each line represents reefs of constant height (D), which are given by the numbers at the end of the line.

5.2.3 Influence of reef height on breaker distance

In Figure 5.11, the effect of varying D at constant W on breaker distance (X_{reef}) is presented. For all reef simulations, X_{reef} was greater than X_{beach} (35 m) for the plane case (no reef). The calculated values for X_{reef} were integers of 5 m (i.e., the grid spacing).

For all reefs of constant W, X_{reef} increased linearly with increasing D (Figure 5.11). This increase would be expected greatly due to the seaward bed offset caused by the reef; i.e., the gamma effect (X_{γ}, see Section 3.3.2) is included.

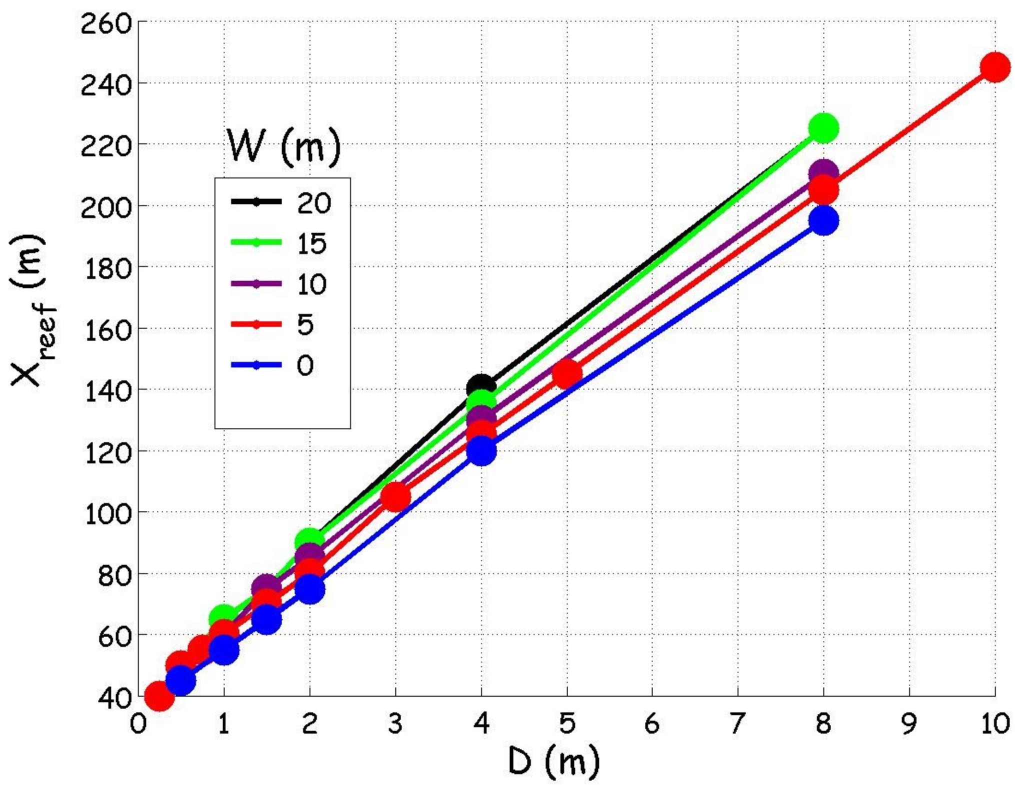

Figure 5.11: Breaker distance with reef (X_{reef}) related to reef height (D) for infinitely long reefs. For the plane case (no reef) X_{beach} = 35 m. Each line represents reefs of constant width (W), which are given by the numbers at the end of the line.

In order to determine the distance that can be attributed to wave focusing, i.e., the augmented breaker distance (X_{focus}, see Section 3.3.2), the distances X_{γ} and X_{beach} were subtracted from X_{reef}. In Figure 5.12, X_{focus} is plotted against D. For the W = 0 m reefs, X_{focus} was 0 m for D ≤ 2 m, for D = 4 m X_{focus} was 5 m and for D = 8 m X_{focus} decreased to 0 m. For the W = 5 m and 10 m reefs, X_{focus} increased to 10 m and 15 m for D ≤ 3 m and D ≤ 4 m, respectively, and thereafter remained constant. However for the W = 15 m and 20 m reefs, X_{focus} increased the same with increasing D, except for D = 4 m where X_{focus} was different.

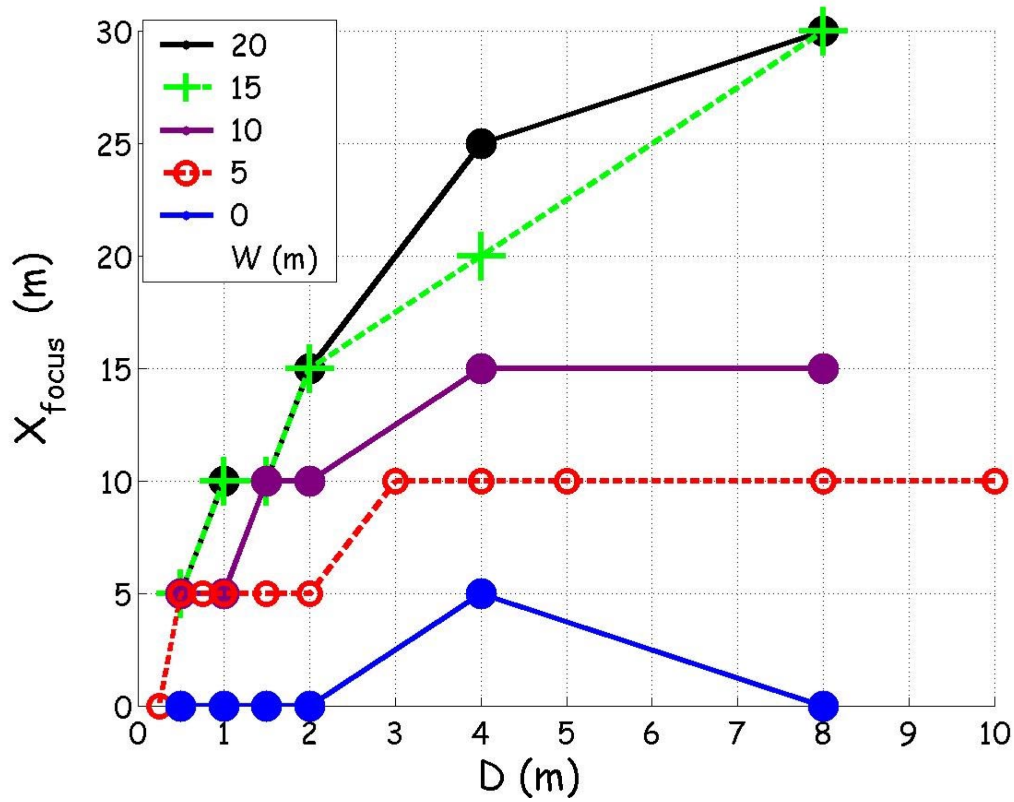

Figure 5.12: Augmented breaker distance (X_{focus}) related to reef height (D) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

The relative wave focusing effect causing the wave to break earlier; i.e., the relative augmented breaker distance (A_{focus}, see Section 3.3.2), has been plotted against D_{rel} (Figure 5.14). When $A_{focus} > 1$, means the surf zone width is augmented due to wave focusing.

Thus, for the W = 0 m reefs, there was no focusing effect ($A_{focus} = 1$), except for $D_{rel} = 2$ where A_{focus} was 1.04. For reefs of constant W > 0 m, A_{focus} was maximum at 1.09, 1.15, 1.20 and 1.22 for D_{rel} of 1.78, 0.67, 0.80 and 1.33, respectively and thereafter decreased. Again, for constant W = 15 m and 20 m, A_{focus} was the same with D_{rel}, but this was not the case for D = 4 m (where D_{rel} was 1.45 and 1.33, respectively).

This decrease of A_{focus} after a certain D_{rel} was expected, because X_{focus} stayed constant after certain D (for constant W = 0 m, 5 m and 10 m, see Figure 5.13). However, this decrease of A_{focus} was also the case for constant W = 15 m and 20 m.

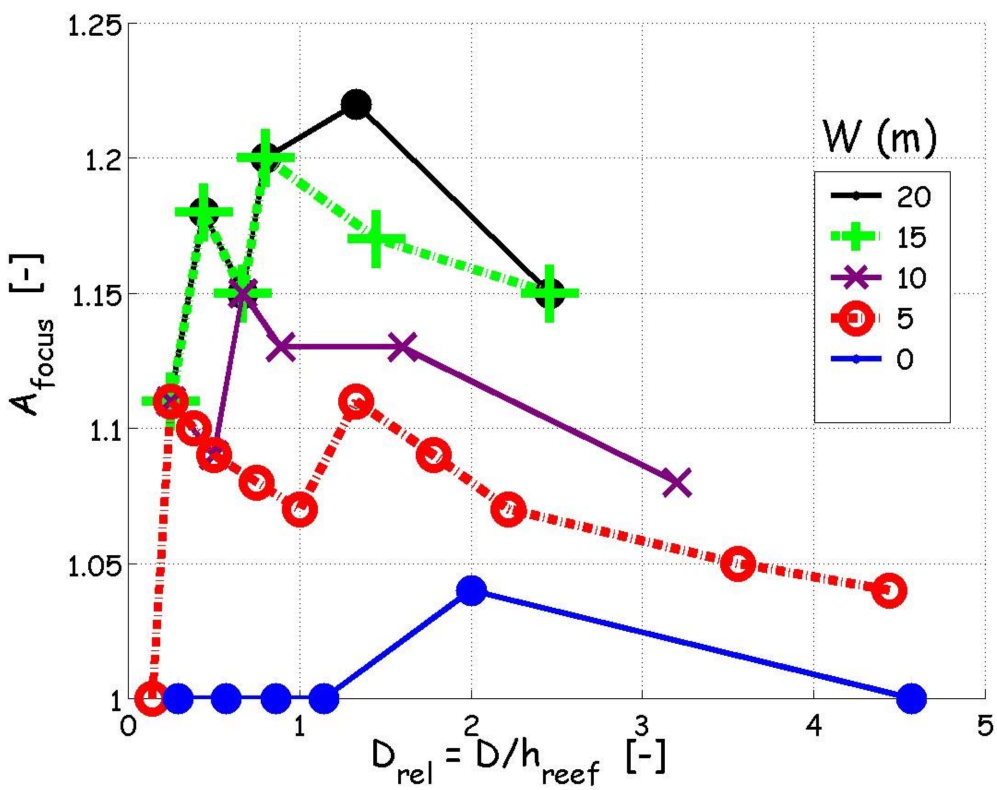

Figure 5.13: Relative augmented breaker distance (A_{focus}) related to relative reef height (D_{rel}) for infinitely long reefs. $A_{focus} > 1$ means the surfzone width is augmented due to wave focusing. Each line represents reefs of constant width (W), which are given in the legend.

5.2.4 Influence of reef width on breaker distance

In Figure 5.14 the effect of varying W, at constant D, on X_{reef} is plotted. The breaker distance (X_{reef}) for all reef simulations was greater than X_{beach} (35 m) for the plane case (no reef).

For reefs of greater D, X_{reef} was greater, due to the seaward bed offset caused by the reef (Figure 5.14). For all reefs of constant D, X_{reef} increased with W (Figure 5.14). However, unlike the increase of X_{reef} with D (see Figure 5.11), this increase of X_{reef} with W, was not due to the seaward bed offset, because the gamma effect was the same for reefs of constant D (see Equation 3.10). Thus, the increase of X_{reef} with W could be attributed to wave focusing.

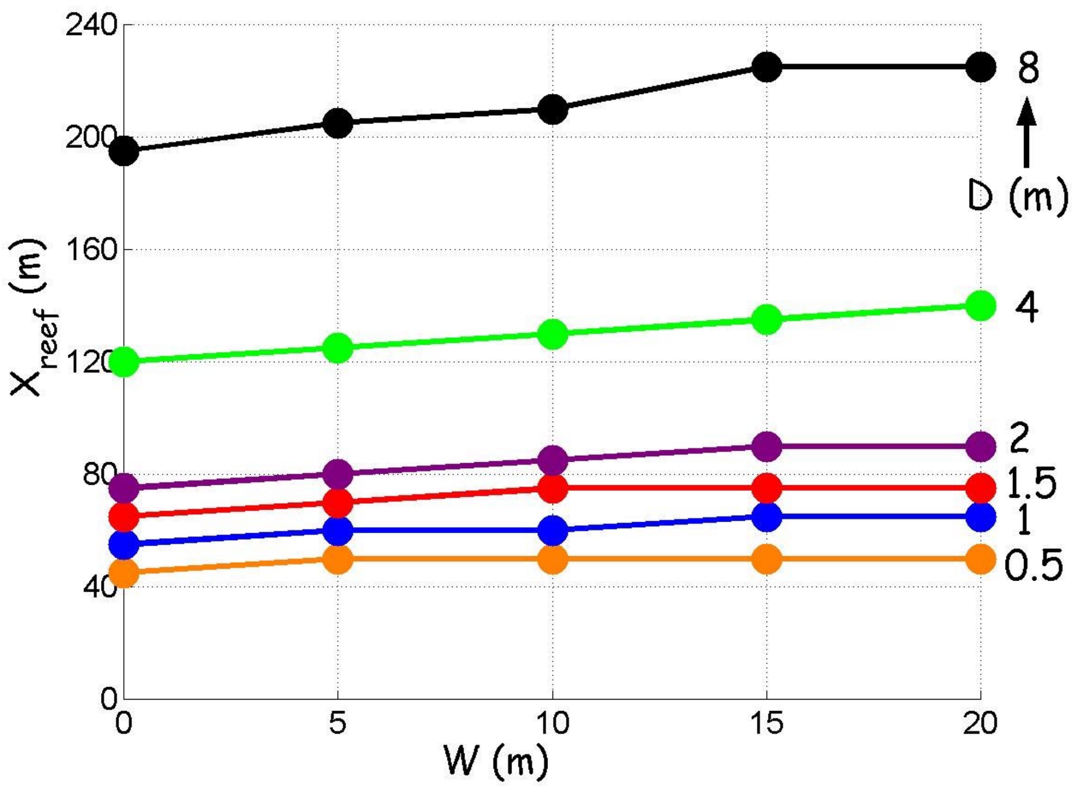

Figure 5.14: Breaker distance with reef (X_{reef}) related to reef width (W) for infinitely long reefs. For the plane case (no reef) X_{beach} = 35 m. Each line represents reefs of constant height (D), which are given by the numbers at the end of the line.

In Figure 5.15, X_{focus} is plotted against W. For constant D = 0.5 m, X_{focus} was 0 m for W = 0 m, and X_{focus} was 5 m for W > 0 m. For constant D = 1 m, X_{focus} increased to 10 m for W ≤ 15 m, and thereafter remained constant. For constant D = 1.5 m and 2 m, X_{focus} increased linearly to 10 m and 15 m for W ≤ 10 m and W ≤ 15 m, respectively, and thereafter remained constant. However for constant D = 4 m, X_{focus} increased linearly with increasing W. The 8 m-high reefs increased to X_{focus} = 30 m with W up to 15 m.

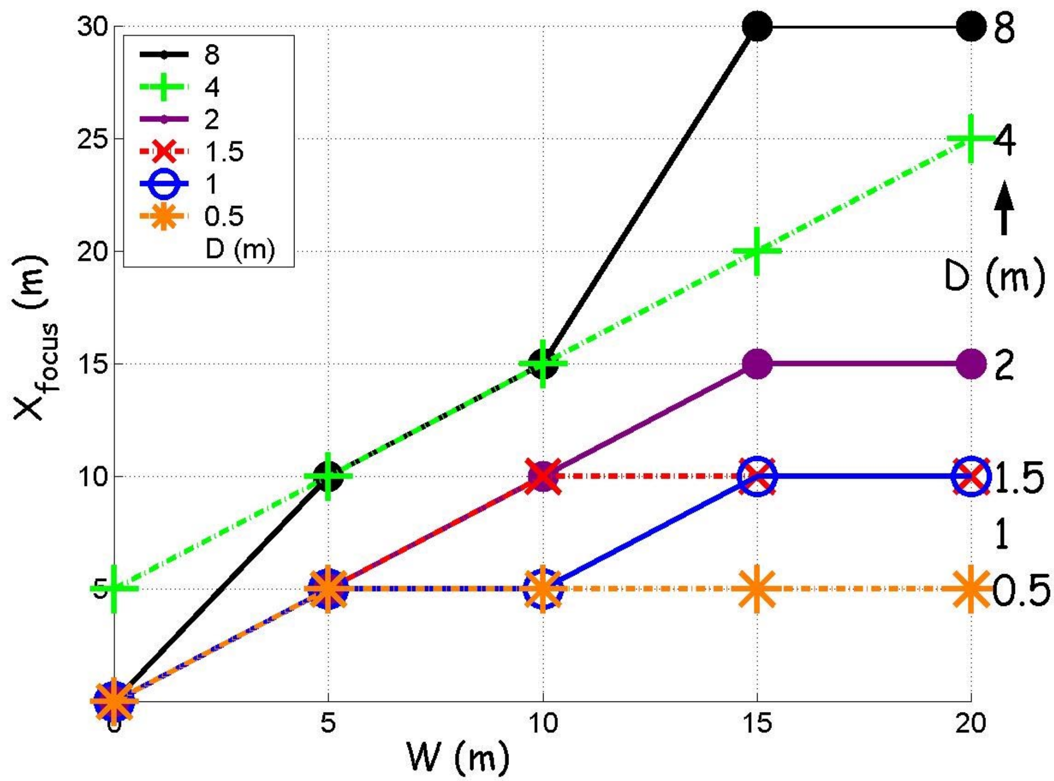

Figure 5.15: Augmented breaker distance (X_{focus}) related to reef width (W) for infinitely long reefs. Each line represents reefs of constant height (D), which are given by the numbers at the end of the line and given in the legend.

In Figure 5.16, A_{focus} is plotted against W_{rel}. For constant D = 0.5 m, A_{focus} was 0 for W_{rel} = 0, and A_{focus} was 1.11 for $W_{rel} > 0$. For constant D = 1 m, 1.5 m and 2 m, A_{focus} was maximum at 1.18, 1.15 and 1.20 for $W_{rel} \leq$ 0.41, 0.27 and 0.39, respectively, and thereafter remained constant. However for constant D = 4 m, A_{focus} increased linearly with increasing W_{rel}. For constant D = 8 m, A_{focus} increased to 1.15 with W_{rel} up to 0.34.

Thus for constant D, A_{focus} increased with W_{rel} until a certain W_{rel} (Figure 5.16). However, this positive trend of dA_{focus}/dW_{rel}, was not seen for A_{focus} with D_{rel} (Figure 5.14).

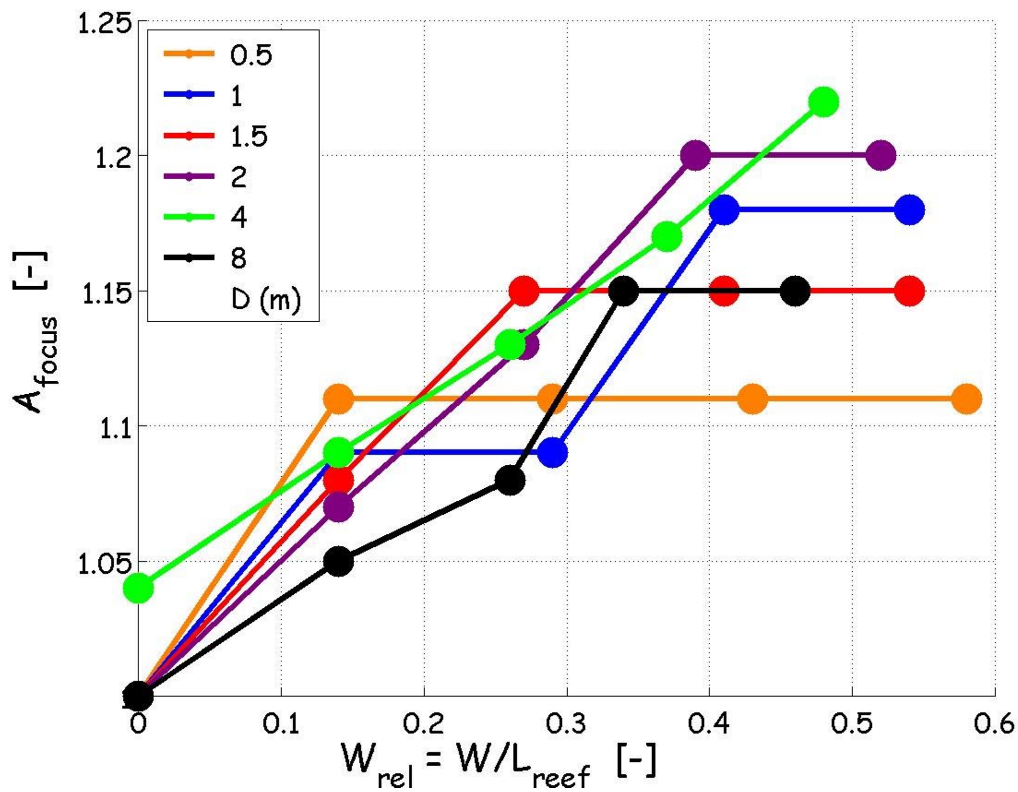

Figure 5.16: Relative augmented breaker distance (A_{focus}) related to relative reef width (W_{rel}) for infinitely long reefs. $A_{focus} > 1$ means the surfzone width is augmented due to wave focusing. Each line represents reefs of constant height (D), which are given in the legend.

The combination of minimum reef height and width for infinitely long reefs, which is required to produce a certain, X_{focus} are given in Table 5.2. For X_{focus} = 10 m, the product of the minimum D and W was 15 m^2. However for X_{focus} = 5 m and 15 m, the product of minimum D and W were not equal.

Table 5.2: Minimum reef height (D) and width (W) of infinitely long reefs required for a given augmented breaker distance (X_{focus})

W (m)	**D (m)**	**X_{focus} (m)**
5	0.5	5
5	3	10
10	1.5	10
15	1	10
10	4	15
15	2	15

5.2.5 Wave-focusing effects along reef axis

In order to find out how wave focusing varies (increases) as waves travel towards shore, the wave height along the reef axis has been compared for infinitely long reefs with different heights and widths.

First, the influence of D on wave height along the reef axis was compared for reefs with W = 5 m and D = 0.5 m, 1 m, 1.5 m, 2 m and 4 m. In Figure 5.17, the wave factor along the reef axis ($K_{axis} = H/K_sH_0$, see Section 3.3.1) was related to the distance from shore (x).

Above the reef, waves were effected by the reef from the start ($K_{axis} > 1$) and K_{axis} increased as waves travelled to shore (Figure 5.17). The values for K_{axis} at breakpoint (X_{reef}), were far greater than K_{focus}, because K_{focus} is the ratio of breaker heights at different distances from shore; i.e., H_{reef}/H_{beach}, where H_{beach} is for a point closer to shore ($X_{beach} < X_{reef}$).

The peaks in the lines in the graph show where breaking occurred (i.e. X_{reef}). For D = 0.5 m, 1 m, 1.5 m, 2 m and 4 m, the maximum values for K_{axis} were 1.13, 1.25, 1.35, 1.43 and 1.63. Closer to shore K_{axis} decreased because of earlier wave breaking caused by the reef.

Up until wave breaking, K_{axis} increased with D (Figure 5.17) and also dK_{axis}/dx increased with D. For the lowest reef D = 0.5 m, the wave-focusing effect was marginal.

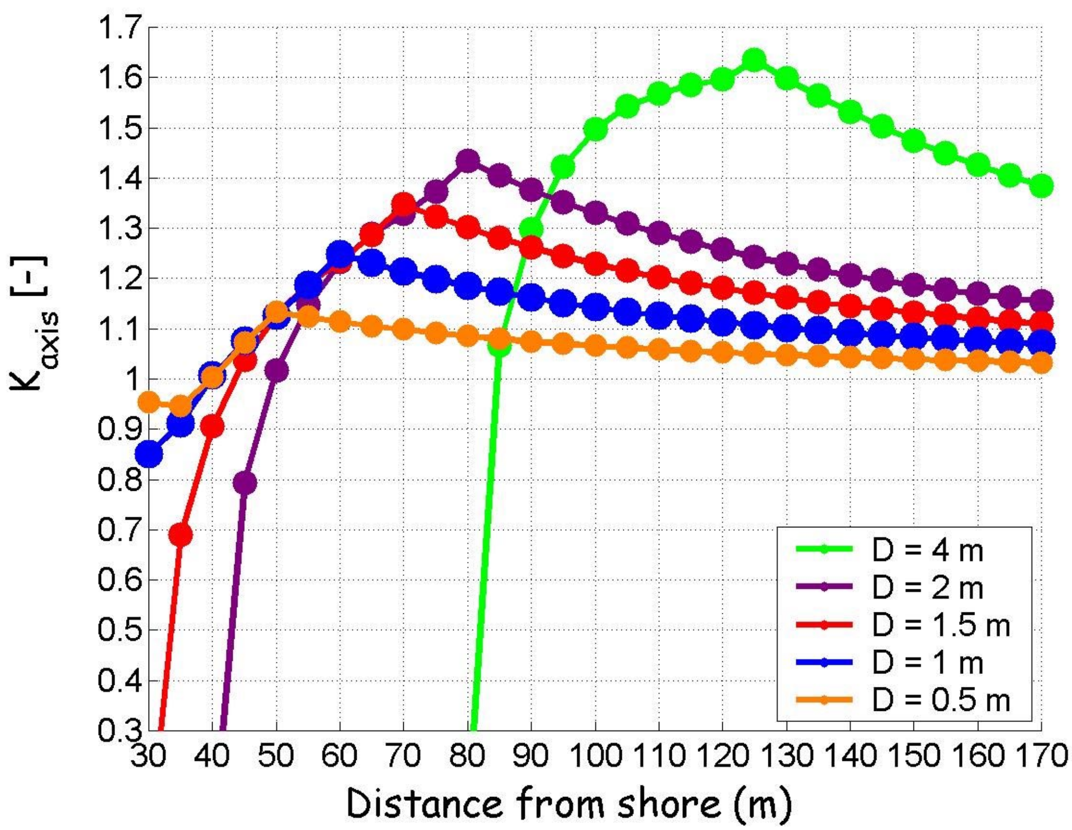

Figure 5.17: Wave factor along reef axis (K_{axis}) related to distance from shore, for infinitely long reefs with reef width of 5 m and various reef heights (D), which are given in the legend.

The influence of W on H along the reef axis was compared for reefs with D = 1.5 m and W = 0 m, 5 m, 10 m, 15 m and 20 m. In Figure 5.18, K_{axis} was plotted against the distance from shore (x).

K_{axis} increased for all reefs as waves travelled to shore (Figure 5.18). For W = 0 m, 5 m, 10 m, 15 m and 20 m, the maximum values for K_{axis} were 1.22, 1.35, 1.48, 1.57 and 1.61.

Up until wave breaking occurred, K_{axis} increased with W (Figure 5.18).

For W ≤ 10 m, dK_{axis}/dx increased with W (for $X > X_{beach}$). However, dK_{axis}/dx did not increase for W > 10 m. This is consistent with the results in Section 5.2.2 there was shown that H_{reef} increased proportionally with W for W ≤ 10 m (Figure 5.9).

For the narrowest reef W = 0 m, the wave-focusing effect was marginal. However, for W = 5 m and 10 m, wave-focusing effects were much greater but increased marginally for W = 15 m and 20 m.

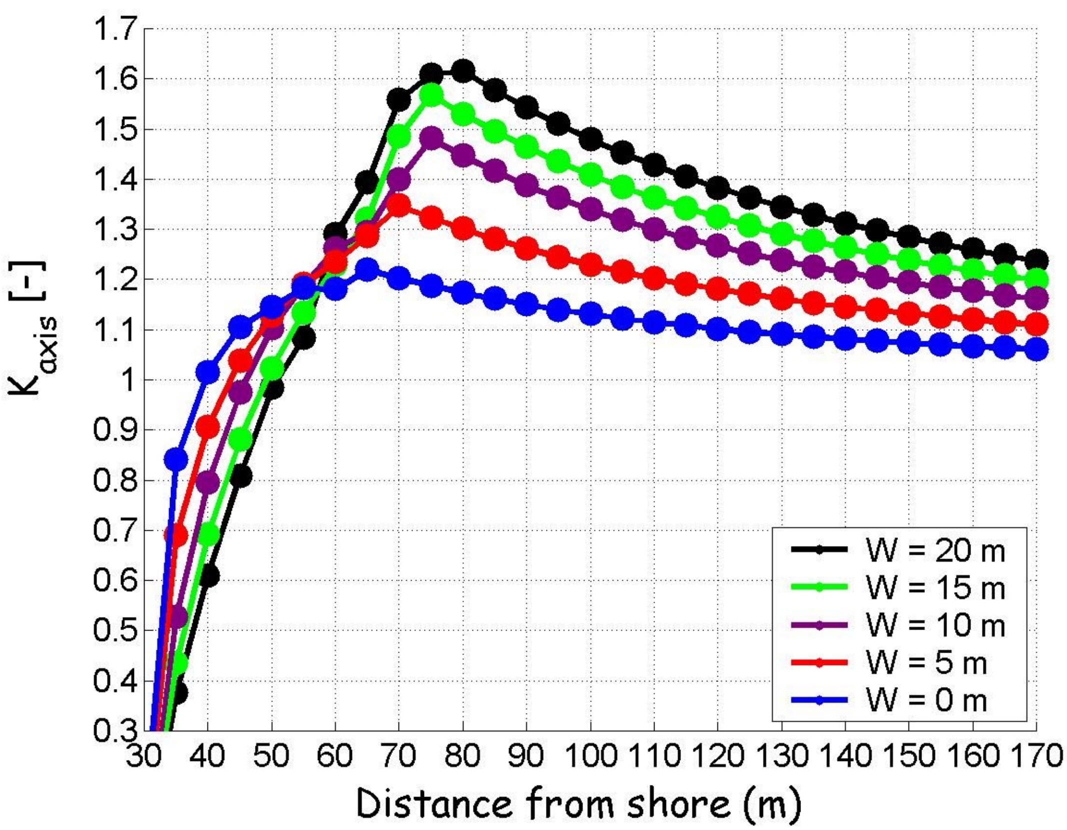

Figure 5.18: Wave factor along reef axis (K_{axis}) related to distance from shore, for infinitely long reefs with reef height of 1.5 m and various reef widths (W), which are given in the legend.

5.3 Influence of reef length

5.3.1 Influence of reef length on breaker distance

In Figure 5.19, the effect of varying reef length (Λ) of shore-connected reefs on X_{reef} is presented for D = 1.5 m and W = 5 m.

X_{reef} increased proportionally with Λ for reefs with Λ of 40 m up to 65 m. Thus, waves started to break at the seaward tip of the reef. However for reefs with Λ of 70 up to 90 m, X_{reef} did not increase and was constant at 65 m, thus wave breaking occurred on the reef. This was also the expected value for X_{reef} due to the seaward bed offset caused by the reef; i.e., the sum of X_γ = 30 m, and X_{beach} = 35 m. Therefore, for reefs with Λ < 95 m, X_{reef} was not augmented due to wave focusing (X_{focus} = 0 m). However for reefs with $\Lambda \geq 95$ m, X_{reef} was 70 m, and the distance attributable to wave focusing (X_{focus}) was 5 m. Thus Λ > 95 m, would not result in a greater X_{focus} (see Figure 5.19 and Appendix C.2).

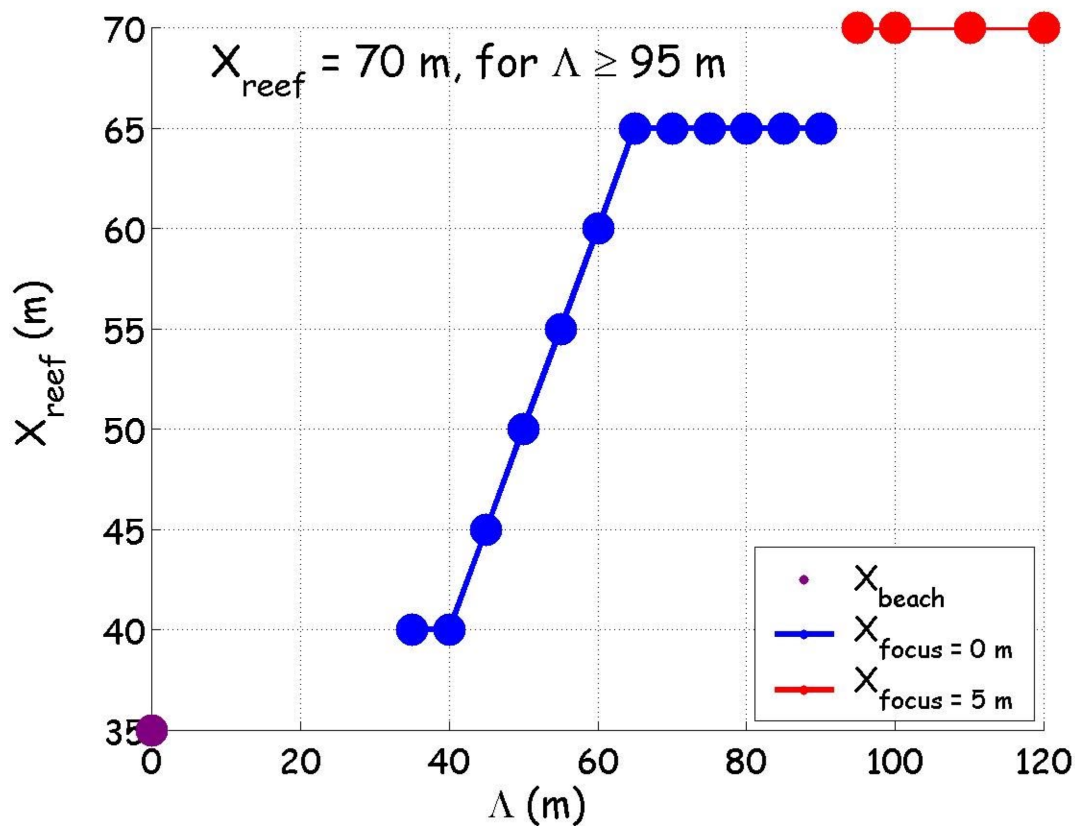

Figure 5.19: Breaker distance (X_{reef}) related to reef length (Λ) for shore-connected reefs with W = 5 m and D = 1.5 m. The augmented breaker distances (X_{focus}) are given in the legend. Λ = 0 m is the plane case (no reef, X_{focus} = 0 m).

5.3.2 Influence of reef length on breaker height

In Figure 5.20, the effect of Λ on H_{reef} is presented. For reefs with $\Lambda \leq 65$ m, wave breaking occurred at the end of the reef and for Λ of 40 up to 60 m, H_{reef} decreased with increasing Λ. For $\Lambda > 65$ m, waves broke on the reef, and H_{reef} increased with Λ. The increase of H_{reef} with Λ ($dH_{reef}/d\Lambda$) was greatest for Λ of 70 m to 90 m and thus wave-focusing effects were becoming more obvious. However when Λ = 95 m, there was an inconsistency in the trend of $dH_{reef}/d\Lambda$ (see Figure 5.20). For $\Lambda \geq 95$ m, X_{reef} increased with 5 m due to wave focusing.

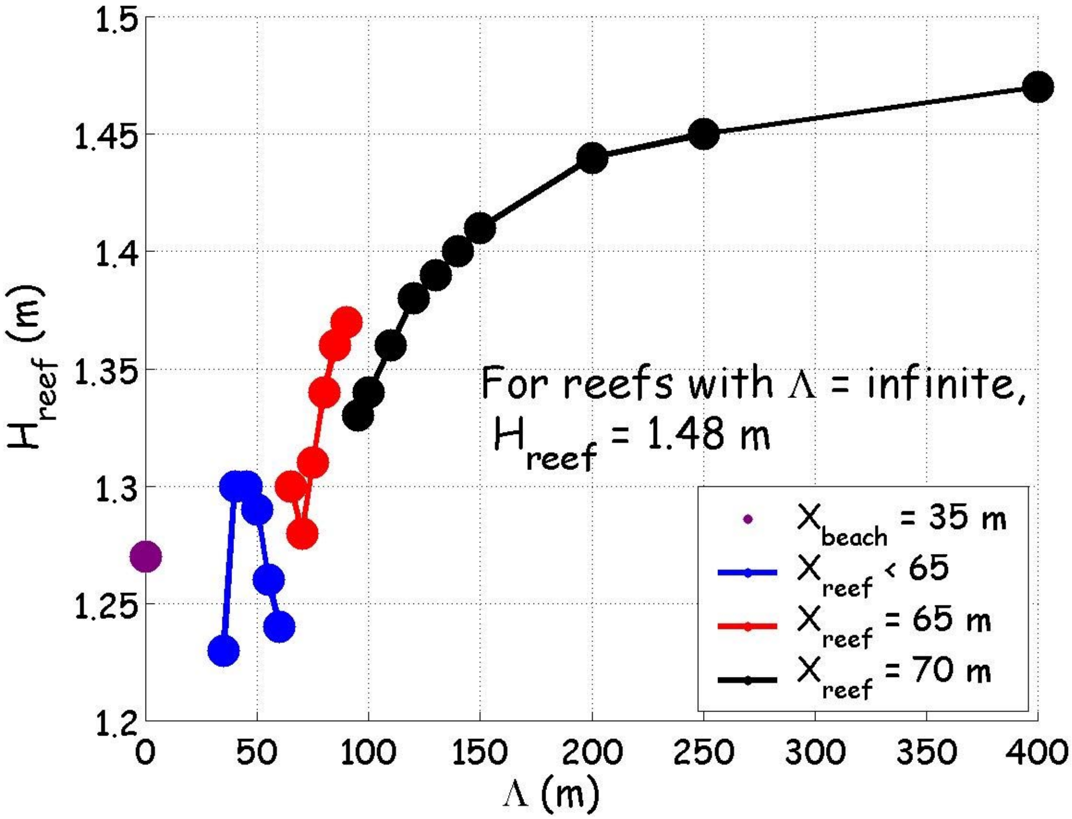

Figure 5.20: Breaker height (H_{reef}) related to reef length (Λ) for shore-connected reefs with W = 5 m and D = 1.5 m. The breaker distances (X_{reef}) are given in the legend. Λ = 0 m is the plane case (no reef).

The relationship between, K_{focus} and relative reef length (Λ_{rel}, see Section 3.3.3) is shown in Figure 5.21. For $\Lambda_{rel} > 2$, K_{focus} increased with increasing Λ_{rel}. The trend of $dK_{focus}/d\Lambda_{rel}$ was greatest for values of Λ_{rel} 2 up to 3, where K_{focus} increased from 1.0 up to 1.1. A further increase of $\Lambda_{rel} > 4$, where $K_{focus} = 1.1$ showed diminishing marginal returns. For $\Lambda_{rel} = 11.53$, $K_{focus} = 1.16$ and for infinitely long reefs the maximum for $K_{focus} = 1.17$.

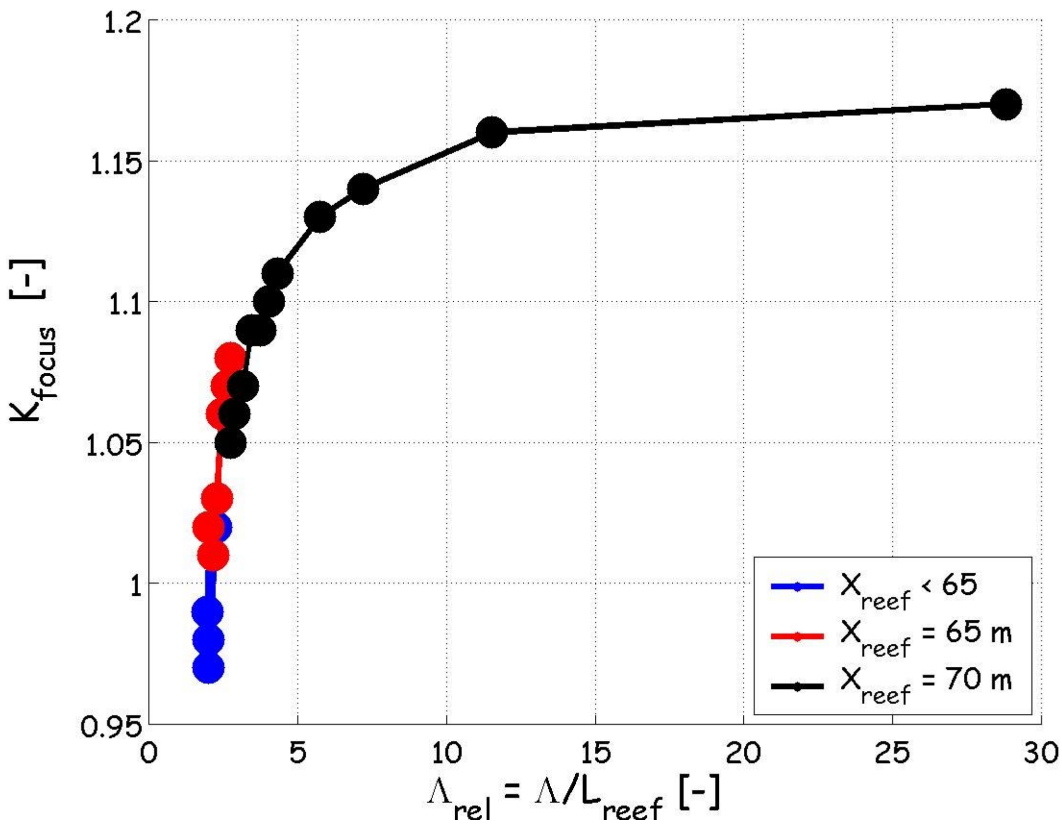

Figure 5.21: Wave-focusing factor (K_{focus}) related to relative reef length (Λ_{rel}) for shore-connected reefs, with W = 5 m and D = 1.5 m. The breaker distances (X_{reef}) are given in the legend.

Thus for a reef with W = 5 m and D = 1.5 m, wave focusing occurs ($K_{focus} > 1$) for $\Lambda_{rel} > 2$. In addition for $\Lambda_{rel} > 2.7$, the surf zone width was augmented due to focusing effects ($A_{focus} = 1.08$) but did not increase with a further increase of Λ_{rel} (see Appendix C.2).

5.3.3 Wave-focusing effects along reef axis

The influence of Λ on K_{axis} along reef axis was compared for reefs with D = 1.5 m, W = 5 m and for Λ = 60 m, 80 m, 130 m and 1000 m (where Λ_{rel} = 1.99, 2.45, 3.75 and 28.82, respectively). In Figure 5.22, K_{axis} is plotted against the distance from shore (x).

For Λ = 1000 m (the infinite length reef), K_{axis} increased from the start as waves travelled to shore (Figure 5.22). For the finite length reefs $K_{axis} = 1$ for $x > \Lambda$, and thereafter K_{axis} increased towards shore. The maximum values for K_{axis} were 1.10, 1.20, 1.26 and 1.35 for Λ = 60 m, 80 m, 130 m and 1000 m, respectively (Figure 5.22).

For the reef with Λ = 60 m, wave breaking occurred at the end of the reef and thus, only for Λ = 60 K_{axis} > 1. For the reef with Λ = 80 m the increase of K_{axis} at the end of the reef was greater than for the reef with Λ = 130 m.

For the shortest reef Λ = 60 m, the wave-focusing effect was marginal, but for Λ > 60 m wave-focusing effects increased from the start of the reef (which was also seen in Section 5.3.2.).

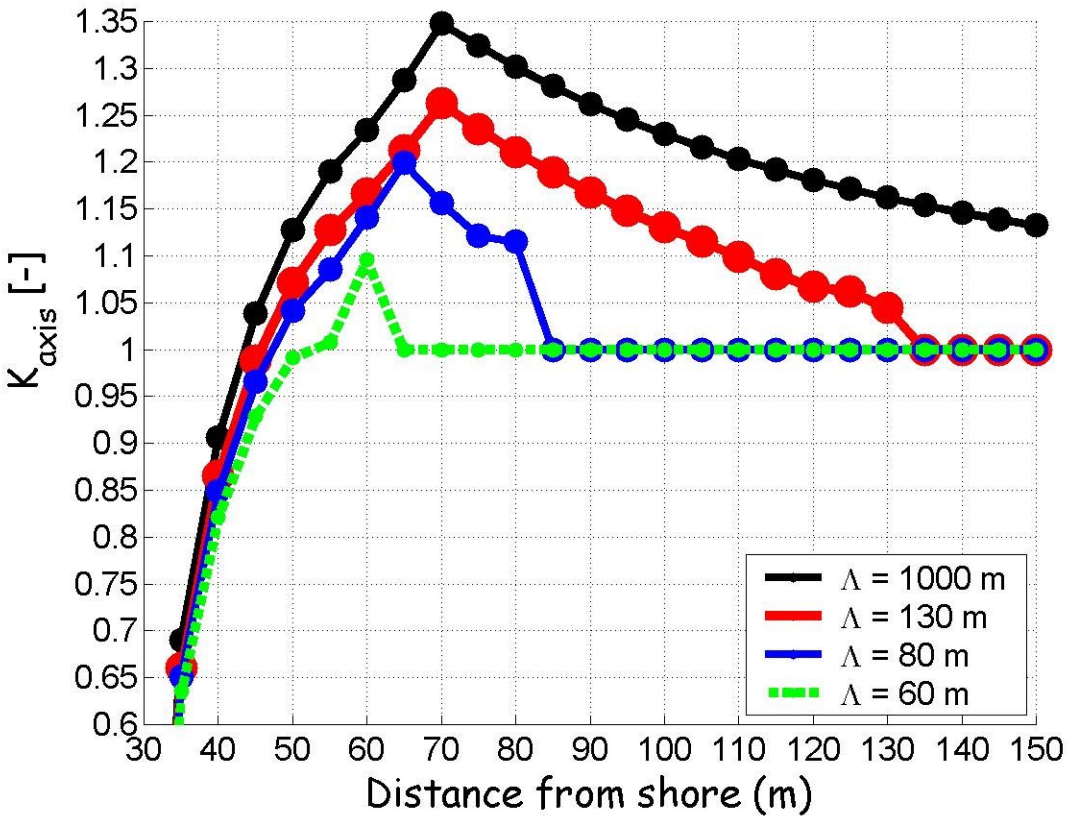

Figure 5.22: Wave factor along reef axis (K_{axis}) related to distance from shore, for shore-connected reefs with reef height of 1.5 m, width of 5 m and various lengths (Λ), which are given in the legend.

5.4 Influence of reef position offshore

5.4.1 Influence of reef position on breaker distance

In Figure 5.23 presents the effect of varying reef position (X_{OP}, see Section 3.2.2 and 4.4.6) of shore-detached reefs of semi-infinite length with D = 1.5 m and W = 5 m, on X_{reef}.

X_{reef} was 70 m for the shore-connected reef (X_{OP} = 0 m) and X_{reef} was augmented due to wave focusing, where X_{focus} = 5 m (see Section 5.4.1). For the reef with X_{OP} = 35 m, where the shoreward end of the reef was placed at the seaward end of the surf zone (i.e., $X_{OP} = X_{beach}$), X_{reef} was also 70 m, thus wave breaking occurred on the sloping part of the reef and X_{focus} = 5 m. For X_{OP} = 40 m, the reef was positioned 5 m beyond the surf zone (compared to the plane case), X_{reef} = 50 m and wave breaking started on the horizontal shoreward end of the reef (see Figure 4.5). However for reefs with 45 m ≤ X_{OP} ≤ 100 m, X_{reef} was constant at 40 m, thus waves broke after passing the reef. For reefs with X_{OP} > 100 m, waves also broke after passing the reef where X_{reef} = 35 m, thus X_{reef} was the same as for the plane case without reef (i.e., $X_{reef} = X_{beach}$).

Thus for X_{OP} ≥ 45 m, when reefs are placed seaward of the surf zone, waves break after passing the reef.

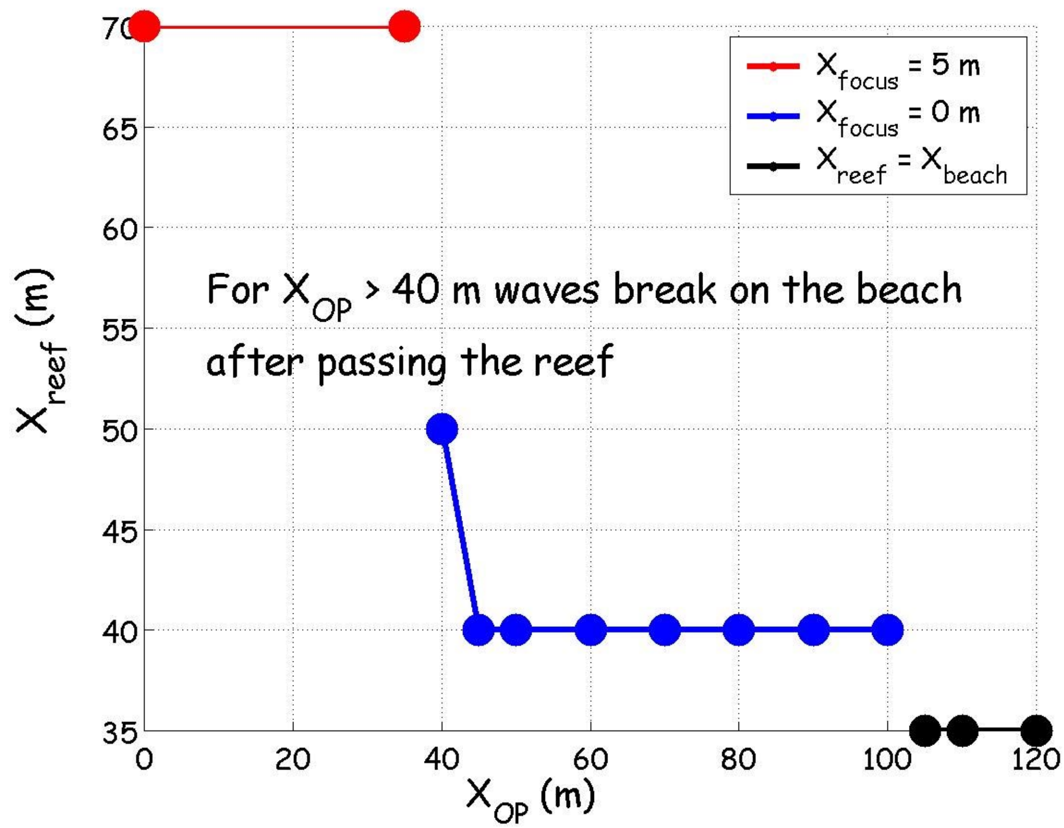

Figure 5.23: Breaker distance (X_{reef}) related to reef position (X_{OP}) for reefs, which extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m. The augmented breaker distances (X_{focus}) and when the breaker distances are the same as for the plane case (no reef, X_{beach} = 35 m) are given in the legend.

In Figure 5.24, A_{focus} is plotted against the ratio of the minimum water depth over the reef (h_{min}, see Sections 3.2.2 and 4.4.6) and the breaker depth (h_{reef}). For $h_{min}/h_{reef} < 1$, wave breaking occurred on the sloping part of the reef and $A_{focus} = 1.08$, thus X_{reef} was augmented due to wave focusing. When $h_{min}/h_{reef} = 1$, wave breaking occurred on the horizontal shoreward section of the reef, where A_{focus} was 0.77.

For the reefs where wave breaking occurred shoreward of the reef, the values for $h_{min}/h_{reef} > 1$ were the same as for X_{OP}/X_{reef}. However the use of h_{min}/h_{reef} is preferred because a value of 1 means wave breaking occurs on the horizontal part of the reef, otherwise the value for X_{OP}/X_{reef} would then be < 1. For $1.13 \leq h_{min}/h_{reef} \leq 2.50$ and for $h_{min}/h_{reef} \geq 3$, A_{focus} was 0.62 and 0.54, respectively. Thus for the reefs with $X_{OP} \leq 40$ m, when $h_{min}/h_{reef} \leq 1$, wave breaking occurred on the reef, which is the conventional approach to surfing reefs. For the reefs with $X_{OP} > 40$ m, when $h_{min}/h_{reef} > 1$, waves broke after they had passed the reef, which is the aim of a wave focusing reef.

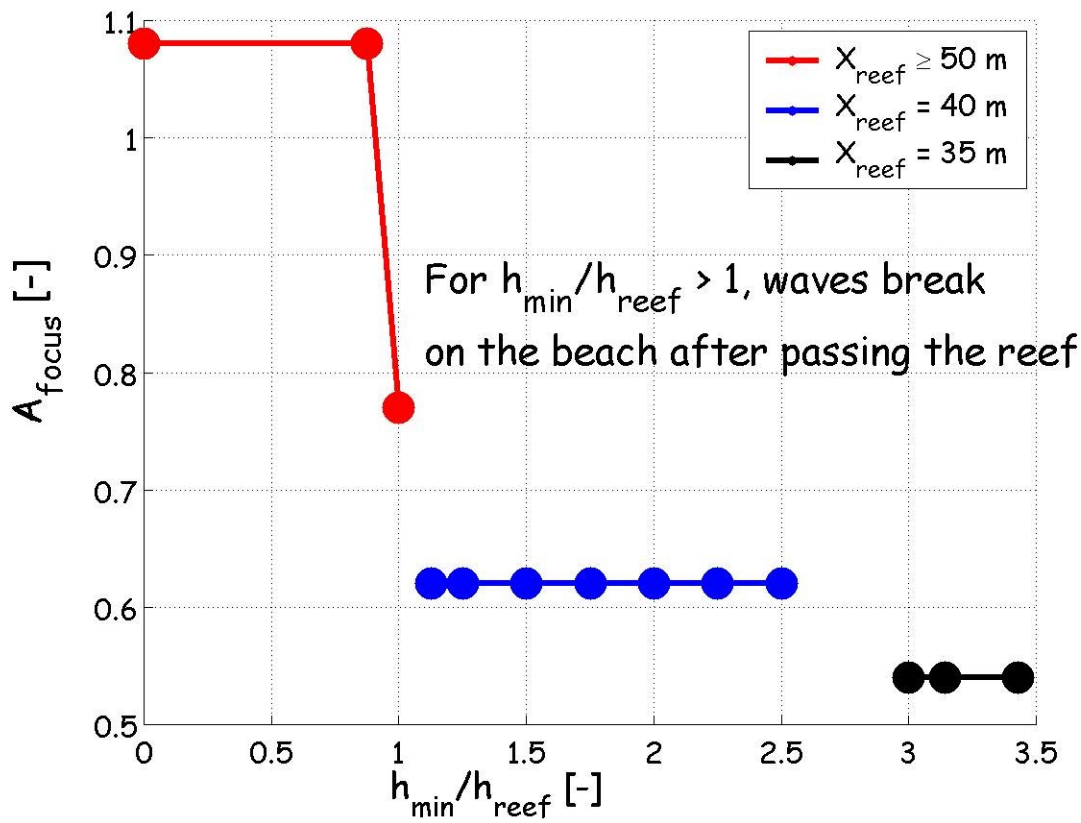

Figure 5.24: Relative augmented breaker distance (A_{focus}) related to the ratio of the minimum water depth over the reef (h_{min}) and the breaker depth (h_{reef}), for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m. $A_{focus} > 1$ means that the surf zone width is augmented due to wave focusing. The breaker distances (X_{reef}) are given in the legend.

5.4.2 Influence of reef position on breaker height

The effect of X_{OP} on H_{reef} is presented in Figure 5.25. For reefs with $X_{OP} \leq$ 35 m, thus within the surf zone, H_{reef} was constant at 1.48 m. H_{reef} was maximum at 1.51 m, for the reef with X_{OP} = 40 m, where wave breaking occurred on the shoreward tip of the reef. For the reefs with X_{OP} of 45 m up to 100 m, H_{reef} decreased with increasing X_{OP} from H_{reef} of 1.49 m to 1.34 m. However when X_{OP} = 105 m, there was an inconsistency in the trend of dH_{reef}/dX_{OP}. For $X_{OP} \geq$ 105 m, X_{reef} was 5 m smaller than for reefs with 45 m $\leq X_{OP} \leq$ 100 m and therefore waves shoaled longer before breaking. For X_{OP} = 105 m, H_{reef} was 1.37 m and decreased with increasing $X_{OP.}$

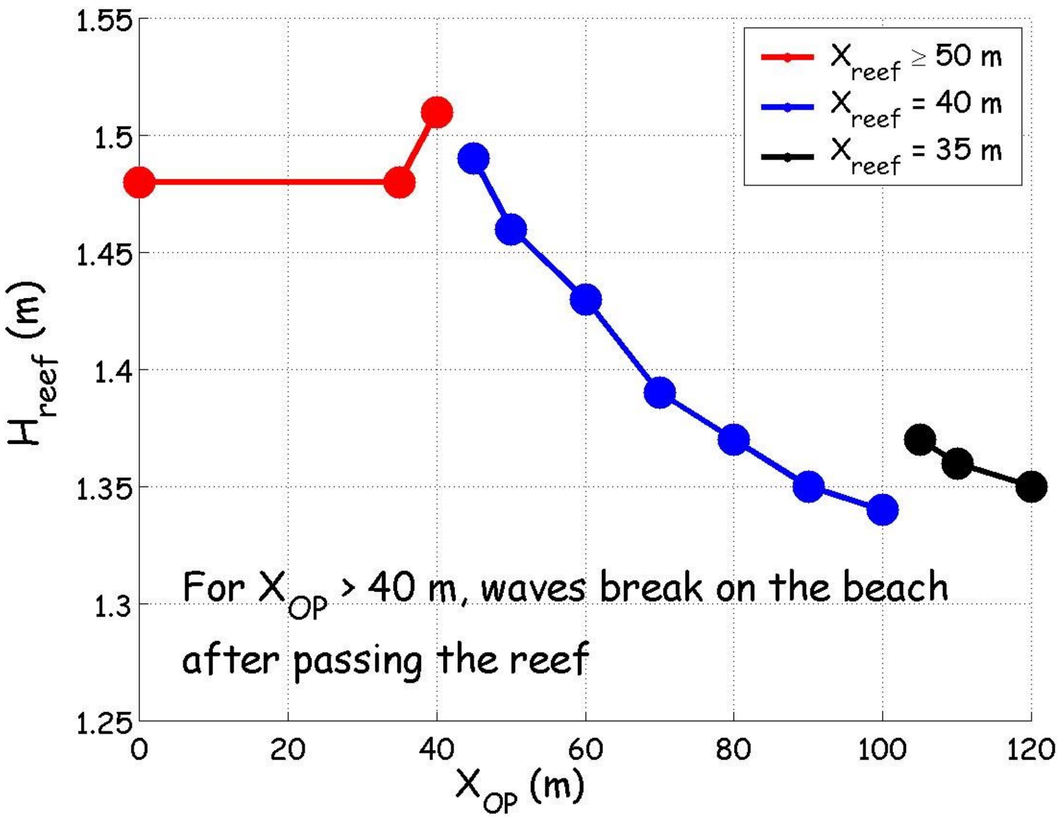

Figure 5.25: Breaker height (H_{reef}) related to reef position (X_{OP}), for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m. The breaker distances (X_{reef}) are given in the legend.

The relationship between K_{focus} and h_{min}/h_{reef} is presented in Figure 5.26. K_{focus} was 1.17, for $h_{min}/h_{reef} < 1$, for waves breaking on the sloping part of the reef. The maximum value for K_{focus} was 1.19 for $h_{min}/h_{reef} = 1$, when wave breaking occurred on the horizontal part of the reef. For $1.13 \leq h_{min}/h_{reef} \leq 2.5$, K_{focus} decreased from 1.17 to 1.06 with increasing h_{min}/h_{reef}. And for $3.0 \leq h_{min}/h_{reef} \leq 3.43$, K_{focus} decreased from 1.08 to 1.06 with increasing h_{min}/h_{reef}. The inconsistency in the trend of K_{focus} and h_{min}/h_{reef} between h_{min}/h_{reef} of 2.5 to 3.0 can be explained by the change in X_{reef} (see Figure 5.26).

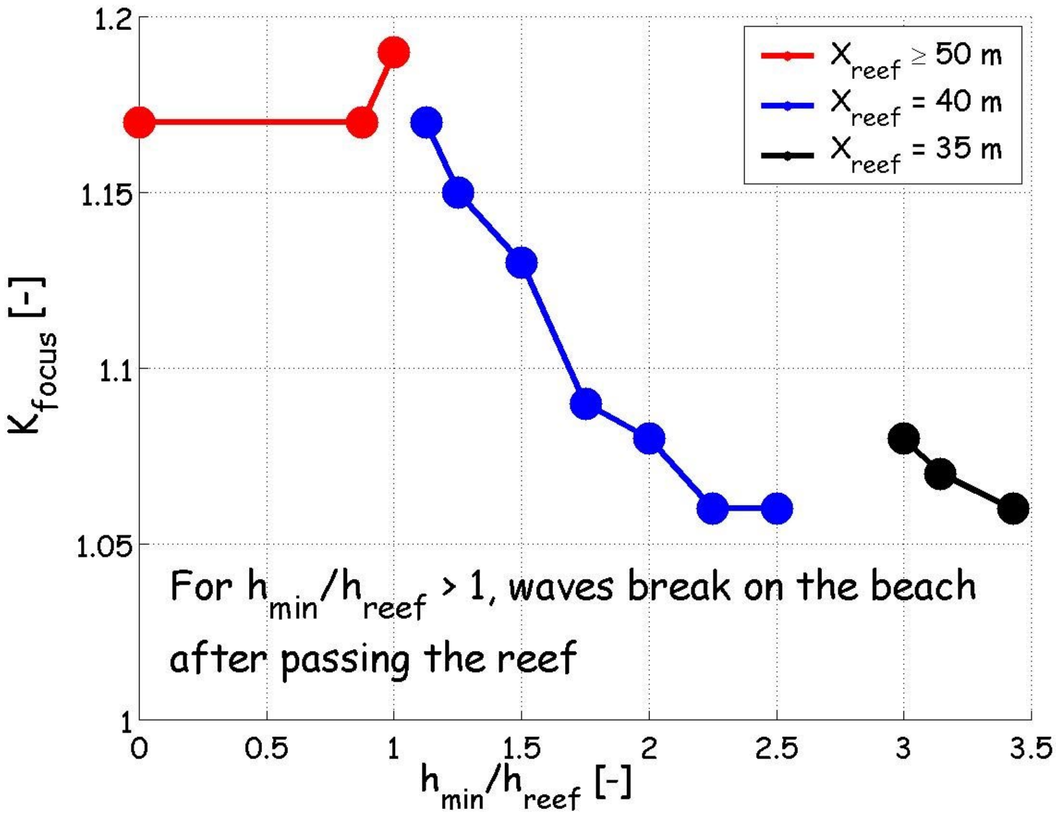

Figure 5.26: Wave-focusing factor (K_{focus}) related to the ratio of reef position (X_{OP}) and breaker distance (X_{reef}), for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m. The breaker distances (X_{reef}) are given in the legend.

5.4.3 Wave-focusing effects along reef axis

In Figure 5.27, H_{axis} is plotted against the distance from shore (x). For the reef with X_{OP} = 105 m, H_{axis} increased towards the shore until x = 35 m, where waves started to break. However H_{axis} was constant from x = 105 m to 135 m; i.e., over the horizontal part of the reef from x = X_{OP} to x = X_{OP} + $X\gamma$, where $X\gamma$ = 30 m. For X_{OP} = 45 m and 70 m, the trend of H_{axis} with x was similar to that of X_{OP} = 105 m, thus H_{axis} increased towards the shore and was constant for x = X_{OP} to x = X_{OP} + $X\gamma$, and thereafter increased until x = X_{reef}. However for the reef with X_{OP} = 35 m, H_{axis} increased towards shore up until breaking occurred on the sloping part of the reef.

For reefs with X_{OP} > 40 m, where waves break after passing the reef, the peak in the wave crest was of constant height from x = X_{OP} + $X\gamma$ to x = X_{OP}, and thereafter increases until wave breaking occurred at x = X_{reef}.

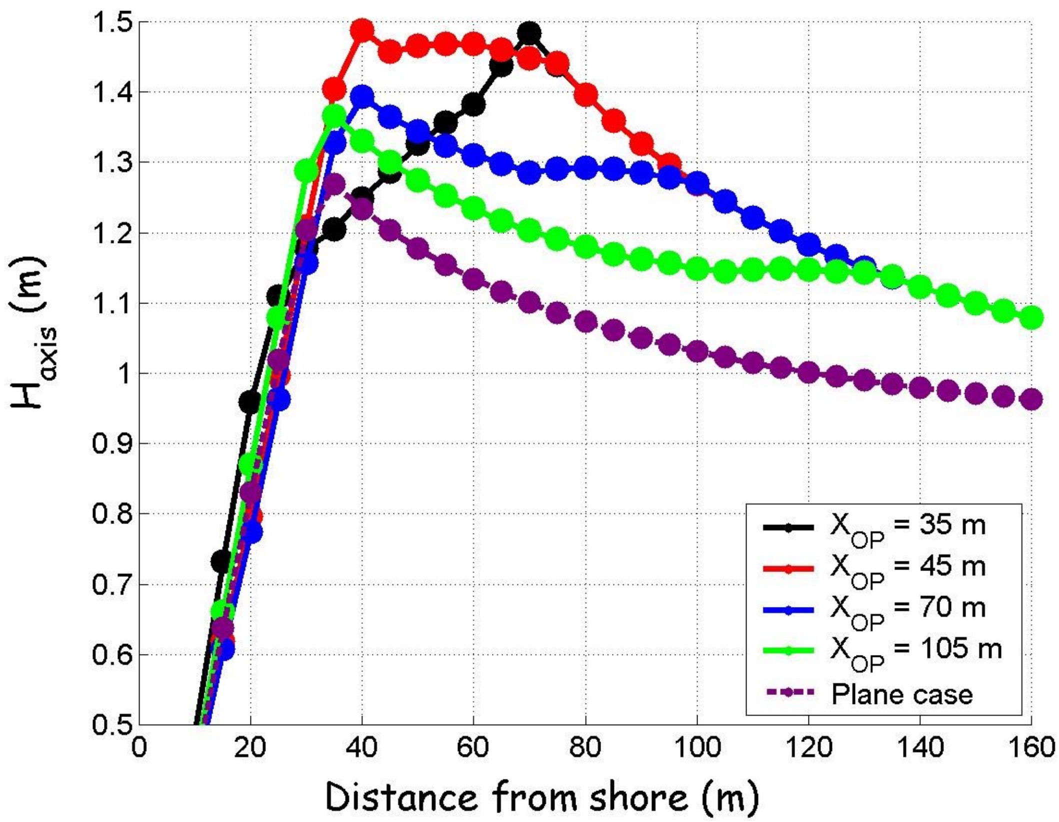

Figure 5.27: Wave height along reef axis (H_{axis}) related to distance from shore, for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m, and various reef positions (X_{OP}) which are given in the legend.

In Figure 5.28, K_{axis} is plotted against distance from the shore (x), in order to show how the relative increase in wave height along the reef axis varies as waves travel towards the shore.

For the reefs with X_{OP} = 45 m, 70 m and 105 m, K_{axis} increased towards shore until $x = X_{OP} + X\gamma$, which is at x = 75 m, 100 m and 135 m, where K_{axis} was maximum at 1.33, 1.23 and 1.16, respectively. For these reefs, K_{axis} decreased most over the horizontal part of the reef, which was from $x = X_{OP} + X\gamma$ to $x = X_{OP}$ until breaking occurred.

For X_{OP} = 35 m, K_{axis} increased towards shore up until x = 70 m (i.e., X_{reef}), where K_{axis} was maximum at 1.35.

Reefs should be placed far enough beyond the surf zone so that waves do not break on the reef, however for optimum effect, a reef should be placed close enough to the surf zone.

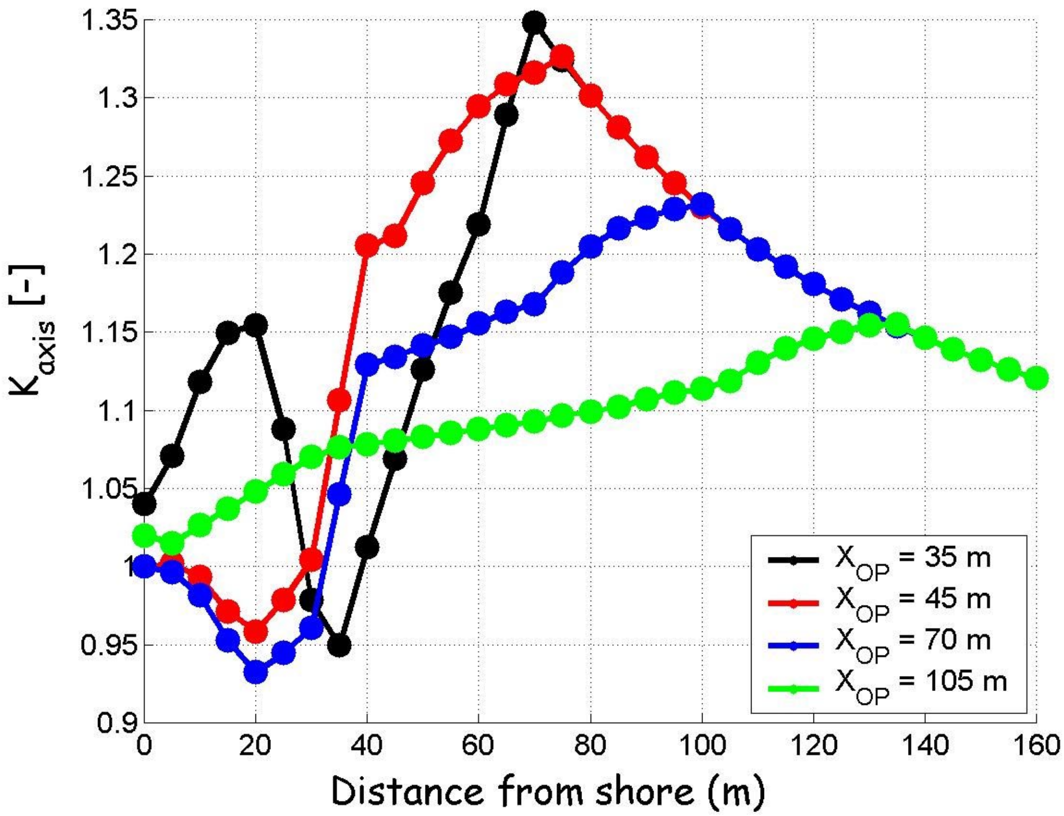

Figure 5.28: Wave factor along reef axis (K_{axis}) related to distance from shore, for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m, and various reef positions (X_{OP}) which are given in the legend.

5.4.4 Influence of reef on spatial variation of wave breaking

For a reef with X_{OP} of 35 m a plot of the instantaneous surface elevation has been presented in Figure 5.29. For this case where the wave starts breaking on the side of the reef, the peel rate (α, see Section 2.2.4) can be determined. For X_{OP} = 35 m, the peel rate is approximately 40 degrees.

For the reefs with X_{OP} is 40 m and 45 m, it is not possible to determine the peel rate (see Figures 5.28 and 5.29). This is because the break points can only be determined to the resolution of the bathymetry grid, which is 5 m.

Simulations with numerical models might not give a reliable picture for determining wave peel in detail. Breakpoint criteria give a wide range of relations. Dynamics in the region of the overturning crest, such as instability induced along the crest by the antecedent instability, may be critical to wave peel [Cowell 2002]. That is, subsequent breaking further along the crest may be induced by the previous breaking at the peak. This is known to surfers from the effects of a drop in; the wave, which is makeable for the first surfer (the rightful owner of the wave), often closes out for this surfer because the drop in surfer causes an instability in the crest that causes the wave to break at the point of the drop in take off [Cowell 2002]. With the rightful owner of the wave is meant that the surfer closest to the breaking section of the wave has the right (of way) to surf the wave and therefore the surfer further away from the breaking section should not take-off (surf etiquette).

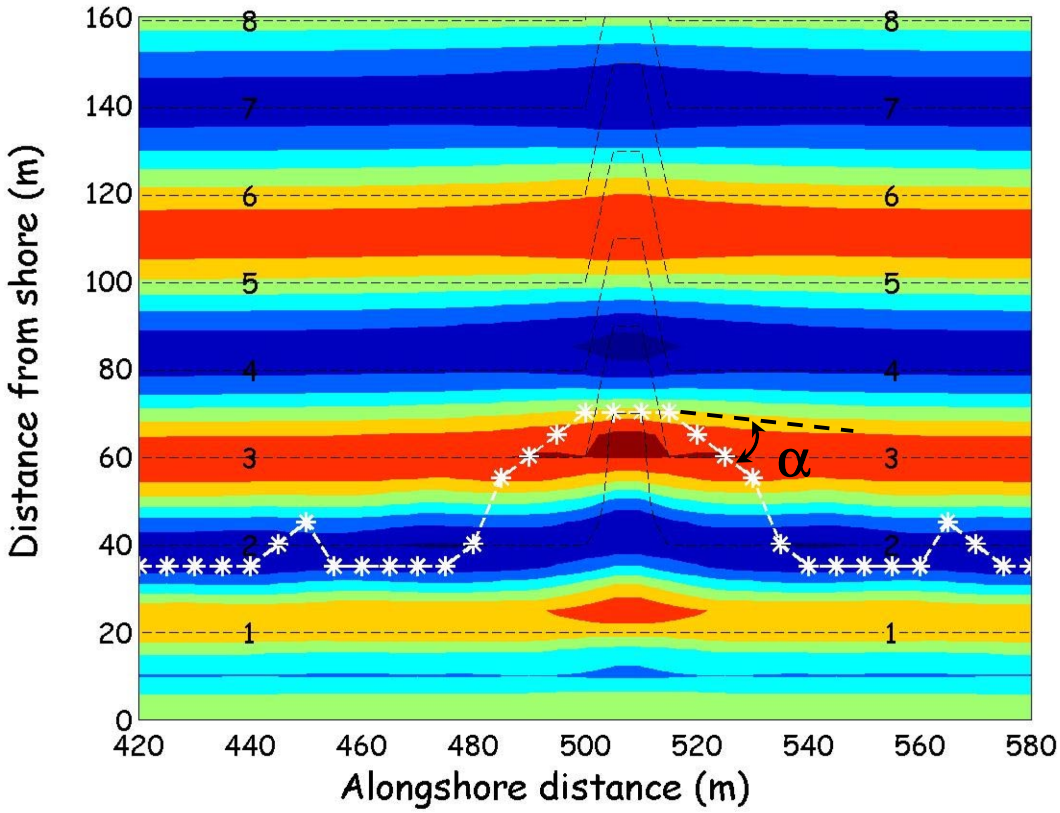

Figure 5.29: Instantaneous surface elevation for reef positioned 35 m from shore, which extends to the offshore boundary of the modelling grid with reef height of 1.5 m and width of 5 m. The black dashed lines are depth contours where the numbers denote the local water depths. The white dashed line is the breaker line, where the calculated breakpoints are given by a *. On either side of the reef the peel angle (α) is 40^0 approximately. At alongshore a distance of 450 m and 570 m, the breakerline is not straight as on either sides, for an unknown reason.

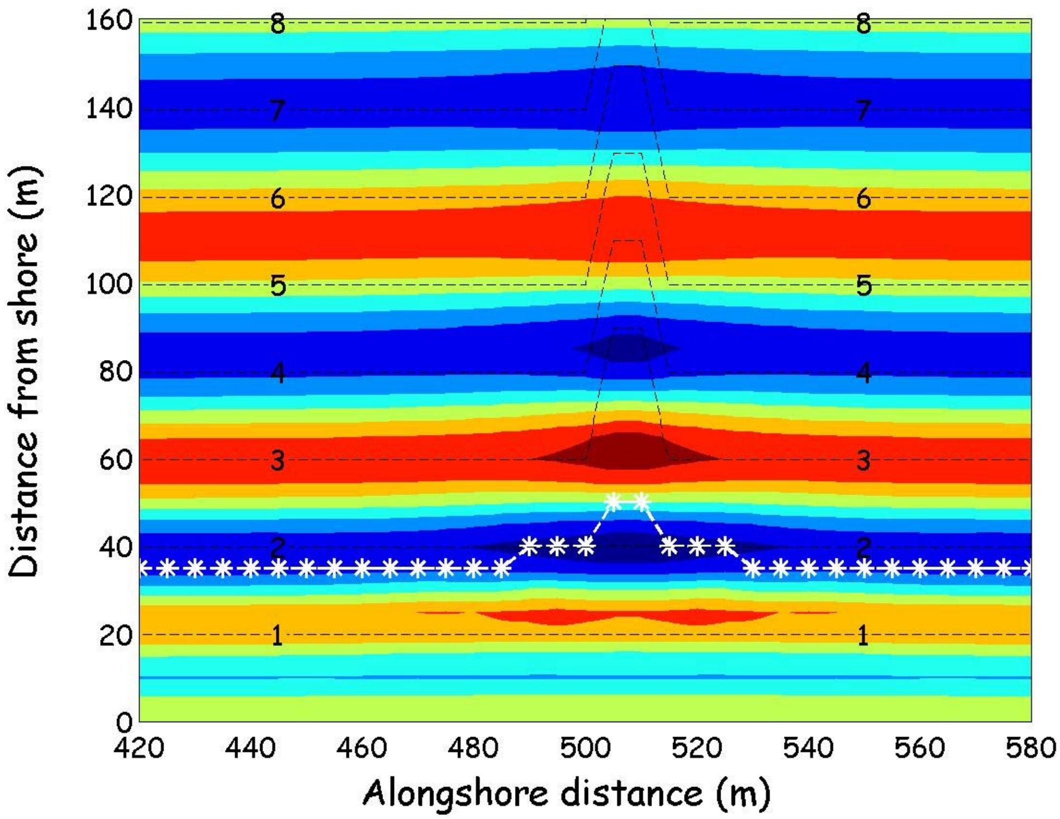

Figure 5.30: Instantaneous surface elevation of reef positioned 40 m from shore, which extends to the offshore boundary of the modelling grid with reef height of 1.5 m and width of 5 m. The black dashed lines are depth contours where the numbers denote the local water depths. The white dashed line is the breaker line, where the calculated breakpoints are given by a *.

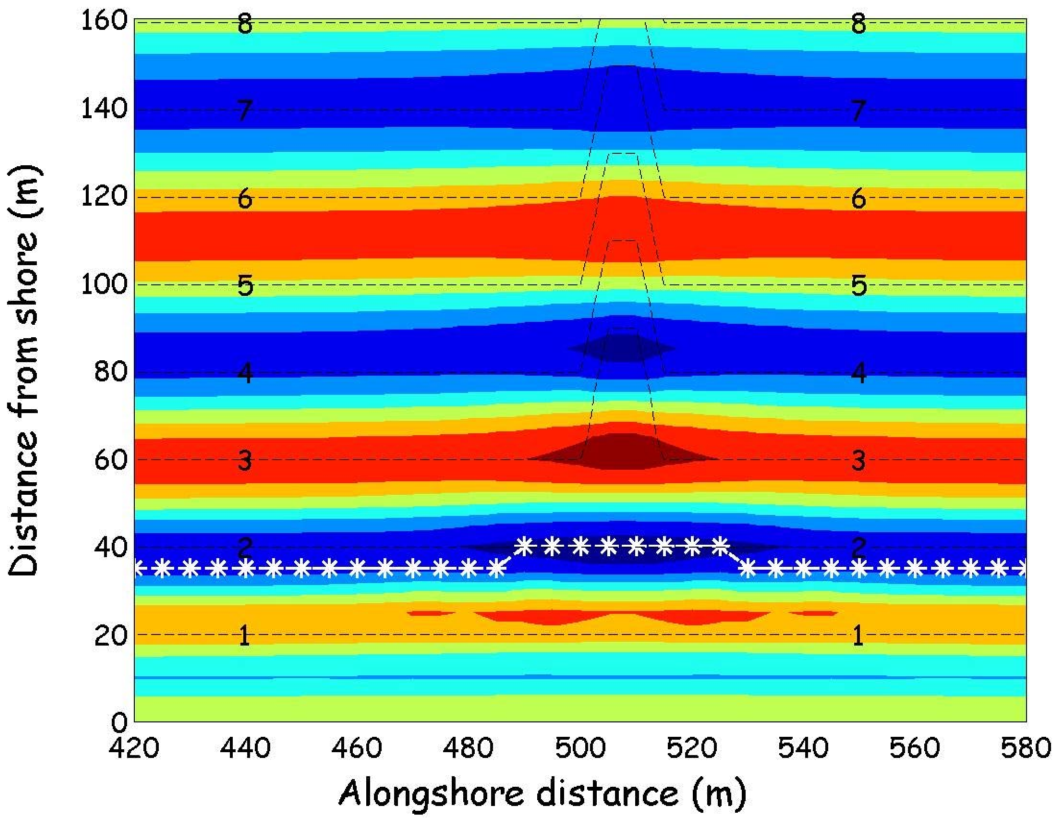

Figure 5.31: Instantaneous surface elevation of reef positioned 45 m from shore, which extends to the offshore boundary of the modelling grid with reef height of 1.5 m and width of 5 m. The black dashed lines are depth contours where the numbers denote the local water depths. The white dashed line is the breaker line, where the calculated breakpoints are given by a *.

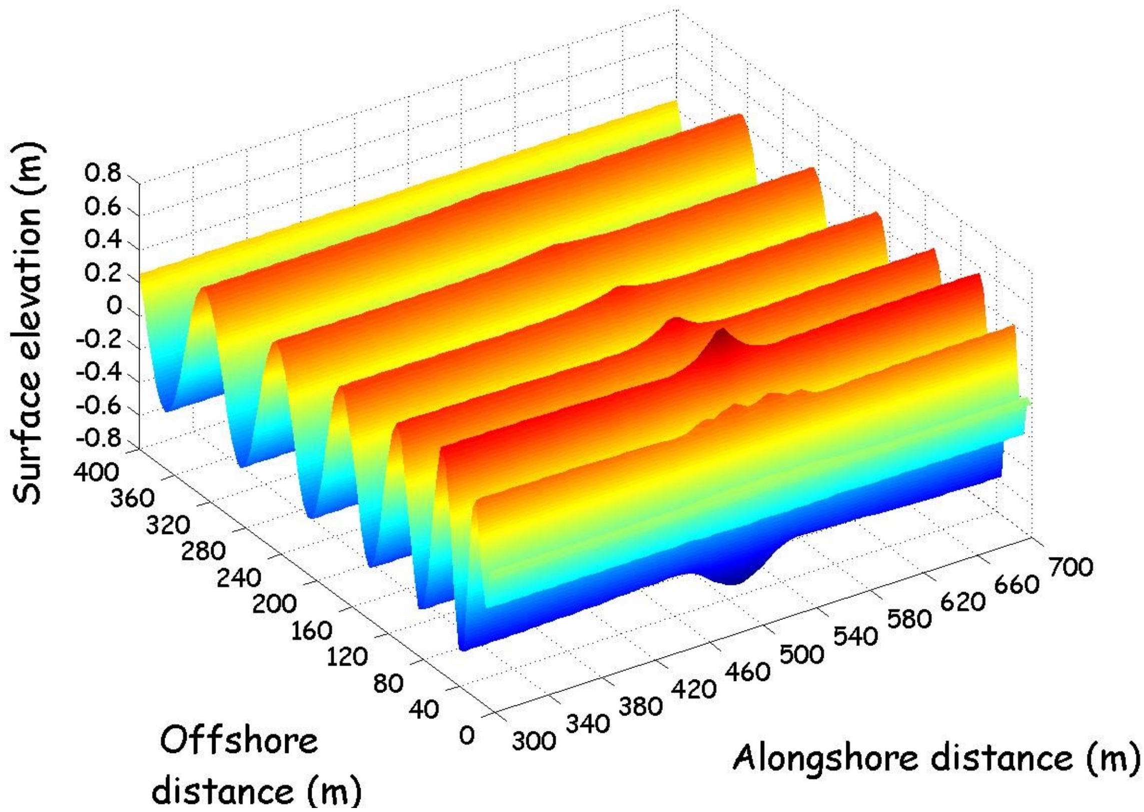

Figure 5.32: Water surface elevation for reef positioned 45 m from shore, which extends to the offshore boundary of the modelling grid with reef height of 1.5 m and width of 5 m.

5.5 Influence of wave period

For an infinitely long reef with W = 5 m and D =1.5 m, simulations were carried out of waves with H_0 = 1 m and varying T of 4 s, 8 s, 12 s and 16 s.
In Figure 5.33, K_{axis} is plotted against the distance from shore (x). The maximum values for K_{axis} were 1.60, 1.35, 1.17 and 1.11 for T = 4 s, 8 s, 12 s and 16 s, respectively (Figure 5.33). The maximum values for k_{axis} occurred at breakpoint but were larger than values for K_{focus} (see Table 5.3). Thus K_{focus} was greatest for lowest T, however for T = 12 s and 16 s K_{focus} was 1.01.

For the reef X_γ was 30 m, and the breaker distances attributable to wave focusing, X_{focus} were 5 m, 5 m and 0 m for T = 4 s, 8 s and 12 s, respectively. However, for T = 16 s, X_{reef} was 5 m less (i.e., X_{reef} – X_{beach} - X_γ) than would be expected due to the seaward bed offset. A_{focus} was greatest for lowest T of 4 s at 1.17, and A_{focus} was 1.08, 1.0 and 0.94 for T = 8 s, 12 s and 16 s, respectively.

Table 5.3: Parameters for waves with an offshore wave height (H_0) of 1 m and varying wave periods (T) breaking on a plane sloping beach and on an infinitely long reef with reef height of 1.5 m and width of 5 m.

T (s)	H_{beach} (m)	X_{beach} (m)	H_{reef} (m)	X_{reef} (m)	K_{focus} [-]	A_{focus} [-]
4	0.99	30	1.46	70	1.47	1.17
8	1.27	35	1.48	70	1.17	1.08
12	1.55	45	1.62	75	1.01	1.00
16	1.74	50	1.76	75	1.01	0.94

Thus for these simulations, waves with lower periods were influenced relatively most by the reef. However, the waves with T = 12 s and 16 s were not focused by the reef.

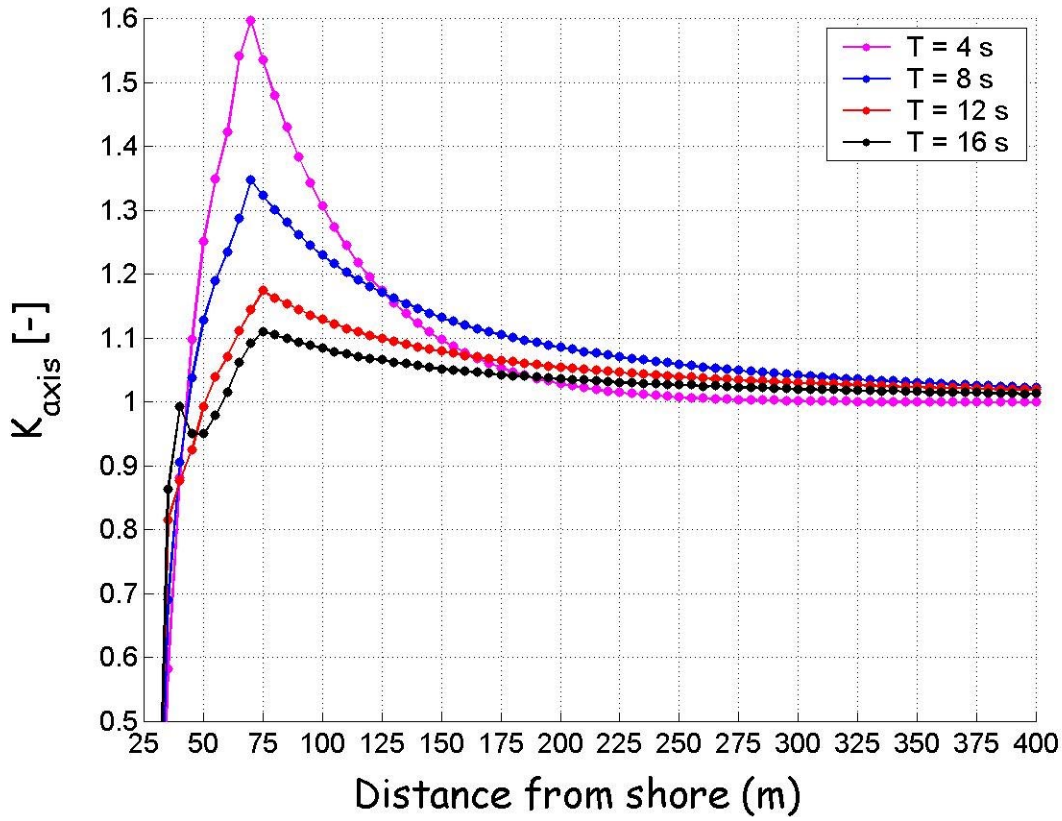

Figure 5.33: Wave factor along reef axis (K_{axis}) related to distance from shore, for infinitely long reefs with reef height of 1.5 m, width of 5 m for various wave periods (T), which are given in the legend.

For the simulations of varying T, the breaker types were compared with Iribarren numbers calculated with H_0 (ξ_0, see Section 2.2.3) and with the breaker heights (ξ_b, see Section 2.2.3), which are given in table 5.4. Because for all simulations H was 1 m, the wave steepness (H/L_0) was greater for waves with smaller T. Therefore waves with smaller T broke in a more spilling nature (or less plunging nature) than the waves simulated with greater T (i.e., spilling when $\xi_0 < 0.5$ and $\xi_b < 0.4$, see Section 2.2.3).

For T = 4 s and 8 s, H_{reef} was greater than H_{beach} and therefore ξ_b on the reef was smaller than ξ_b for the plane case. Thus, on the reef the waves broke in a more spilling nature. However for T = 12 s and 16 s, the reef had practically no wave-focusing effect and therefore there was very little difference in ξ_b for the plane case and on the reef.

Table 5.4: Iribarren numbers are given for waves with varying wave periods breaking on a plane sloping beach and on an infinitely long reef. The indices 0 and b denote to use of offshore wave height and breaker height, respectively.

T	ξ_0	ξ_b for plane case	ξ_b on reef
4	0.25	0.25	0.21
8	0.5	0.44	0.41
12	0.75	0.60	0.59
16	1.0	0.76	0.75

5.6 Generalising reef specifications

The influence of various combinations of reef dimensions such as reef height and width on breaker height and breaker distance were examined. First in Section 5.6.1, the influence of the West-Cowell surfing reef factor (S_{RF}, see Section 3.3.3) on wave-focusing factor (K_{focus}) was examined. In Section 5.6.2, the influence of S_{RF} on the relative augmented breaker distance (A_{focus}) was examined and in Section 5.6.3, other relationships were examined.

5.6.1 Influence of reef height and width on breaker height

The increased wave height due to the focusing effect of the reef can be related to the reef dimensions, which may be expressed in a dimensionless relationship.

In Section 5.2 it was shown that, the wave-focusing factor (K_{focus}) increased with the relative reef height (D_{rel}) for constant reef width (W) and that K_{focus} increased with the relative reef width (W_{rel}) for constant reef height (see Figure 5.8 and Figure 5.10). Therefore, a relationship was sought for K_{focus} with D_{rel} and W_{rel} combined.

K_{focus} increased proportionally with S_{RF} (Figure 5.34). Because S_{RF} is the product of D_{rel} and W_{rel}, this means that waves are focused proportionally to the area of the cross-section of the reef.

There was a close correlation between K_{focus} and S_{RF} for $S_{RF} < 0.4$. However for $S_{RF} > 0.4$, the correlation was not as strong. There were fewer points for these higher values of S_{RF} because only few simulations were conducted with very large D, such as 4 m and 8 m. These large reef heights were not regarded as realistic for a surfing reef, because such heights would not be economically or logistically feasible. The maximum value for S_{RF} when reefs with D = 4 m and 8 m are not included was 0.41.

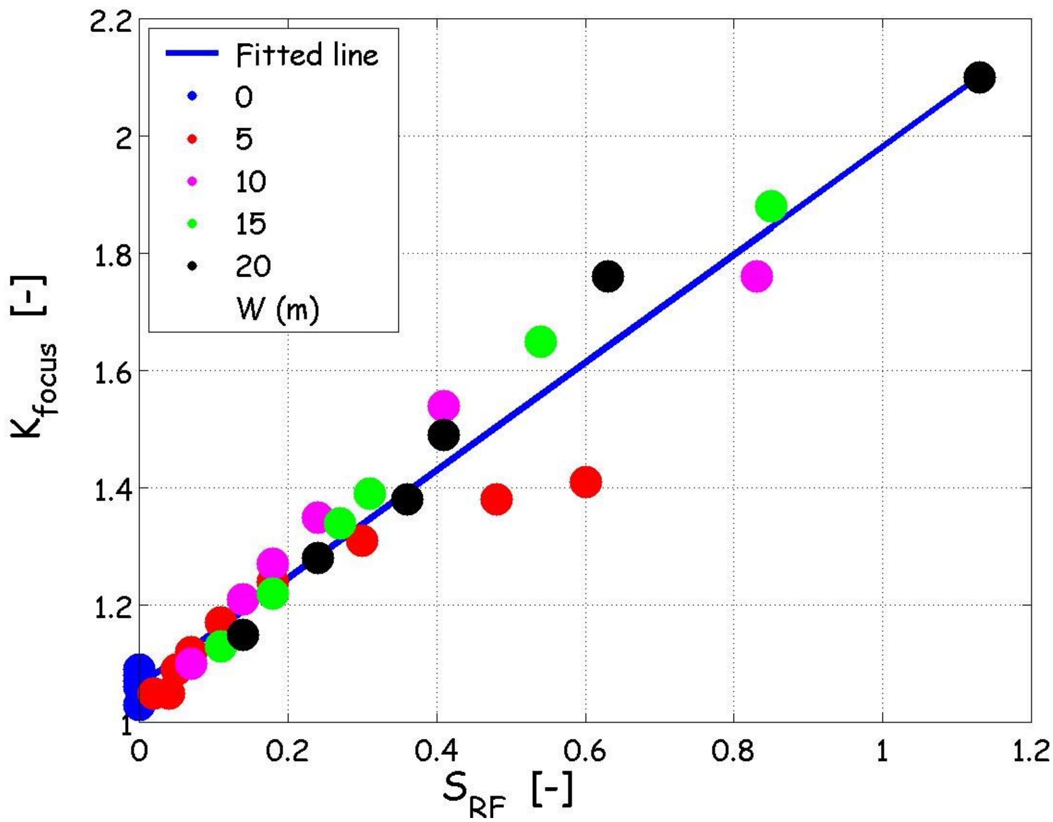

Figure 5.34: Wave focusing factor (K_{focus}) related to the West-Cowell surfing reef factor (S_{RF}) for infinitely long reefs. Points of the same colour represent reefs of constant width (W), which are given in the legend. A line of best fit has been fitted with the method of least squares.

5.6.2 Influence of reef height and width on breaker distance

In Figure 5.35, the augmented breaker distance (X_{focus}) has been related to the product of D and W (i.e., DW), which is not the cross-sectional area of the reef (i.e., DW + (5 m)D). X_{focus} increases with DW, however there is a large scatter of the points in the graph (Figure 5.35).

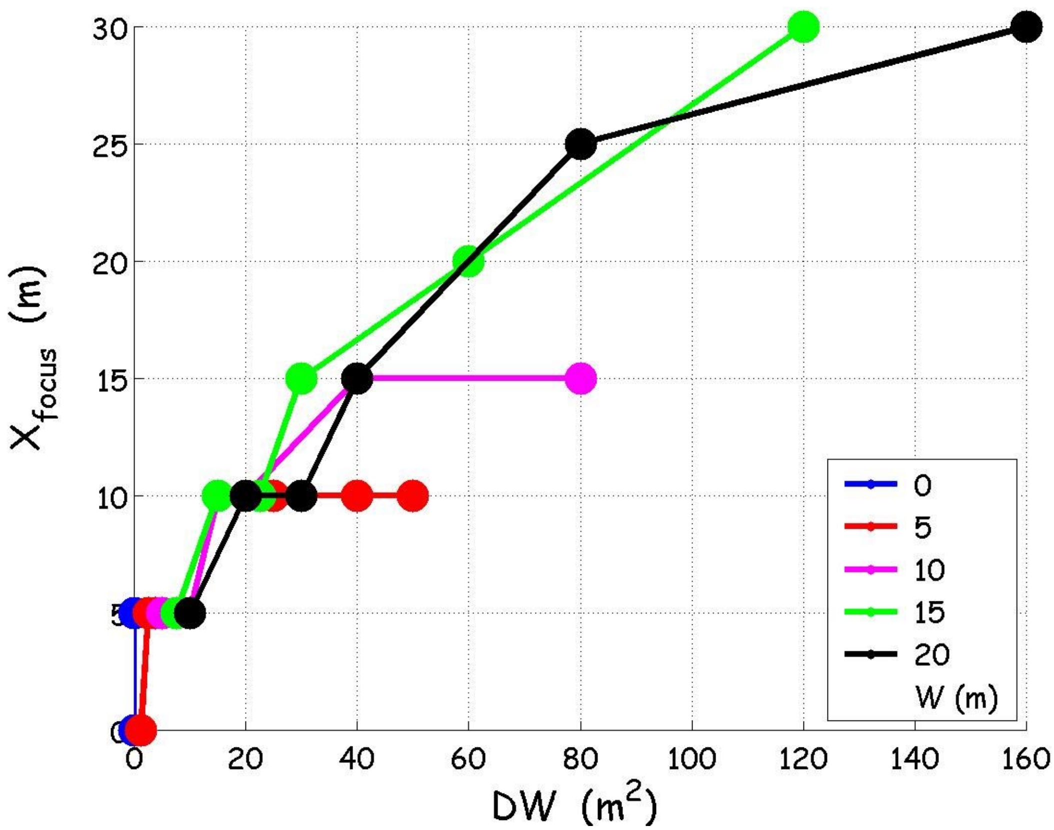

Figure 5.35: Augmented breaker distance (X_{focus}) related to the product of reef height (D) and reef width (W) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

In Figure 5.36, the relative augmented breaker distance (A_{focus}) is related to the West-Cowell surfing reef factor (S_{RF}). Unlike the increase of X_{focus} with DW, A_{focus} did not increase with S_{RF}. There is no relationship between A_{focus} and S_{RF}.

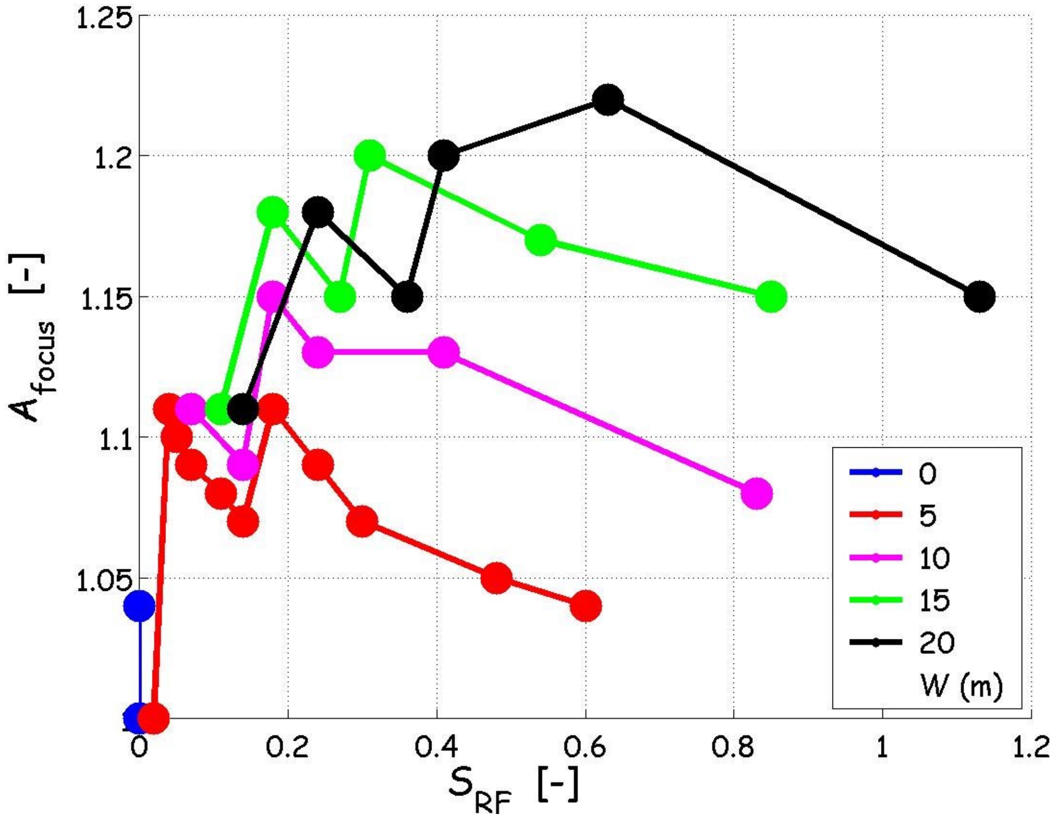

Figure 5.36: Relative augmented breaker distance (A_{focus}) related to the West-Cowell surfing reef factor (S_{RF}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

5.6.3 Wave focusing related to various parameters

In Figure 5.37, K_{focus} has been related to the ratio of relative reef height (D_{rel}) and relative reef width (W_{rel}): i.e.,

$$\frac{D_{rel}}{W_{rel}} = \frac{D}{h_{reef}} \frac{L_{reef}}{W} \tag{5.1}$$

K_{focus} increased with D_{rel}/W_{rel} for constant W (Figure 5.37). If lines were to be drawn through points of equal D, than K_{focus} would be seen to decrease with increasing D_{rel}/W_{rel} for constant D. The reefs with W = 0 m (thus W_{rel} = 0), were not included here, because D_{rel} would have to be divided by 0.

Thus, K_{focus} related to D_{rel}/W_{rel} does not provide a general relationship that relates wave focusing to reef dimensions.

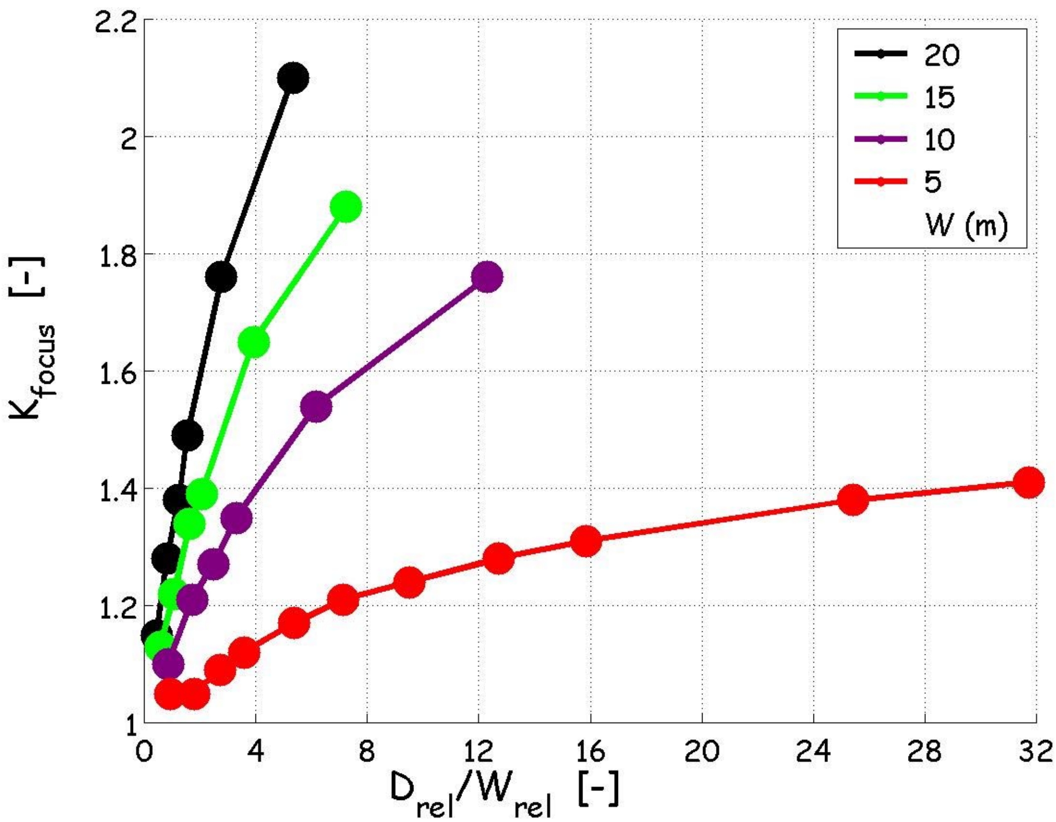

Figure 5.37: Wave focusing factor (K_{focus}) related to the ratio of relative reef height (D_{rel}) and relative reef width (W_{rel}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

In Figure 5.38, A_{focus} has been related to D_{rel}/W_{rel}. The trends of the lines of constant W resemble that of A_{focus} and D_{rel} (see Section 5.2, Figure 5.14).

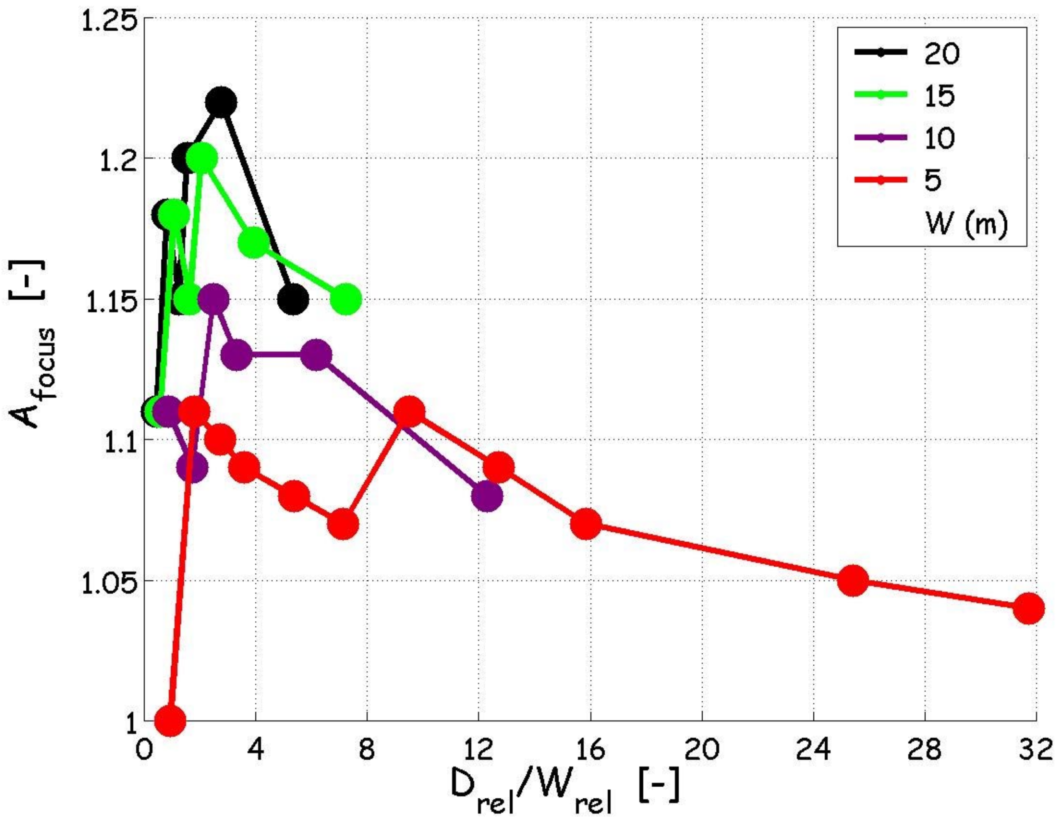

Figure 5.38: Relative augmented breaker distance (A_{focus}) related to the ratio of relative reef height (D_{rel}) and relative reef width (W_{rel}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

6 Discussion, recommendations and conclusions

The primary question asked in the research outlined in this thesis was: 'Can a wave-focusing surfing reef be created that will initiate early wave breaking in such a way that waves otherwise closing out can be made more surfable?' The research has clearly shown that the concept of wave-focusing surfing reefs is valid. Such submerged reefs allow waves to be focused and cause a peak in the wave crest where wave breaking will be initiated. Thus, waves will break earlier than they otherwise would. This makes the waves more surfable by increasing the peel angle, which will prevent them from closing out. The earlier breaking will provide more time for the surfer to catch a wave. The required dimensions of a wave-focusing reef would be smaller than that of a conventional artificial surfing reef. Another advantage of a wave-focusing reef is that surfers can catch waves at the so-called 'take off point' that, for given wave conditions, is at a fixed location along the reef axis.

Using the West-Cowell surfing reef factor derived in this research, the cross-section of the reef required for the wave focusing effect can be calculated. With increasing reef height and width, the wave focusing increases resulting in an increase in the breaker height and breaker distance (i.e., surfzone width) on the reef. The reef should be longer than the reef height and longer than the reef width (see Section 5.3). Such a reef would be positioned just beyond the breaker zone (see Section 5.4). Because a wave-focusing surfing reef can be a lot smaller than a conventional reef, it could be constructed more cheaply and be designed in such a way that it would be removable and tuneable.

Surfing reefs, both wave focusing and conventional, have many advantages not only for surfers but also for those involved in other beach activities such as diving, fishing and swimming [Pitt 1997]. Such reefs may enhance marine life and therefore make the reef environmentally friendly [Mead and Black 1999]. They could also be incorporated into beach protection strategies as the reefs could be engineered in such a way that they would enhance beach stability. For such purposes, a wave-focusing reef has the advantage that it is smaller and therefore cheaper than a conventional reef. On the other hand, conventional artificial surfing reefs may have a greater surfing capacity by inducing more wave peaks and thus more take off points. However, wave-focusing reefs providing one peak in the wave crest may still be more attractive because the reef volume and cost of conventional reefs is far greater.

Because the concept of wave-focusing surfing reefs is valid it is important to determine the dimensions of such a structure, and how does varying the dimensions of the reef influence the wave-breaking pattern. These issues are discussed below. In addition, environmental and engineering aspects are discussed and recommendations for further research are presented.

6.1 Reef dimensions

Numerical simulations showed that wave-focusing surfing reefs indeed focused waves in the desired way. Thus, the second and third questions in this research to be addressed were:

- What reef dimensions are required to produce the desired wave focusing effect?
- How does varying the dimensions of the reef influence the wave-breaking pattern and what are the effective minimum and maximum dimensions of the reef?

A reef can be characterised by its cross-section, length and position from the shore. Wave focusing, which is a function of an increased breaker height and breaker distance, increases with increasing reef height at constant reef width, and similarly with increasing reef width at constant reef height. The combined influence of reef height and width on wave focusing is described by the West-Cowell surfing reef factor derived in this research. The factor, which is the product of the relative reef height and relative reef width, is related to wave focusing in an almost linear way (see Section 5.6).

Prior to the development of the West-Cowell surfing reef factor, other dimensionless functions relating reef dimensions to wave focusing were considered. Wave focusing was related to the ratio of relative reef height and relative reef width. This factor is positively related to wave focusing, for a constant reef width, and negatively related to wave focusing for a constant reef height (see Figure 5.35). However, unlike the West-Cowell surfing reef factor, none of the relationships considered were generally applicable because they were restricted to a constant reef width or height. With respect to conventional reef design, no dimensionless relationships describing reef dimensions have been developed so far. However, a qualitative study on natural surfing reefs was conducted that classified large-scale reef components [Mead 1999]. Certain combinations of these components were found to produce high quality surfing waves. The reef component most resembling the concept of a wave-focusing reef was named the 'Focus' [Mead 1999]. Another study on natural surfing reefs related breaking wave characteristics such as breaking intensity and 'wave hollowness' (shape of plunging breaker) to the bathymetry [Sayce 1999]. These studies of natural surfing reefs described breaking wave characteristics but did not relate reef dimensions to wave breaking.

The total wave focusing effect of a finite length reef is not only dependent on reef height and width but also on reef length. For a given reef height and width, wave focusing is maximum at infinite reef length. Thus, wave focusing is a function of the West-Cowell surfing reef factor and reef length. Of course, only that part of the reef that extends beyond the breaker line contributes to wave focusing. In future, it may well be possible to incorporate length into a dimensionless factor. However, in order for this to be achieved, many simulations of reefs, involving variation of length with cross-sections varying in height and length, would be required.

With increasing reef height and width, the breaker distance will become greater. Reef height has a larger impact than the reef width on making the wave break further offshore. When the reef height is increased the breaking water depth on the reef will be situated further offshore. The increase in breaker distance with increasing reef height can be attributed partly to the influence of shallower water depth and partly to wave focusing. The breaker distance due to wave focusing increases with increasing West-Cowell surfing reef factor, thus with the cross-section of the reef. The reef height is the most effective dimension to increase the breaker distance. However, the reef height and width separately can only be increased to a certain value to be effective in increasing the breaker distance.

For most conventional reefs, the reef width is of the same order of magnitude as the reef length. However, for a wave-focusing reef, the reef length should be far greater than the reef cross-section. The orientation of the reef is such that the length-axis of the reef is perpendicular to the shoreline and to the wave crests. The required dimensions of a wave-focusing reef would be smaller than that of a conventional artificial surfing reef. Such a reef would be positioned just beyond the breaker zone and for waves with a height of 1 m and period of 8 s, could have the following dimensions: height, 1.5 m; width, 10 m; and length, 40 m. Smaller reef dimensions would also produce wave focusing but would not be sufficient to allow surfing.

In this research, relationships between reef dimensions and wave breaking patterns were developed. However, in future it will be necessary to develop criteria for the design of wave-focusing reefs. Such criteria would include the degree of wave focusing required in order to make waves more surfable, in particular those that would initially close-out. The time required to catch a wave will also need to be determined. However this parameter is not a constant but probably depends on wave height, peel angle and breaker type.

6.2 Environmental aspects

Apart from influencing waves to improve surfing conditions, reefs influence the morphology of the coast. Sand bars may be formed on either side of the reef, which will cause waves to break further from shore over a larger area than that produced directly by the reef. This provides more waves suitable for surfers such as has occurred at Narrowneck Reef on the Gold Coast (Queensland, Australia) where good surfing waves break on the bars induced by the reef [McGrath 2000]. In fact, a wave-focusing reef may increase surfability even though waves may not actually break on the reef. Thus, the reef may have fulfilled its purpose and could be removed and placed elsewhere. However, the bars may not remain for long after removal of the reef, because the bars form as a product of topographically controlled rip currents that develop in response to the reef [Short 1999]. These rip currents may have adverse effects causing offshore transport of sand and a hazard for inexperienced swimmers.

Improved surfing conditions on beaches can also be found around shipwrecks such as at 'the Wreck' at Byron bay, where good surfing waves are produced by the altered sandbars.

Because waves break further offshore, the water in the lee of the reef close to the shore will be calmer providing a safer area for swimmers. On the other hand, the altered sandbars and currents may cause rip currents on either side of the reef. Such rip currents are hazardous especially for weak swimmers [Short 1999] and this needs to be taken into account when considering beach safety.

The reduced wave action in the reef's lee may reduce the sediment transport and a salient may be formed [Turner et al. 1999]. Thus, Narrowneck Reef was built not only to improve surfing conditions but also to trap sand in the lee of the reef in order to stabilise the beach, which suffered from great erosion. On the other hand, Cable Station Reef (Perth, Western Australia), which was solely designed to improve the local surfing conditions, was built on a rock bottom where there were no coastal erosion problems, and such problems have not arisen since construction of the reef.

The primary aim when designing and placing wave-focusing reefs is to influence waves in order to improve their surfability. However, reefs need to be designed also to enhance beach protection and to reduce coastal erosion. Thus, if a reef is placed and is shown to have negative effects on the coast such as erosion or the formation of a salient, it could be removed.

The interaction of the altered hydrodynamic conditions with the submerged reef may cause scouring around the reef that may endanger its stability and cause problems such as subsidence of the reef. These aspects should be taken into consideration in reef design.

6.3 Engineering aspects

In designing and constructing a reef, just like any other structure, functionality has to be balanced against cost in monetary terms and in environmental and social terms. Structures in the surf zone are subjected to hydrodynamic forces such as waves and currents. These forces place great demands on the reef as far as stability and strength are concerned. The problems vary depending on the type of environment in which they are placed. For example, Narrowneck Reef was built on a sand base and Cables Station Reef was built on a rock base [Pattiaratchi 1999].

At Narrowneck, the reef was made from many large geotextile sandbags. The sand could be obtained offshore to the planned reef location. The sandbags were filled by a dredging installation in a ship and brought to the location where the bags were dropped out of the split barge. About 500 bags each containing approximately 150-300 tonne of sand were placed over a period of about one year up until the end of 2000 [Turner et al. 2000]. Such reefs may have the disadvantage that scouring and subsidence will occur. However, insufficient time has passed to enable the long-term performance of the reef to be evaluated. With a wave-focusing reef, less than 5 percent of the number of bags would be required. However, this technique would probably not be chosen for wave-focusing reefs because such reefs would not be removable or tuneable.

Cable Station Reef was built using rock to enhance an existing reef by placing large rocks on a stable rock bottom. The required fill was 11.000 tonnes of granite armour stone. The construction began in February 1999 and was 95 % complete in May 1999. Construction of the reef was completed in December 1999 after an interruption of work during the winter months [Pattiaratchi and Bancroft 2000]. Because the coast is stable due in part to the presence of rocky cliffs, no coastal stability problems would be encountered at this site [Pattiaratchi 1999]. Because of the size of the reef and because construction could only take place during periods of calm weather, the time to complete the construction of Cable Station reef was 11 months. As for the sand-based Narrowneck Reef, a wave-focusing reef would be much smaller.

An idea for the construction of a relatively smaller reef was put forward by Ross [1997] who proposed the use of high-density polyethylene pipes connected together to form a transportable reef. Ideally, the reef would be constructed on land in close proximity to the proposed site of the reef from where it could be transported across water, and then submerged and anchored to the seabed. Adjustments to the orientation of the reef or its removal could be done by filling it with air for removal or repositioning [Ross 1997]. There would most likely be many difficulties in installing such a reef in the surfzone as the forces on the reef of breaking waves are very large. Once in place, the reef would also have to withstand very large waves during storms.

6.4 Recommendations

Based on the research carried out, a series of recommendations can be made, which can be divided into a number of categories. The first recommendations concern numerical modelling. In this study, a number of parameters were varied. However, further studies will need to examine such additional parameters as wave direction, period and height. In addition simulations could also be conducted with non-linear numerical models and also with irregular waves.

The second type of recommendations concerns testing reef designs. Studies in a wave basin would provide an opportunity to see how the wave peak forms and how breaking occurs in detail. However, because wave-focusing surfing reefs are relatively small, it may also be attractive to field test them. However, unlike tests in the wave basin where waves can be generated, field testing would depend on wave conditions at the time of testing. Working in the surf zone would also be very difficult.

In addition to the above, consideration will need to be given to design criteria, possible designs and ways to construct the designs developed. In addition, not only performance but also price, tuneablity, removeablity, durability and a variety of environmental issues will need to be taken into account.

6.5 Conclusions

In conclusion, the concept of wave-focusing surfing reefs was found to be viable and the required dimensions of such reefs have been established. A parameter referred to as the West-Cowell surfing reef factor, which relates reef cross-section to wave focusing, has been derived. Wave-focusing surfing reefs have a number of advantages over conventional reefs. The work carried out provides sufficient basis for conducting field trials. However, more attention will need to be given to construction methods and to refining the relationships of reef dimensions to wave-breaking patterns.

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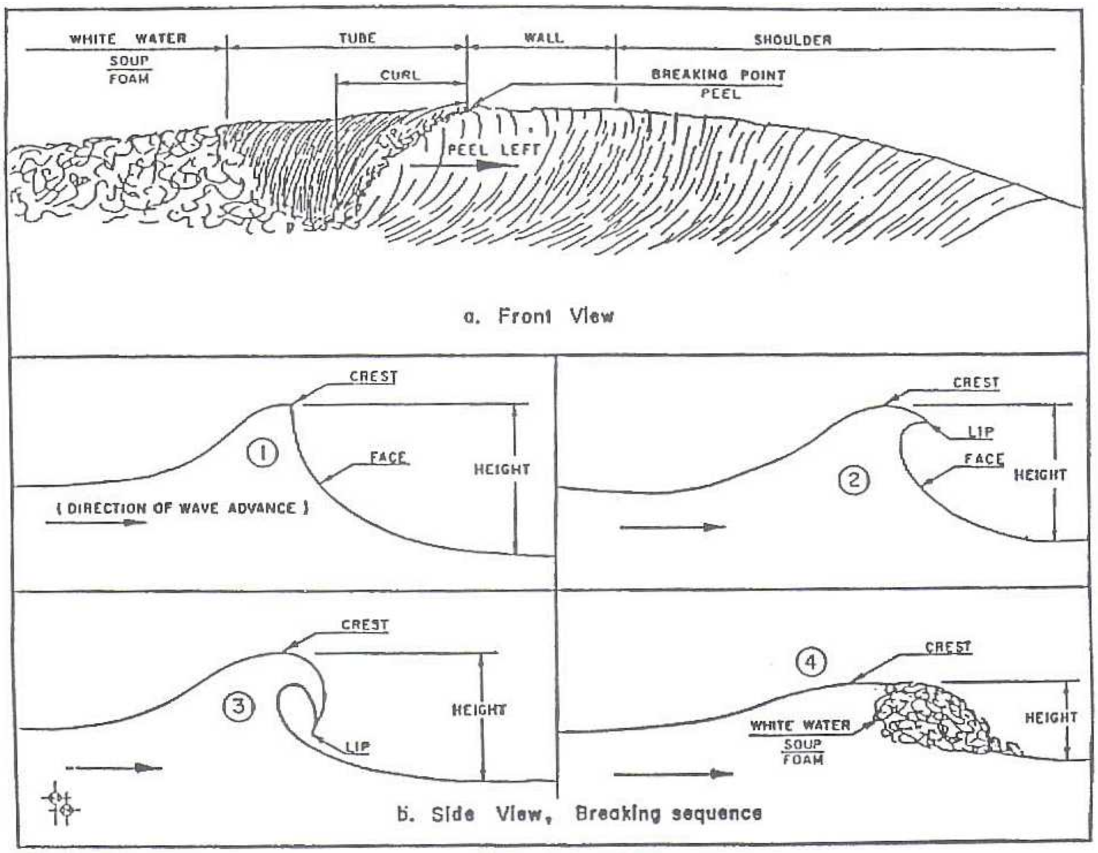
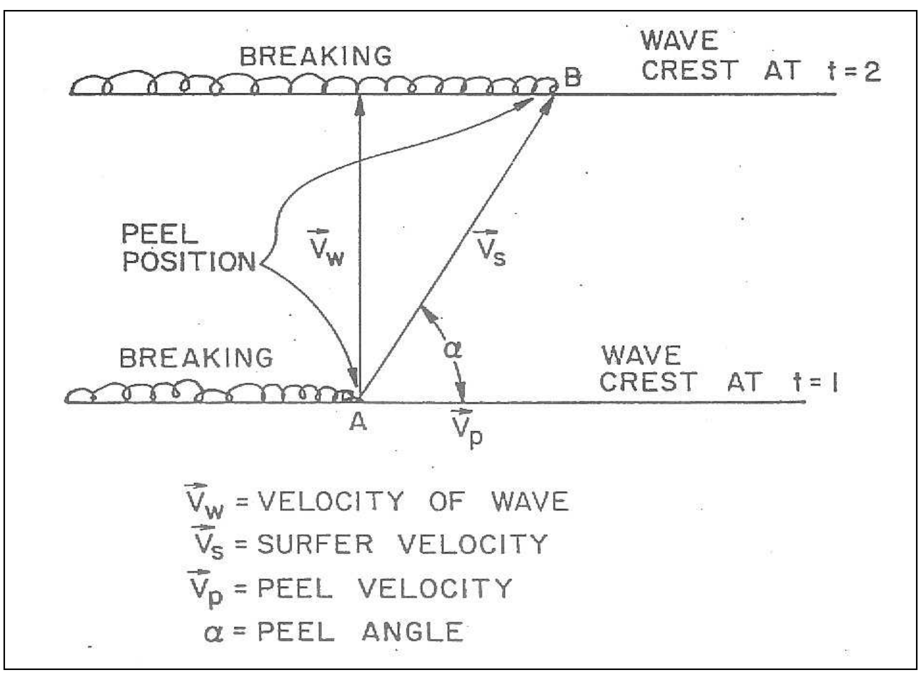
Appendix A: Parameters of surfing waves

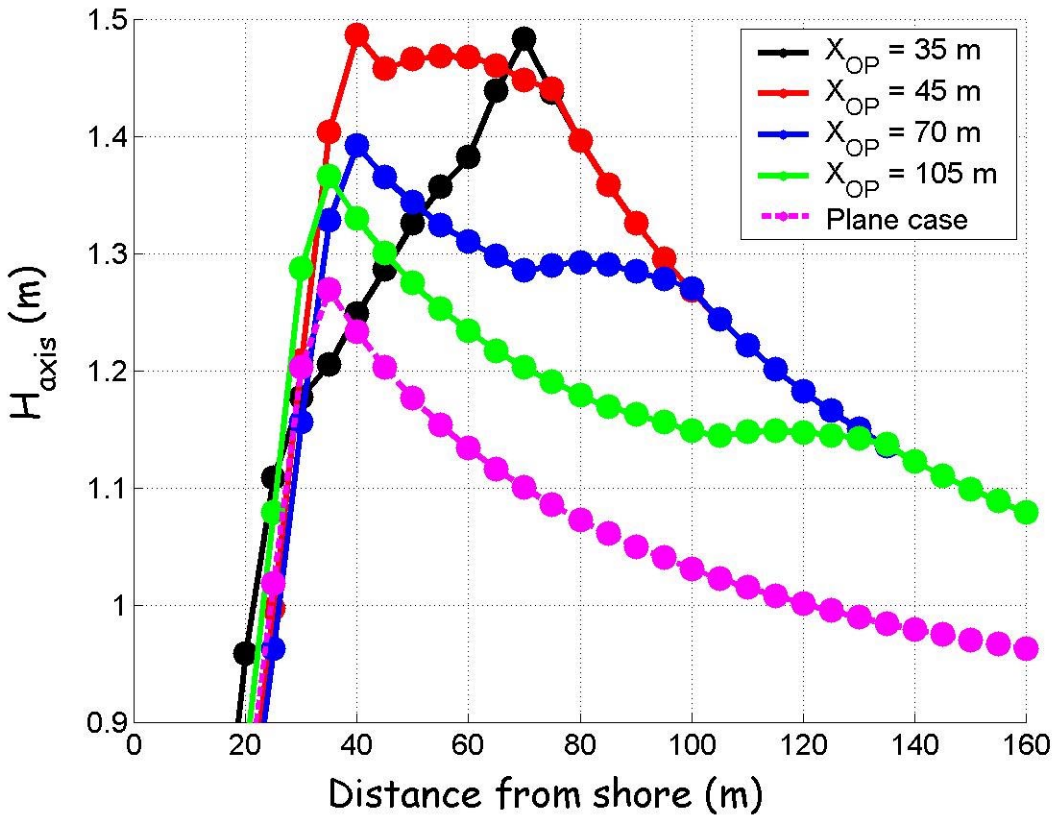


Appendix A.1: Surfing wave terminology and sequence of breaking [Walker 1974]

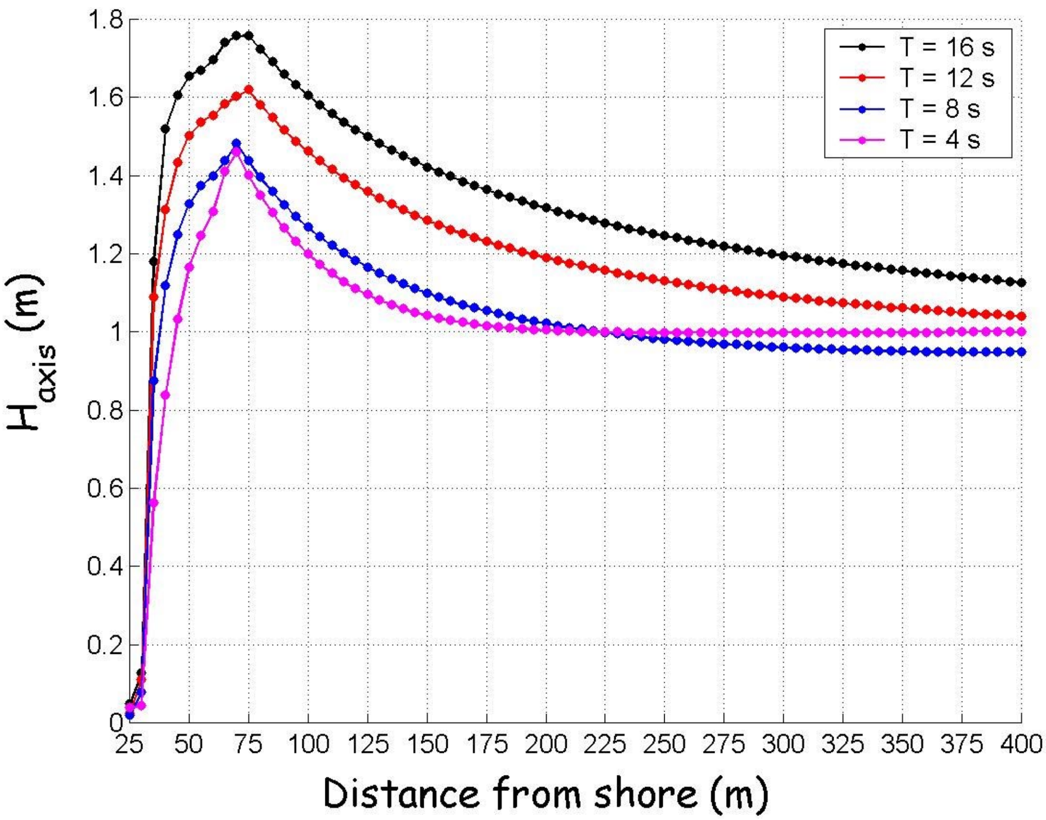


Appendix A.2: Schematic representation of a peeling wave [Walker 1974]

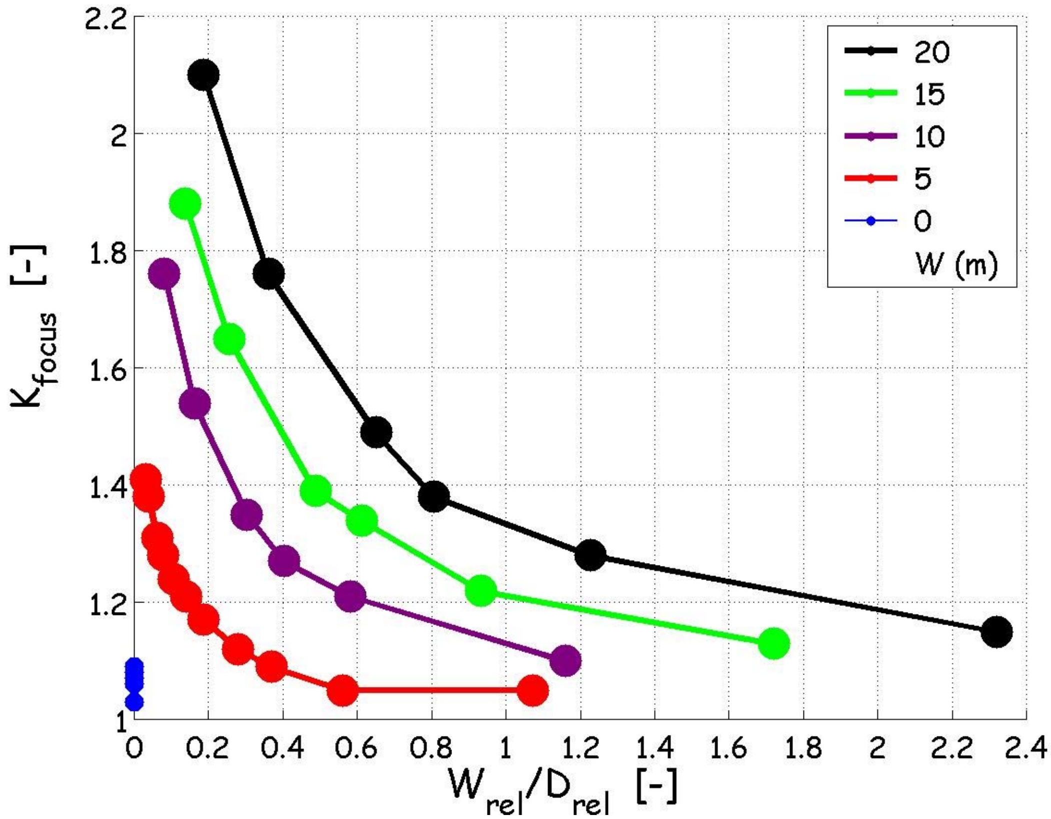
Appendix B: Figures of simulations with Ref/Dif



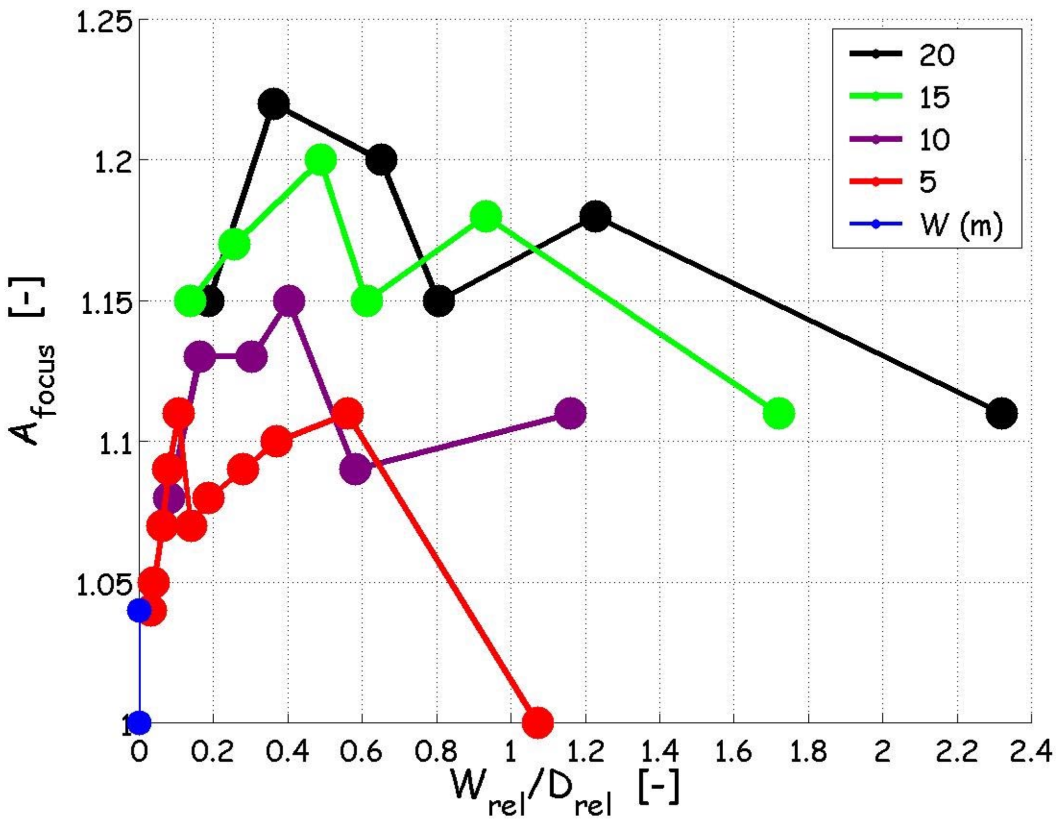
Appendix B.1: Wave height along reef axis (H_{axis}) related to distance from shore, for reefs that extend to the offshore boundary of the modelling grid with W = 5 m and D = 1.5 m, and various reef positions (X_{OP}) which are given in the legend.



Appendix B.2: Wave height along reef's axis (H_{axis}) related to distance from shore, for infinitely long reefs with reef height of 1.5 m, width of 5 m for various wave periods (T), which are given in the legend.



Appendix B.3: Wave focusing factor (K_{focus}) related to the ratio of relative reef width (W_{rel}) and relative reef height (D_{rel}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.



Appendix B.4: Relative augmented breaker distance (A_{focus}) related to the ratio of relative reef width (W_{rel}) and relative reef height (D_{rel}) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

Appendix C: Data tables of simulations with Ref/Dif

Appendix C.1: Simulations of infinitely long reefs with varying cross-section, results are presented in Section 5.2

W (m)	D (m)	X_{reef} (m)	H_{reef} (m)	h_{reef} (m)	γ [-]	L_{reef} (m)	ΔX (m)	X_{focus} (m)	A_{focus} [-]	ΔH (m)	K_{focus} [-]	D_{rel} [-]	W_{rel} [-]	S_{RF} [-]
0	0	35	1.27	1.75	0.73	32.63								
0	0.50	45	1.31	1.75	0.75	32.63	10	0	1.00	0.04	1.03	0.29	0.00	0.00
0	1.00	55	1.34	1.75	0.77	32.63	20	0	1.00	0.07	1.06	0.57	0.00	0.00
0	1.50	65	1.36	1.75	0.78	32.63	30	0	1.00	0.09	1.07	0.86	0.00	0.00
0	2.00	75	1.37	1.75	0.78	32.63	40	0	1.00	0.10	1.08	1.14	0.00	0.00
0	4.00	120	1.36	2.00	0.68	34.70	85	5	1.04	0.09	1.07	2.00	0.00	0.00
0	8.00	195	1.39	1.75	0.79	32.63	160	0	1.00	0.12	1.09	4.57	0.00	0.00
5	0.25	40	1.33	1.75	0.76	32.63	5	0	1.00	0.06	1.05	0.14	0.15	0.02
5	0.50	50	1.33	2.00	0.67	34.70	15	5	1.11	0.06	1.05	0.25	0.14	0.04
5	0.75	55	1.38	2.00	0.69	34.70	20	5	1.10	0.11	1.09	0.38	0.14	0.05
5	1.00	60	1.42	2.00	0.71	34.70	25	5	1.09	0.15	1.12	0.50	0.14	0.07
5	1.50	70	1.48	2.00	0.74	34.70	35	5	1.08	0.21	1.17	0.75	0.14	0.11
5	2.00	80	1.54	2.00	0.77	34.70	45	5	1.07	0.27	1.21	1.00	0.14	0.14
5	3.00	105	1.57	2.25	0.70	36.76	70	10	1.11	0.30	1.24	1.33	0.14	0.18
5	4.00	125	1.63	2.25	0.72	36.76	90	10	1.09	0.36	1.28	1.78	0.14	0.24
5	5.00	145	1.67	2.25	0.74	36.76	110	10	1.07	0.40	1.31	2.22	0.14	0.30
5	8.00	205	1.75	2.25	0.78	36.76	170	10	1.05	0.48	1.38	3.56	0.14	0.48
5	10.0	245	1.79	2.25	0.80	36.76	210	10	1.04	0.52	1.41	4.44	0.14	0.60
10	0.50	50	1.40	2.00	0.70	34.70	15	5	1.11	0.13	1.10	0.25	0.29	0.07
10	1.00	60	1.54	2.00	0.77	34.70	25	5	1.09	0.27	1.21	0.50	0.29	0.14
10	1.50	75	1.61	2.25	0.72	36.76	40	10	1.15	0.34	1.27	0.67	0.27	0.18
10	2.00	85	1.71	2.25	0.76	36.76	50	10	1.13	0.44	1.35	0.89	0.27	0.24
10	4.00	130	1.95	2.50	0.78	38.59	95	15	1.13	0.68	1.54	1.60	0.26	0.41
10	8.00	210	2.24	2.50	0.90	38.59	175	15	1.08	0.97	1.76	3.20	0.26	0.83
15	0.50	50	1.43	2.00	0.72	34.70	15	5	1.11	0.16	1.13	0.25	0.43	0.11
15	1.00	65	1.55	2.25	0.69	36.76	30	10	1.18	0.28	1.22	0.44	0.41	0.18
15	1.50	75	1.70	2.25	0.76	36.76	40	10	1.15	0.43	1.34	0.67	0.41	0.27
15	2.00	90	1.77	2.50	0.71	38.59	55	15	1.20	0.50	1.39	0.80	0.39	0.31
15	4.00	135	2.10	2.75	0.76	40.40	100	20	1.17	0.83	1.65	1.45	0.37	0.54
15	8.00	225	2.39	3.25	0.74	43.67	190	30	1.15	1.12	1.88	2.46	0.34	0.85
20	0.50	50	1.46	2.00	0.73	34.70	15	5	1.11	0.19	1.15	0.25	0.58	0.14
20	1.00	65	1.62	2.25	0.72	36.76	30	10	1.18	0.35	1.28	0.44	0.54	0.24
20	1.50	75	1.75	2.25	0.78	36.76	40	10	1.15	0.48	1.38	0.67	0.54	0.36
20	2.00	90	1.89	2.50	0.76	38.59	55	15	1.20	0.62	1.49	0.80	0.52	0.41
20	4.00	140	2.23	3.00	0.74	42.05	105	25	1.22	0.96	1.76	1.33	0.48	0.63
20	8.00	225	2.67	3.25	0.82	43.67	190	30	1.15	1.40	2.10	2.46	0.46	1.13

Appendix C.2: Simulations of shore-connected reefs with varying length (Λ), results are presented in Section 5.3

Λ (m)	X_{reef} (m)	H_{reef} (m)	h_{reef} (m)	γ [-]	L_{reef} (m)	ΔX (m)	X_{focus} (m)	A_{focus} [-]	ΔH (m)	K_{focus} [-]	Λ_{rel} [-]
0	35	1.27	1.75	0.73	32.63	0	0	1.00	0.00	1.00	0.00
35	40	1.23	0.50	2.46	17.63	5	0	1.00	-0.04	0.97	1.99
40	40	1.30	0.50	2.60	17.63	5	0	1.00	0.03	1.02	2.27
45	45	1.30	0.75	1.73	21.84	10	0	1.00	0.03	1.02	2.06
50	50	1.29	1.00	1.29	24.80	15	0	1.00	0.02	1.02	2.02
55	55	1.26	1.25	1.01	27.79	20	0	1.00	-0.01	0.99	1.98
60	60	1.24	1.50	0.83	30.22	25	0	1.00	-0.03	0.98	1.99
65	65	1.30	1.75	0.74	32.63	30	0	1.00	0.03	1.02	1.99
70	65	1.28	1.75	0.73	32.63	30	0	1.00	0.01	1.01	2.15
75	65	1.31	1.75	0.75	32.63	30	0	1.00	0.04	1.03	2.30
80	65	1.34	1.75	0.77	32.63	30	0	1.00	0.07	1.06	2.45
85	65	1.36	1.75	0.78	32.63	30	0	1.00	0.09	1.07	2.60
90	65	1.37	1.75	0.78	32.63	30	0	1.00	0.10	1.08	2.76
95	70	1.33	2.00	0.67	34.70	35	5	1.08	0.06	1.05	2.74
100	70	1.34	2.00	0.67	34.70	35	5	1.08	0.07	1.06	2.88
110	70	1.36	2.00	0.68	34.70	35	5	1.08	0.09	1.07	3.17
120	70	1.38	2.00	0.69	34.70	35	5	1.08	0.11	1.09	3.46
130	70	1.39	2.00	0.70	34.70	35	5	1.08	0.12	1.09	3.75
140	70	1.40	2.00	0.70	34.70	35	5	1.08	0.13	1.10	4.03
150	70	1.41	2.00	0.71	34.70	35	5	1.08	0.14	1.11	4.32
200	70	1.44	2.00	0.72	34.70	35	5	1.08	0.17	1.13	5.76
250	70	1.45	2.00	0.73	34.70	35	5	1.08	0.18	1.14	7.20
400	70	1.47	2.00	0.74	34.70	35	5	1.08	0.20	1.16	11.53
1000	70	1.48	2.00	0.74	34.70	35	5	1.08	0.21	1.17	28.82

Appendix C.3: Simulations of reefs with varying position offshore (X_{op}), results are presented in Section 5.4

X_{op} (m)	Λ (m)	h_{min} (m)	X_{reef} (m)	H_{reef} (m)	h_{reef} (m)	γ [-]	L_{reef} (m)	ΔX (m)	X_{focus} (m)	A_{focus} [-]	ΔH (m)	K_{focus} [-]	Λ_{rel} [-]	h_{min}/h_{reef} [-]
0	0	0.00	35	1.27	1.75	0.73	32.63	0	0	1.00	0.00	1.00	0.00	0.00
0	995	0.00	70	1.48	2.00	0.74	34.70	35	5	1.08	0.21	1.17	28.67	0.00
35	960	1.75	70	1.48	2.00	0.74	34.70	35	5	1.08	0.21	1.17	27.67	0.88
40	955	2.00	50	1.51	2.00	0.76	34.70	15	0	0.77	0.24	1.19	27.52	1.00
45	950	2.25	40	1.49	2.00	0.75	34.70	5	0	0.62	0.22	1.17	27.38	1.13
50	945	2.50	40	1.46	2.00	0.73	34.70	5	0	0.62	0.19	1.15	27.23	1.25
60	935	3.00	40	1.43	2.00	0.72	34.70	5	0	0.62	0.16	1.13	26.95	1.50
70	925	3.50	40	1.39	2.00	0.70	34.70	5	0	0.62	0.12	1.09	26.66	1.75
80	915	4.00	40	1.37	2.00	0.69	34.70	5	0	0.62	0.10	1.08	26.37	2.00
90	905	4.50	40	1.35	2.00	0.68	34.70	5	0	0.62	0.08	1.06	26.08	2.25
100	895	5.00	40	1.34	2.00	0.67	34.70	5	0	0.62	0.07	1.06	25.79	2.50
105	890	5.25	35	1.37	1.75	0.78	32.63	0	0	0.54	0.10	1.08	27.28	3.00
110	885	5.50	35	1.36	1.75	0.78	32.63	0	0	0.54	0.09	1.07	27.12	3.14
120	875	6.00	35	1.35	1.75	0.77	32.63	0	0	0.54	0.08	1.06	26.82	3.43

Appendix D: Comparison of Ref/Dif with Triton

Because it is expected that the Triton Boussinesq-type model may better describe non-linear effects, simulations were also conducted with Triton. Results of which were used for comparison with results obtained with Ref/Dif.

Simulations were conducted of reefs with reef height (D) of 1.5 m with reef width (W) of 5 m and 15 m with various lengths. Two shore-connected reefs with an infinite length and reef length (Λ) of 90 m and of a shore-disconnected reef with offshore position of the reef (X_{OP}) of 25 m and Λ = 70 m were chosen. For these simulations the specifications were used as stated in Section 4.4.1.

For the simulations with Triton a grid of 750 m in offshore direction and 300 m in alongshore direction was chosen with grid spacing of 1.25 m in both directions. For simulations a time step was chosen of 0.05 seconds. The other model settings were as follows:

- Dissipation coefficients:
  - Linear dissipation coefficient = 0.05
  - Non-linear dissipation coefficient = 1
- Boussinesq-type modelling:
  - Dispersion coefficient = 0.395
  - Shoaling coefficient = 0.36
- Breaker model
  - Initial breaker angle = 20^0
  - Terminal breaker angle = 10^0
  - Scaling parameter = 20^0

In Table D.1, the results of simulations used for the comparison of Ref/Dif with Triton are presented.

For the reef simulations with Ref/Dif, the relative augmented breaker distance (A_{focus}) was 1.08 except for the infinitely long reef with W = 15 m where A_{focus} was 1.15. For the infinitely long reefs with W of 5 m and 15 m, the wave-focusing factor (K_{focus}) was 1.17 and 1.34, respectively. For the finite length reefs, which all reached to 95 m offshore, K_{focus} was 1.05 and 1.13 for W = 5 m and 15 m, respectively. The reefs with X_{OP} = 25 m reached to within the surfzone (i.e., $X_{OP} < X_{beach}$) and therefore the breaking patterns very similar for the finite length reefs with the same width.

For the plane case simulation in Triton, the breaker distance (X_{reef}) was 37 m and breaker height (H_{reef}) was 1.64 m. For all the reef simulations with Triton X_{reef} was 52 m except for the infinitely long reef with W = 15 m, where X_{reef} was 51 m. However, unlike the simulations with Ref/Dif, waves did not initiate to break along the reef axis but at some distance from the reef (Y, see Table 5.5). This alongshore breaker distance offset, which was measured perpendicular from the centre of the reef, varied from 28 m to 46 m.

A_{focus} was 1.41 for all Triton reef simulations except for the reef with Λ = infinite and W =15 m, where A_{focus} was 1.38. For the reef with X_{OP} = 25 m and W = 5 m, K_{focus} was smallest at 1.04. For the reefs with W = 5 m, K_{focus} was 1.04, 1.09 and 1.07 for Λ = infinite, 95 m and 70 m, respectively. While for the reefs with W = 15 m, K_{focus} varied little and was 1.10, 1.12 and 1.10 for Λ = infinite, 95 m and 70 m, respectively.

Table D.1: Results of simulations conducted with Ref/Dif and with Triton for reefs with height of 1.5 m and varying width and length. W = 0 m is the plane case (no reef).

W (m)	Λ (m)	X_{OP} (m)	X_{reef} (m)	H_{reef} (m)	h_{reef} (m)	X_{focus} [-]	A_{focus} [-]	K_{focus} [-]	Y[1] (m)
Results for Ref/Dif									
0	0	0	35	1.27	1.75	0	1	1	0
5	70	25	70	1.33	2	5	1.08	1.05	0
5	95	0	70	1.33	2	5	1.08	1.05	0
5	Infinite	0	70	1.48	2	5	1.08	1.17	0
15	70	25	70	1.44	2	5	1.08	1.13	0
15	95	0	70	1.44	2	5	1.08	1.13	0
15	Infinite	Infinite	75	1.70	2.25	10	1.15	1.34	0
Results for Triton									
0	0	0	37	1.64	1.88	0	1	1	0
5	70	25	52	1.71	2.63	15	1.41	1.04	28
5	95	0	52	1.78	2.63	15	1.41	1.09	34
5	Infinite	0	52	1.75	2.63	15	1.41	1.07	40
15	70	25	52	1.81	2.63	15	1.41	1.10	34
15	95	0	52	1.83	2.63	15	1.41	1.12	40
15	Infinite	0	51	1.80	2.56	14	1.38	1.10	46

[1] Y is the alongshore distance from the centre of the reef

For the plane case for Ref/Dif and for Triton, X_{reef} was approximately the same, however there was a great difference in H_{beach}, which was 29 % greater for Triton.

For the reef simulations with Ref/Dif, waves initiated to break at the centre of the reef, which was not the case with Triton where wave breaking started next to the reef. While with Triton waves broke closer to shore than with Ref/Dif, the augmented breaker distances due to wave focusing (A_{focus}) were greater. However, these larger values of A_{focus} for Triton, did not include the bed offset due to the presence of the reef (i.e., $X\gamma$ = 30 m, see Section 3.3.2) because waves did not break on the reef.

For reef simulations with Triton, values for K_{focus} ranged from 1.04 to 1.10, while for Ref/Dif, values for K_{focus} ranged from 1.05 to 1.13 for finite length reefs, and for infinitely long reefs values for K_{focus} were as great as 1.34. Thus, with Ref/Dif the breaker heights were increased more than with Triton.

The relationships between reef dimensions and wave breaking patterns were modelled with the weakly non-linear phase resolving wave model Ref/Dif. This model was used because it is possible to study individual waves and the way they wrap around a reef in the process referred to as wave focusing. Because the model is weakly non-linear, the breaker heights and breaker distances calculated are probably underestimates. In reality, waves are not linear and have higher peaks with longer troughs. The peakiness is a critical property in wave breaking. Thus in reality, more wave focusing may occur than is predicted by the Ref/Dif model. In order to examine whether this may be the case, the higher order non-linear model Triton was used. The comparison showed that Ref/Dif underestimates wave height thus leading to estimates that are more conservative. However the breaker distances calculated with Triton were smaller. This means that waves would be more amplified but would break closer to shore than found with Ref/Dif.

In order to be able to explain the great differences in the results with the two models more simulations would need to be conducted with Triton. However this was not possible in the time available for this research.

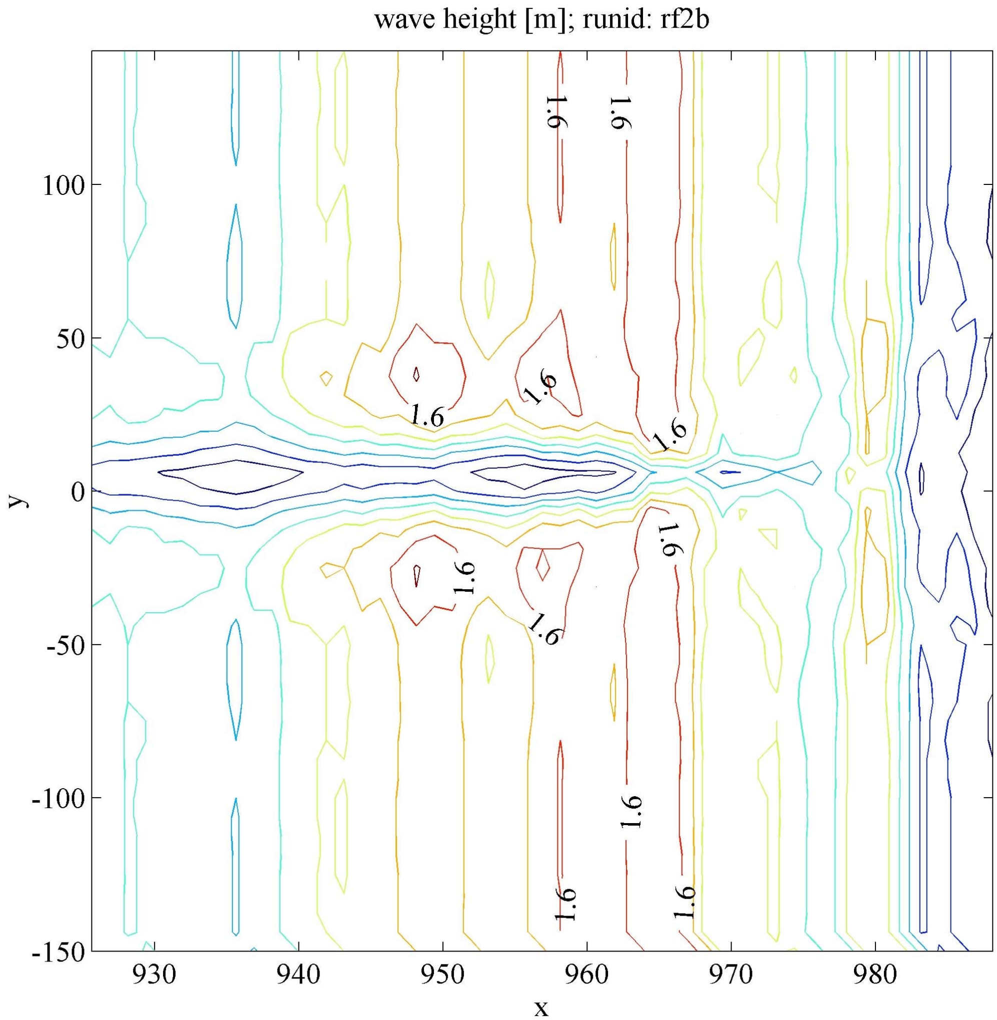


Figure D.1: Wave height contours, for a 70 m long reef placed 25 m from shore with height of 1.5 m and width of 5 m, modelled with Triton.

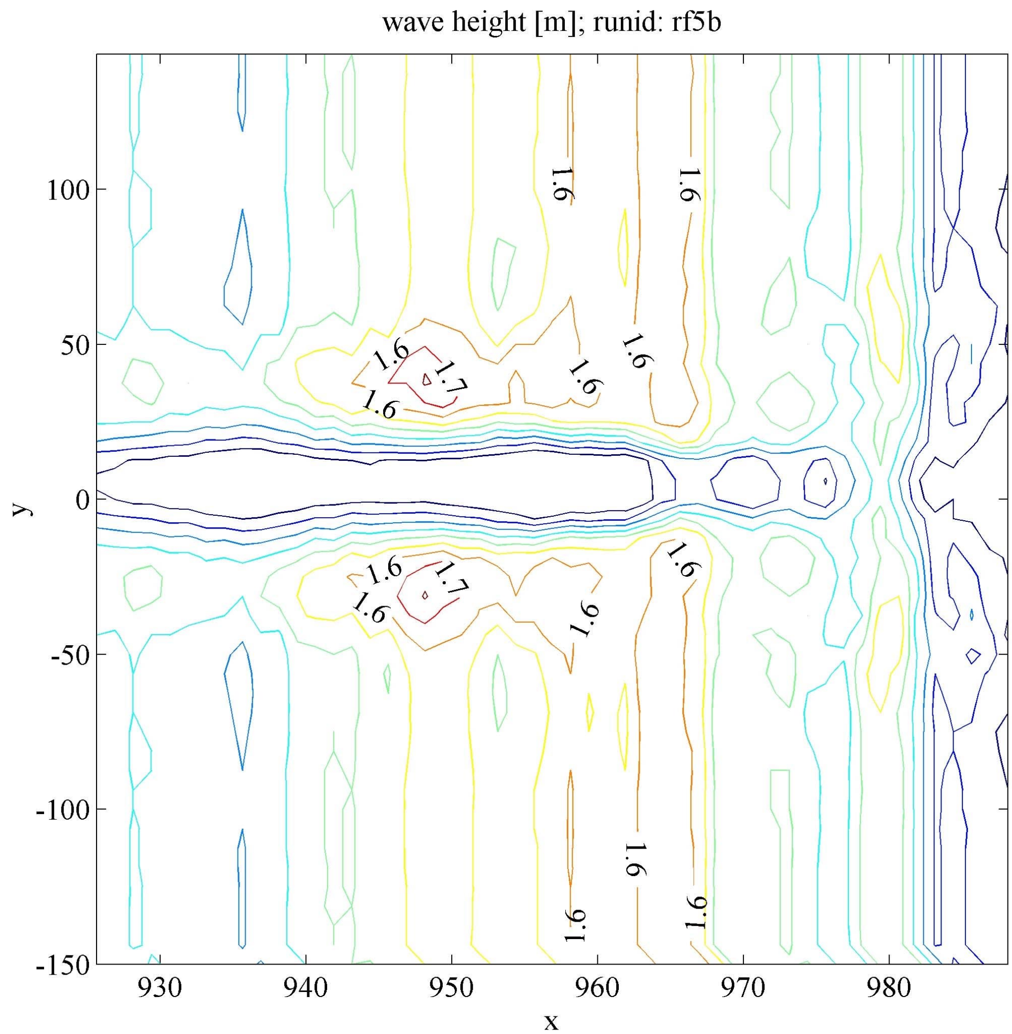


Figure D.2: Wave height contours, for a 70 m long reef placed 25 m from shore with height of 1.5 m and width of 15 m, modelled with Triton.