Artificial surf reef design

Dutch swell conditions

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Erik van Ettinger
Abstract

Artificial surf reefs (ASRs) are structures specifically aimed at modifying the nearshore wave field transformation to improve surfing conditions or 'surfability'. With the increasing popularity of surfing, the demand for such artificial reefs is ever growing. Thus far, three ASRs have been realized over the last decade (see e.g. Black & Mead 2001) and many more are planned to be constructed in the near future. ASRs are planned to be constructed in big wave pools for indoor surfing. Nevertheless, artificial surf reef design is often done fairly ad hoc and there remains great uncertainty as to what the optimal dimensions of the artificial surf reef should be.

Henriquez (2004) investigated, through a combination of numerical and experimental modelling, how ASR design affects the resulting surfability. The quality of a surf break is generally expressed in three measurable parameters: breaker height, peel angle and breaker shape. Together these parameters determine the surfability of the wave. In particular, the peel angle (a measure related to the rate at which the wave breaks along its crest) is an important measure that plays a dominant role in ASR design. The numerical modelling (Henriquez, 2004) was done without taking into account wave-driven currents. The experimental modelling by Henriquez showed that, approximately 20% of the wave ride was negatively affected by rip currents driven by wave breaking over the ASR. The waves in the rip current were breaking in sections, irregular and with a rough water surface, in other words: unsuitable for surfing.

Through combination of numerical and experimental modelling this study aims at: 1) Gaining insight in reef properties that influence the wave-driven currents over the reef and associated effects on the surfability parameters; 2) Designing a reef shape optimized for surfing purposes, taking into account both waves and effects of wave-driven currents by means of numerical wave and wave-current models; 3) Verification of design (and thus numerical predictions) by means of a laboratory experiment, specifically designed to obtain measurements of currents and surfability parameters.

The models applied in the numerical study are: 1) a spectral wave model (nonlinear RefDif, www.coastal.udel.edu), this model is a frequency-domain, parabolic mild-slope equation that takes quadratic non-linearity's into account; 2) a surf-beat model which is a research version of Delft3D (www.wldelft.nl). New wave and roller modules describing wave propagation and breaking, operating on the timescale of wave groups, are coupled to a depth averaged non-linear flow model to predict the time-dependent flow field; 3) A fully nonlinear Boussinesq wave model (Funwave2D, www.coastal.udel.edu) that is operating on the intra-wave timescale. The Boussinesq model uses the Extended Boussinesq equations as derived by Wei et al. (1995), which are suitable for modelling wave-current interaction as shown by Kirby (1997).

Optimal dimensions were estimated in the numerical study for varying reef shapes. The resulting ASR design was constructed in the Laboratory of Fluid Mechanics of Delft University of Technology. Unidirectional bichromatic incident waves were generated by three piston type wave makers with second-order board control. The measurements obtained from the laboratory experiment were used to verify four parameters that were predicted in the numerical study: breaker heights, peel angles, breaker shapes and the current field.
In the design, a rip-channel was applied in the middle of the reef, where surfers do not surf, to minimize the rip currents through the breakers. In the rip channel no wave breaking occurs and the cross-shore set-up gradients in the channel are thus smaller. The alongshore variations in wave set-up produce feeder currents to the channel and to the sides of the reef. The rip currents through the breakers are therefore smaller than in a design without a rip channel.

The combined numerical and experimental study showed that three important topographic features affect the wave-driven currents. The first one is the rip channel width; this is the distance between both halves of the reef. By decreasing the rip channel width, the rip current velocities through the channel increase and the rip current strength through the breakers over the reef decrease. This is valid up to a certain width above which the rip current through the channel no longer exists and the rip currents through the breakers increase again. The width of the rip channel does also have a large influence on the stability of the rip currents.

The two other topographic features are the cross- and alongshore extent of the reef. The internal reef angle and reef length are the reef variables used to influence the cross-shore extent of the reef. The internal reef angle again and internal reef slope are the reef variables used to influence the alongshore extent of the reef. In general, the rip current through the channel and the rip currents through the breakers decrease with decreasing reef widths.

The numerical study showed that the rip currents in the final reef design are approximately 40% decreased in strength in comparison with conventional ASR designs. The Boussinesq model is able to indicate whether a rip current is affecting the surfability or not. However, the sectional, irregular breaking of the waves and the rough water surface when a rip current is travelling through the breaker could not be determined numerically.

The measurements showed that the rip currents through the breakers were very asymmetrical; One being almost twice as strong as the other one. The measurements of the surfability parameters: the time series of the surface elevation at the breakpoints of the bichromatic wave field, the peel angles and the breaker types agreed all very well at the side of the reef where the rip current was weak. At the other side, where the rip current was stronger, the surface elevations agreed, but the peel angles and breaker types were very irregular and the water surface was rough at the location of the rip current.

A primitive relationship was found for the effect of rip currents through the breakers on the surfability for typical Dutch swell conditions. This is done by non-dimensionalizing the rip currents with the shallow-water wave speed $\sqrt{gh}$ where $g$ is the gravitational constant and $h$ is the water depth. If the Froude number of the rip current is equal to or smaller than 0.1 the rip currents through the breakers have a negligible influence on the surfability. And if the Froude number of the rip is equal to or larger than 0.2 the rip currents through the breakers negatively affect the surfability.
## Contents

Acknowledgements ........................................................................ iv

Abstract ....................................................................................... v

1 Introduction .................................................................................. 1
   1.1 General .................................................................................. 1
   1.2 Study objectives ..................................................................... 2
   1.3 Outline of thesis ..................................................................... 2

2 Artificial surf reef (hydro)dynamics ........................................ 3
   2.1 Wave breaking ....................................................................... 3
   2.2 Wave-driven currents ............................................................ 8
      2.2.1 Conventional artificial surf reefs ...................................... 9
      2.2.2 Integral artificial surf reef .............................................. 13

3 Numerical study ............................................................................ 14
   3.1 Design features and demands ................................................... 14
   3.2 Artificial surf reef design with a spectral model ......................... 15
      3.2.1 The spectral model ....................................................... 15
      3.2.2 Reef shape .................................................................. 16
      3.3.3 Modelling results .......................................................... 16
   3.3 Artificial surf reef design with a surf-beat model ......................... 18
      3.3.1 The surf-beat model ...................................................... 18
      3.3.2 Reef shapes .................................................................. 19
      3.3.3 Numerical Modelling, results and interpretation ................. 22
   3.4 Artificial surf reef design with a Boussinesq model ..................... 30
      3.4.1 The Boussinesq model ................................................... 30
      3.4.2 Modelling results and interpretation .................................. 33
   3.5 Conclusions ........................................................................... 36

4 Experimental study ........................................................................ 37
   4.1 Experimental set-up ............................................................... 37
   4.2 Test conditions ....................................................................... 38
   4.3 Instruments .......................................................................... 39
   4.4 Experimental and numerical data .......................................... 40
      4.4.1 Wave-driven currents .................................................... 40
      4.4.2 Wave heights ............................................................... 44
      4.4.3 Down-line velocities ..................................................... 47
      4.4.4 Breaker shapes .............................................................. 49
   4.5 Summary .............................................................................. 53

5 Conclusions and recommendations .............................................. 54
   5.1 Key findings and conclusions .................................................. 54
   5.2 Recommendations ................................................................... 56

Bibliography ..................................................................................... 57
1 Introduction

1.1 General

Artificial surf reefs (ASRs) are constructions specially aimed at modifying the near-shore wave field transformation to improve the surf conditions or ‘surfability’. With the increasing popularity of surfing, the demand for such artificial reefs is ever growing. Thus far, three ASRs have been realized over the last decade (see e.g. Black & Mead 2001) and many more are planned to be constructed in the near future. ASRs are planned to be constructed in big wave pools for indoor surfing. Even though a hot topic, artificial surf reef design is often done fairly ad hoc and there remains great uncertainty as to what the optimal dimensions of the artificial surf reef should be.

Henriquez (2004) investigated, through combination of numerical and experimental modelling, how ASR design affects the resulting surfability. The quality of a surf break is generally expressed in three measurable parameters: breaker height, peel angle and breaker shape. Together these parameters determine the surfability of the wave. In particular, the peel angle (a measure related to the rate at which the wave breaks along its crest) is an important measure that plays a pivoting role in ASR design. The numerical modelling by Henriquez was done without taking into account wave-driven currents. However, his experimental modelling showed that, approximately 20% of the wave ride was negatively affected by rip currents, driven by wave breaking over the ASR. The waves in the rip current were breaking in sections, irregular and with a rough water surface, in other words: unsuitable for surfing. The numerical data (Henriquez, 2004) does not predict the existence of a rip current.

In this study, the reef parameters that influence the wave-driven currents over the reef and associated effects on the surfability parameters were investigated. Through modelling with state-of-the-art numerical models an ASR is designed taking the wave-driven currents into account. A laboratory experiment was conducted to verify the overall ASR design and the numerical predictions of the relevant parameters and currents. Figure 1.1 e.g. shows an excellent comparison of computed and measured time series of surface elevation located in the rip current at breakpoint.

![Figure 1.1 Comparison of computed (dashed lines) and measured (solid lines) time series of surface elevation $\eta$ in the rip current at breakpoint.](image)
1.2 Study Objectives

The main objective is to design an artificial surf reef taking into account the currents driven by wave breaking over the reef. The main objective is divided in the following sub-objectives:

1. Gain insight in reef properties that influence the wave-driven currents over the reef and associated effects on the surfability parameters.
2. Design a reef shape optimized for surfing purposes, taking into account both waves and effects of wave-driven currents by means of numerical wave and wave-current models.
3. Verification of design (and thus numerical predictions) by means of a laboratory experiment, specifically designed to obtain measurements of currents and surfability parameters.

1.3 Outline of thesis

In Chapter 2 the waves and wave-driven currents over artificial surf reefs are described. The waves breaking over an ASR are described and the influence of the reef bathymetry on the surfability is explained. Hereafter the wave-driven currents over the ASR are described and the associated influence on the surfability. Finally an integral ASR concept is presented taking the wave-driven currents into account.

The numerical modelling is discussed in Chapter 3. First an optimal reef shape is designed with a spectral wave model, without taking the currents into account. Various reef shapes are presented and an optimal reef is designed taking the wave-driven currents into account. This is done with a numerical surf beat model operating on the timescale of wave groups. A Boussinesq model operating on the intra-wave timescale is used to determine the influences of the currents on the surfability.

The laboratory experiments are presented in Chapter 4. A description is given of the laboratory set-up. The measurements are described, and the observations are compared to the predictions obtained with the numerical models. Conclusions and recommendations for further research are presented in Chapter 5.
2 Artificial surf reef (hydro) dynamics

Over the last ten years numerous ASRs have been designed and a few are actually built. In order to design an artificial surf reef, it is important to understand the basics of ocean wave transformation over topography, including the effects of e.g. shoaling, refraction and diffraction. It is also important to understand waves from a surfer’s point of view to understand what kind of wave an ASR should produce. The interaction between the waves and the reef are explained in this chapter.

In previous research (Henriquez, 2004), the currents driven by wave breaking over the reef had not been taken into the design. It appeared that wave-driven currents play an important role in ASR design. Therefore research was done for an integral reef design, taking the currents into account.

In this study the x-axis is chosen in the cross-shore direction and the y-axis is chosen in the alongshore direction.

2.1 Wave breaking

In Figure 2.1 a conventional surf reef is presented with the breaker line. Surfers start their wave ride at point S, the take-off, and surf along the breaker line to point E, the end of the wave ride. The wave between point S and point E should break in such a manner that they are considered surfable. In order for an ASR to produce surfable breakers, it is important to understand the characteristics of such breakers. These are described by a set of surfability parameters which together determine the surfability.

![Figure 2.1 Artificial surf reef, thin solid lines denote depth contours, dashed line denotes breaker line and the thick arrows denote the wave ride of a surfer.](image-url)
Peel angle

Surfable waves never break all at once along the wave crest. If this occurs, surfers would say that the waves are closing-out and not suitable for surfing. In order for a wave to be surfable, the wave has to break gradually (read peel) along the wave crest. The velocity with which this happens is called the ‘peel rate’ $|\mathbf{V}_p|$ of the wave. See Figure 2.2 for an illustration.

![Figure 2.2 A closed-out wave (left) and a peeling wave (right) (From surflineline.com and surfermag.com, respectively).](image)

The peel angle is the most important surfability parameter. In order to explain this parameter we use Figure 2.3. The peel angle is the angle $\alpha$ enclosed by the wave crest and the breaker line (Walker, 1974). In this figure also the wave celerity $c$ and the peel rate $V_p$ vectors are indicated. The absolute value of the vector sum of these velocities is the actual velocity experienced by the surfer, called down-line velocity $V_s$, which is the magnitude of the velocity vector along the breaker line.
Whether a wave is surfable or not depends mainly on the value of the peel angle $\alpha$.

The down-line velocity is related to the peel angle as: $|\vec{V}_d| = \frac{c}{\sin \alpha}$. Thus, when the peel angle becomes too small, the down-line velocity becomes very high and too fast for the surfer. The value of the peel angle needs to be sufficiently large in order for a wave to be surfable. The velocity a surfer can reach depends, mainly on the wave height $H$ and the skill of the surfer. Hutt et al. (2001) investigated what the necessary peel angle has to be for a given wave height $H$ and surfer skill. The higher the waves, the smaller the peel angle can be; likewise with increasing surfer skill a smaller peel angle can is acceptable. The definition of these surfer skills and the peel angle related to the skill of the surfer and the wave height are described in Hutt et al. (2001).

The phenomenon of peeling waves is not as obvious as one would think. Waves approaching a sloping shore with straight and parallel depth contours under an angle $\theta$ will refract such that the wave angle at breakpoint $\theta_b$ of the waves is nearly zero. The main challenge of an ASR is to obtain peel angles which are large enough to be surfable. This can be achieved by using a reef with relatively steep slopes and with an angle $\beta$ enclosed between the reef normal and the beach normal. The ASR, and thus wave refraction over the reef, has to start in sufficiently shallow water such that the peel angles can be large enough for surfing purposes. This can be understood by considering Snel’s law:

$$\frac{\sin \theta_h}{c_b} = \frac{\sin \theta_r}{c_r} \quad (2.1)$$
where \( c \) is the wave celerity and \( \theta \) is the wave angle, subscripts \( b \) and \( r \) denote the breakpoint and the depth at which the reef starts respectively. Snel’s law only applies to an alongshore uniform beach and therefore the wave angles must be defined with respect to the reef normal. Then the break angles \( \theta_b \) are replaced with the peel angles \( \alpha \) and Equation 2.1 becomes:

\[
\sin \alpha = \frac{c_b \sin \theta}{c_r}
\]  

(2.2)

With \( \theta_r \) constant, variations of the depth at which the reef starts \( h_r \) only weakly affect \( c_b \). Then it follows from Equation 2.2 that the peel angle \( \alpha \) is directly related to the wave celerity \( c_r \). By decreasing the depth at which the reef starts, the wave celerity \( c_r \) is decreased resulting in higher peel angles. This is seen in Figure 2.4. Wave ray 1 starts refracting in shallower water than wave ray 2 and this results in a higher peel angle \( \alpha_1 \) than the peel angle \( \alpha_2 \) of wave ray 2.

**Figure 2.4** Artificial surf reef with peel angles \( \alpha_1 \) and \( \alpha_2 \) of wave ray 1 and wave ray 2, respectively; thin solid lines denote depth contours and dashed line denotes breaker line.
Wave height

Waves can be surfed from 0.15 m up to 25 m high. Long boarders start surfing when waves are 0.5 m, while some professional surfers still surf waves of 25 m. In general, most recreational surfers are surfing waves between 1 m en 5 m.

The wave height at the take-off can be increased by the artificial surf reef, using the phenomenon of wave focussing. Wave focussing occurs where wave rays converge due to wave refraction. This is the case at the tip of the reef (Figure 2.5). Due to wave focussing the wave heights along the wave crest have a gradient, the part with high wave heights will break in deeper water than the part with low wave heights, resulting in a breaker line not parallel to the depth contours. This can also affect the peel angles. The effect of wave focussing on the peel angle can only be estimated with the use of numerical models due to the complexity of the combined effects of wave refraction and diffraction.
Breaker shape

The shape of a breaking wave is of great importance for surfing. The breaker type is a means of classifying the shape of breaking waves. The main surfable types are (technical part of terminology by Galvin (1968)).

- **Spilling breakers** occur if the wave crest becomes unstable and flows down the front face of the wave producing a foamy water surface. Surfers would say a ‘weak’ wave.
- **Plunging breakers** occur if the crest curls over the front face and falls into the base of the wave, resulting in a high splash. Surfers call this a ‘tubing wave’.

The breaker type can be quantified with the inshore Iribarren number defined as (Battjes, 1974):

\[
ξ_b = \frac{s}{H_b^{1/2} L_0^{1/2}}
\]  

(2.3)

where \(H_b\) is the wave height at breakpoint, \(L_0\) the deep water wave length and \(s\) the bottom slope. The parameter can physically be interpreted as the ratio between the bed slope steepness and the local wave steepness. The value of the Iribarren number corresponds to each regime as in Table 2.1.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spilling</td>
<td>(ξ_b \leq 0.4)</td>
</tr>
<tr>
<td>Plunging</td>
<td>(0.4 &lt; ξ_b &lt; 2.0)</td>
</tr>
</tbody>
</table>

It should be noted that these results are based on experiments on plane slopes, with normally incident waves.

2.2 Wave-driven currents

Currents around a surf break are of vital importance when considering the surfability of the break. Rip-currents, narrow strong currents that move seaward through the surf zone (Bowen 1969), negatively affect good surfable waves. When the rip-current flows through the breakers, the wave appears to get a rough surface and breaks in an irregular manner, making the waves unsuitable for surfing. Rip-currents can be advantageous as well; the surfer can use the rip-current to get easily outside the breaker zone. It can also be the case that the waves are perfectly surfable, but yet unreachable due to strong currents.

Table 2.2 shows the results of an experiment by Henriquez (2004) to estimate the typical paddling speed in still water. Three types of paddling are mainly distinguished from each other by the duration a surfer can maintain the paddling speed. Slow paddling can be maintained for more than 10 minutes, moderate paddling can only be maintained for a few minutes and fast paddling, which is specifically used to support the take off, can only be maintained for a few seconds.
2.2.1 Conventional artificial surf reefs

In previous research of ASRs currents, affecting the surfability, had not been taken into account. In order to determine the currents over the reef and the effects of these currents on the surfability, numerical calculations were done with a Boussinesq model. Figure 2.6 and 2.7 show the prediction of the current field by the model for a typical ASR topography for normally incident waves with an offshore wave height $H_0$ of 1.5m.

<table>
<thead>
<tr>
<th>Type of paddling</th>
<th>Shortboard 6’3”</th>
<th>Longboard 9’3”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow/cruise</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Moderate/tough</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Fast/ take-off</td>
<td>1.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Table 2.2** Paddle speed of a surfer (m/s)

**Figure 2.6** Bathymetry of the reef. Arrows denote the current directions and magnitudes, thin solid lines denote the depth contours from 6m to 1.5m, the dashed line denotes the breaker line and the thick solid lines denote the breaker line without the presence of currents.
Figure 2.6 shows, that at the location of the rip-current the breaker line is moved offshore and the wave heights at the location of the rip-current are increased (figure 2.7a). The offshore movement of the breaker line with respect to the breaker line without the presence of currents causes a smaller angle between the breaker line and the wave angles in the rip-current. This is resulting in lower peel angles (figure 2.7b) which can be too low to be surfable and thus making the waves unsuitable for surfing.

The seaward moving breaker line can be explained, in a one dimensional consideration, using the dispersion relationship:

\[ \omega' = \omega + kU \]  \hspace{1cm} (2.4)

where \( \omega' \) is the radian frequency with respect to the bottom, \( \omega \) is the intrinsic radian frequency, \( k \) is the wave number and \( U \) is the current velocity. After rewriting Equation 2.4 the dispersion relationship becomes:

\[ c_g' = c_g + U \]  \hspace{1cm} (2.5)

where \( c_g' \) is the group celerity with respect to the bottom and \( c_g \) is the intrinsic group velocity. The equation for the energy flux outside the breaker zone yields.

\[ F = \frac{1}{8} \rho g H^2 c_g' = \text{constant} \]  \hspace{1cm} (2.6)

Where \( F \) is the energy flux, \( \rho \) is the density of water and \( H \) is the wave height. When encountering opposing currents, the group celerity \( c_g' \) decreases according Equation 2.5. According to Equation 2.6, if the group celerity decreases the wave height \( H \) must increase. Thus when a current flows seawards through the breaker zone, the waves increase in height causing them to break earlier. This is moving the breaker line offshore resulting in peel angles potentially too low to be suitable for surfing.
It is observed by Henriquez (2004) in his experiment that waves in a rip current break irregular and in sections. This might be caused by variations in the velocity of the rip-current resulting, according to Equation 2.4 and 2.5, in variations in wave heights. These variations in wave heights can be the cause of the irregular and in sectional breaking of the waves. It turns out that for the conventional ASR rip currents negatively affect approximately 20% of the wave ride (Figure 2.6). Thus in order to design an improved ASR the wave-driven currents over the reef have to be taken into account. In other words, the currents which are flowing through the breakers have to be minimized. Therefore it is important to understand the driving mechanism of the wave-driven currents over the conventional ASRs.

The main driving mechanisms for the rip currents through the breakers caused by the artificial reef are the currents induced by differences in pressure gradients. These pressure gradients occur due to differences in breaker heights over the reef and at the sides of the reef. The rip currents are also driven by the alongshore current along the reef. These two mechanisms will be explained in the following.

The bathymetry of an artificial surf reef is shown in Figure 2.8. At the tip of the reef the wave rays converge leading to a higher wave height (see also Figure 2.5). At the sides of the reef the wave rays diverge and the wave height is smaller. At the shore next to the reef the wave rays are undisturbed.

---

**Figure 2.8** Bathymetry of the reef where solid lines denote depth contours; convergence at the tip of the reef and divergence at the sides of the reef. At the shore next to the reef the wave rays are undisturbed.

Wave breaking causes dissipation of wave energy over the reef. This wave energy dissipation is leading to a radiation stress gradient over the reef. The equation of the radiation stress yields (Longuet-Higgins and Stewart, 1962):

\[ S_{xx} = \left(2 - \frac{1}{n} + n \cos^2 \theta\right) E \]  

(2.6)
Artificial surf reefdesign

where $S_{xx}$ is the radiation stress in $x$-direction, $n$ is the ratio between the wave celerity and group celerity, $\theta$ is the wave angle with respect to the $x$-axis and $E$ is the wave energy. The gradients of radiation stress over the reef are leading to water level gradients (wave set-up) over the reef according to the momentum equation:

$$\rho gh \frac{d\eta}{dx} = -\frac{dS_{xx}}{dx}$$

(2.7)

Where $h$ is the water depth and $\eta$ is the mean water level. There is a smaller set-up at the sides of the reef, due to smaller wave heights. These alongshore variations in wave set-up are leading to alongshore gradients in the water level $\frac{d\eta}{dy}$ in the surfzone (Figure 2.9). These will produce alongshore directed flows, called the feeder currents, of water toward the sides of the reef where the water level is lowest. At these points the feeder currents turn seaward as a rip current next to the reef (Figure 2.9).

**Figure 2.9** Set-up $\eta$ gradients over the reef for cross section A-A’ (left) and (right) bathymetry of the reef where solid lines denote depth contours, white vertical arrows denote the feeder current-, white diagonal arrows denote the alongshore current- and the black diagonal arrows denote the rip current directions and strengths.

To explain the appearance of the alongshore current, the artificial surf reef is schematized as a sloping shore with straight and parallel depth contours, with waves approaching under an angle. These waves are known to induce an alongshore current (Longuet-Higgins, 1970). This alongshore current can be seen as a feeder current, flowing to the side of the reef (Figure 2.9).
2.2.2 Integral artificial surf reef

In the previous sections, it is made clear that currents driven by wave breaking on ASRs negatively influence the waves over the reefs and the driving mechanism of these currents over the reef was sketched. As the conventional ASRs do not perform well in the presence of wave-driven currents an integral concept for an ASR design is presented in Figure 2.10, taking into account the attendant currents.

In fact this concept was already built on the Gold Coast of Australia. The reef was designed by Black et al. (2001). The main goals for this reef were the decreasing of the alongshore sand transport resulting in widening of the beach and the improvement of the surfing conditions. Black designed the channel: (1) to eliminate wave interference on the take-off zones and main part of the wave; (2) to provide the space needed at the take-off and (3) as a paddling channel to give surfers access during moderate and large wave conditions when the adjacent beaches are closing out.

One of the objectives is to decrease the wave-driven currents which are flowing through the breakers. In this study the rip channel is included to minimize the rip currents at the sides of the reef. This is done by creating a rip-channel in the middle of the reef where surfers do not surf. In the rip channel no wave breaking occurs and the cross-shore set-up gradients in the channel are thus smaller. The alongshore variations in wave set-up (Figure 2.10) produce feeder currents to the channel and to the sides of the reef. The rip currents at the sides of the reef are therefore expected to decrease.

Figure 2.10 Set-up $\eta$ gradients over the reef for cross section A-A’ (left) and (right) bathymetry of the reef where solid lines denote depth contours, white vertical arrows denote the feeder current-, white diagonal arrows denote the alongshore current-and the black diagonal arrows denote the rip current directions and strengths.
3 Numerical study

One objective of the present research is to gain insight in reef properties that influence the currents over the reef and associated effects on the surfability parameters. Another objective is to design a reef shape optimized for surfing purposes. In Chapter 2 theoretical considerations are outlined relevant to ASR design. In this chapter the influence of different reef shapes on the attendant current field is investigated and an optimal artificial surf reef is designed. In this design, both waves and effects of wave-driven currents are taken into account by means of numerical wave and wave-current models.

For the numerical studies three models were used: 1) An ASR was designed with a spectral model without taking into account the wave-driven currents; 2) A surf beat model was used to design the ASR, taking into account the wave-driven currents; this model operates on the time scale of wave groups and therefore the surfability can not be determined with this model (individual waves are not modelled); 3) A Boussinesq model operating on the intra-wave time scale was used. With this model the wave-driven currents and their corresponding effect on the surfability were determined for the ASR designed with the surf beat model. The models are complementary. The spectral model can be used for rapid assessment of the wave transformation of the reef (first guess), but does not include effects of wave-driven currents. The current field can be efficiently estimated with the surf-beat model, which however does not resolve individual waves. Finally, a detailed analysis, at the expense of considerable computational effort, including all the relevant physics, can be made with the Boussinesq model.

3.1 Design features and demands

The wave conditions used represent typical conditions on the North Sea experienced in The Netherlands on good surfing days. The offshore wave height $H_0$ is 1.5 meter and the individual wave period $T$ is 8 seconds. For the numerical modelling, bichromatic waves were used with a group period of $T_g$ is 56 seconds. Bichromatic waves are a much better representation of reality than monochromatic waves. The bathymetry is restricted by the physical dimensions of the laboratory experiment. The experimental set-up was chosen using the largest scale as possible. The maximum water depth for the prototype design is therefore 6 meters and the beach slope used is 1:20.

The required values for the surfability parameters for these design features were derived from Henriquez (2004). The surfer skill should be 5 or higher. Given the offshore wave height the peel angle should be at least 40°; slightly higher values are acceptable but their occurrence should be minimized. The waves should break in a plunging manner: the Iribarren numbers should be larger than 0.4. Since the offshore wave height is relatively small, the waves should not break in a too plunging manner, as this would make them too difficult to surf. An Iribarren number ranging between 0.7 and 0.9 is expected to result in a nice plunger suitable for surfing. At the start of the wave ride the value of $\xi_b \approx 0.7$ is preferred for the take-off. The wave height depends on the offshore wave height and reef angle. Something that should be aimed at is the de-focussing of wave energy. The wave height should not decrease below the offshore wave height. The design should be optimized for surfing purposes taking into account the currents driven by wave breaking over the reef.
This means that the rip currents through the breakers should be minimized. In Table 3.1 the design features and demands are summarized.

<table>
<thead>
<tr>
<th><strong>Table 3.1</strong> Design features and demands</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bichromatic wave field</strong></td>
</tr>
<tr>
<td>Wave period $T$ (s)</td>
</tr>
<tr>
<td>Group period $T_g$ (s)</td>
</tr>
<tr>
<td>Offshore wave height $H_0$ (m)</td>
</tr>
<tr>
<td>Offshore wave angles $\theta$ (deg)</td>
</tr>
<tr>
<td><strong>Topography</strong></td>
</tr>
<tr>
<td>Slope gradient seabed</td>
</tr>
<tr>
<td>Offshore water depth $h$ (m)</td>
</tr>
<tr>
<td><strong>Surfability</strong></td>
</tr>
<tr>
<td>Peel angle $\alpha$ (deg)</td>
</tr>
<tr>
<td>Iribarren number at take-off $\xi_0$</td>
</tr>
<tr>
<td>Range of the Iribarren number</td>
</tr>
<tr>
<td>along wave ride $\xi_0$</td>
</tr>
<tr>
<td>Wave height along wave ride $H_b$ (m)</td>
</tr>
<tr>
<td><strong>Currents</strong></td>
</tr>
<tr>
<td>Rip currents</td>
</tr>
</tbody>
</table>

### 3.2 Artificial surf reef design with a spectral model

#### 3.2.1 The spectral model

The propagation of waves over the artificial surf reef was simulated with nonlinear RefDif (www.coastal.udel.edu) as described in Kaihatu and Kirby (1995), referred to as the spectral model. The model is a frequency-domain, parabolic mild-slope equation that takes quadratic nonlinearities into account.

For the simulations two frequency components were used. One represents the primary frequency $f_1$ and the other the corresponding harmonic $f_2 = 2f_1$. The values of the amplitudes of the primary wave and the corresponding harmonic at the offshore boundary were estimated by the author using the Fourier approximation method of Rienecker and Fenton (1981). The model uses an explicit breaking criterion; waves break when $H \geq 0.8h$ where $H$ is the wave height and $h$ is the water depth at break point.

The surfability parameters were estimated using the output of the wave model. The output of the wave model consist of data files containing the wave angle, the wave height and information as to whether or not the wave breaking condition is met at each grid point. A breaker line was constructed out of the grid points where wave breaking was started. Two consecutive initial break points were connected to each other by one grid block. Peel angles, down-line velocity and the inshore Iribarren number were estimated at these grid points. The inshore Iribarren number was determined by using the local bottom slope in the direction of wave propagation at that location over the reef (this is the actual bottom slope experienced by the wave).
3.2.2 Reef shape

In Henriquez (2004) the design “rules” for an artificial surf reef were described in detail and an optimal reef shape (Figure 3.1) was proposed. However, for the design, currents had not been taken into account. Before designing an optimal artificial surf reef taking into account the currents, a design without currents was made to satisfy the surfability parameters. In order to find the optimal reef shape according to the design features, the following reef parameters were varied:

- The depth at which the reef starts
- The reef angle, the angle enclosed by the reef normal and offshore wave direction
- The slope of the reef normal to the depth contours
- The radius of the tip to influence the Iribarren number at the take-off.

One parameter, the depth of the reef crest with respect to the still water level, was not varied; the depth was chosen the same as the offshore wave height to make sure the waves still break on the reef and the reef does not become too shallow. An explanation of these parameters is to be found in Henriquez (2004). In the next section the modelling results are presented and discussed.

![Figure 3.1](image.png)

**Figure 3.1** Optimal reef shape by Henriquez (2004), solid lines denote depth contours and the dashed line denotes the reef normal.

3.2.3 Modelling results

Since the wave ride is very short with a seabed slope of 1:20 the reef starts as deep as possible to receive the longest wave ride. The first variable to be varied was the reef angle. Since the smaller the reef angle the higher the waves due to less refraction, the minimum reef angle which still meets the demand for the peel angle, had to be found numerically. After the optimal reef angle was found, the reef slope and the radius of the tip should be varied as well to find the values which satisfy the demands for the Iribarren numbers. The optimal values for the reef parameters obtained through extensive trial and error, are presented in Table 3.2 and the results of the numerical modelling utilizing the spectral wave model (providing a first guess) in Figure 3.2
Table 3.2 Results for the reef parameters.

<table>
<thead>
<tr>
<th>Reef parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of reef crest (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Depth at which the reef starts (m)</td>
<td>6</td>
</tr>
<tr>
<td>The reef angle (deg)</td>
<td>55</td>
</tr>
<tr>
<td>The slope of the reef 1:s</td>
<td>1:7</td>
</tr>
<tr>
<td>The radius of the tip (m)</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 3.2 (a) is the reef shape where solid lines denote depth contours, (b), (c) and (d) are respectively the wave heights $H$, peel angles $\alpha$ and Iribarren numbers $\xi$ along the breaker line projected on the $y$-axis. Grayscale bar denotes water depth in meters.

Figure 3.2 shows the surfability parameters of the breaker over the designed ASR. The wave heights stay above the offshore wave height of 1.5 m. The peel angles are between 40 degrees and 50 degrees. The variations in the peel angles are acceptable. The Iribarren number at the take-off is 0.7 and varies along the ride between 0.7 and 0.9.

These calculations do not take the currents into account. Therefore, in the next section numerical calculations are done with the surf beat model to optimize the design while minimizing the wave-driven currents.
3.3 Artificial surf reef design with a surf-beat model

3.3.1 The surf-beat model

This section is partly rewritten from Reniers et al. (2004). The numerical model is a research version of Delft3D (www.wldelft.nl). New wave and roller modules describing wave propagation and breaking, operating on the timescale of wave groups, are coupled to a depth averaged nonlinear flow model to predict the time-dependent flow field. The model concept is illustrated in Figure 3.3, showing the propagation of grouped short waves of which only the wave energy on the group scale, proportional to the square of the wave envelope, is modelled. Under the groups of short high waves, water is forced toward areas with smaller waves, thus creating a bound sub-harmonic wave that is 180° out of phase with the short-wave groups, travelling with the group velocity. Within the surf zone, the wave group modulation is destroyed by wave breaking and consequently the bound sub-harmonic wave is released, reflects off the beach and returns as a free wave.

Figure 3.3: Depiction of wave groups normally incident on a beach with corresponding wave envelope (thick solid line), bound sub-harmonic wave (dashed line) and free returning sub-harmonic wave (dash-dotted line) (from Reniers et al., 2004).

The wave driver input is obtained from a frequency direction energy density wave spectrum, \( E(f,\theta) \). The model considers the wave energy associated with wave groups. The energy associated with the wave groups is propagated shoreward, where the mean wave direction is obtained from the pre-computed wave refraction utilizing the wave model HISWA (Holthuijsen et al., 1989). Wave energy released at wave breaking is first transferred to roller energy prior to dissipation causing a spatial lag between the location of wave breaking and the actual dissipation. Wave diffraction and wave-current interaction are neglected at present. The temporal and spatial variation (on the wave group scale) of the wave and roller energy is used to calculate the radiation stresses. The mean and wave group motions are solved using nonlinear shallow water equations forced by radiation stresses to phase resolve bound and free infragravity waves. The flow model uses eddy viscosity to describe turbulent momentum mixing.
3.3.2 Reef shapes

In order to do sensible simulations, a simplified rip-current system (Figure 3.4) is used to determine the most important parameters which influence the rip currents.

![Figure 3.4](image)

**Figure 3.4** Rip-current system with bars and channels, the onshore and offshore directed arrows denote the currents (the offshore directed arrows denote the so-called rip currents).

The integral ASR design from section 2.2.2 can be schematized to a rip-current system with two bars (see the area with the dotted boundary in Figure 3.4), where the bars denote both halves of the reef. The cross sections of the bars and channels are presented in Figure 3.5.

![Figure 3.5](image)

**Figure 3.5**: Schematized bar (reef) and channel sections; bar (left) and channel (right), $b$ is the wave set-up and $h$ is the water depth.

Bellotti (2004) derived equations for wave-set up and rip-current velocity for a rip-current system on a sloping bottom. In this schematized case the bottom is flat and the equation for the wave set-up $b$ at the inshore toe of the bar simplifies to the following form:

$$b = \frac{3}{16} \left( \frac{H_{b0}^2 - H_{bb}^2}{h} \right)$$

(3.1)

where $H_{b0}$ is the wave height at the offshore toe of the bar, $H_{bb}$ is the wave height at the inshore toe of the bar and $h$ is the water depth.
The wave set-up, which plays a pivoting role in the driving mechanism for the wave-driven currents, depends mainly on the difference in wave heights over the bar and the water depth (Equation 3.1). The difference in wave height over the bar depends on e.g. shoaling, refraction and diffraction. Due to the complexity of the integral ASR design it is impossible to predict the difference in wave heights over the bar. Therefore the numerical study was pursued.

With the knowledge that the wave set-up induced by the difference in wave height over the reef plays a pivoting role, the simulations are set-up. It is to be expected that the rip currents over the reef can be influenced by varying the width of the reef in $x$ and $y$-direction and the width of the rip channel.

All the reef shapes are placed on a plane beach, with the offshore wave direction normal to the depth contours of the beach. To minimize the number of possible shapes and to keep the reef shapes relatively simple, restrictions were applied to the reef shapes. Firstly, the depth contours of the reef can be straight, circular or a combination of both. Secondly, the bed slope normal to the depth contours of the reef is constant and is the same over the whole reef.

In the following a description is given on how to influence the wave-driven currents by changing the reef parameters. The width in $x$-direction can be varied by shortening the reef (Figure 3.6).

![Figure 3.6](image)

**Figure 3.6** Varying the length of the reef in $x$-direction; cross-section of the reef, uncut (left) and cut (right).
The width in $y$-direction of the reef can be varied by the internal slope of the reef (Figure 3.7a). The width of the reef in $x$ and $y$-direction together can be varied by the internal angle of the reef (figure 3.7b). And variations in the width of the rip channel can be made by placing both halves of the reef at different distances (figure 3.7c).

**Figure 3.7** Variations in reef shapes, (a) internal reef slope, (b) internal reef angle and (c) width of the rip channel, lines denote depth contours.
3.3.3 Numerical Modelling, results and interpretation

The time of the simulations with the surf-beat model is 40 minutes; this simulation length is required to minimize the effects of spin-up behaviour. The simulations were performed with varying length of the reef in $x$-direction perpendicular to the shore. This was followed by a set of simulations varying the internal reef angle, the internal reef slope and finally the width of the rip channel. The order of the simulations with respect to the different reef shapes is arbitrary except for the width of the rip channel. The variations of this width were simulated last, as the preferred shape of the channel depends strongly on the other reef shapes. Finding the best reef parameters was done by varying them with step sizes shown in Table 3.3. The length in $x$-direction perpendicular to the shore was only simulated for two values. The first one is the complete length of the reef until the depth contours equal the depth contours of the shore, referred to as the uncut reef. And for the second one the reef is cut just behind the breaker line at the end of the reef, so that the waves will still break on the reef (see also Figure 3.6), referred to as the cut reef. Based on the outcome of the simulations, sensible values for the reef variables were chosen for the next simulation, so that not all the possible combinations of the reef variables are simulated. Moving to simulations with other reef parameters, the knowledge obtained with the previous one was used. Thus by making comprehensive choices the number of required simulations was reduced.

<table>
<thead>
<tr>
<th>Reef parameter</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal reef angle (deg)</td>
<td>10</td>
</tr>
<tr>
<td>Internal reef slope (-)</td>
<td>1</td>
</tr>
<tr>
<td>Rip channel width (m)</td>
<td>5</td>
</tr>
</tbody>
</table>
The first two simulations consisted of varying the length of the reef in $x$-direction perpendicular to the shore. First the uncut reef was simulated followed by the simulation of the cut reef. The results are presented in Figure 3.8.

The numerical simulations show that the rip current through the channel is slightly weaker with the cut reef than with the uncut reef. The rip currents through the breakers are decreased as well with the cut reef. The objective was to minimize rip current velocities and therefore the cut reef appears the better choice.

**Figure 3.8:** Absolute mean current velocities averaged over 40 minutes for the uncut reef (left) and cut reef (right), colour bar is in m/s.
The influence of varying the internal reef angle on the currents driven by wave breaking over the reef is shown in Figure 3.9. The simulations were performed for internal reef angles of 0°, 30°, 60° related to the shore normal. When the internal angles are larger than 60° the wave ride becomes shorter and are therefore not simulated. The mean current fields with mean velocities are presented in Figure 3.9.

**Figure 3.9** Absolute mean current velocities averaged over 40 minutes in m/s for different internal reef angles, colour bar is in m/s.

The numerical simulations show, that by reducing the reef width in $x$ and $y$-direction (through increasing internal reef angle) the rip current through the channel decreases. The rip current through the channel is weaker with an internal reef angle of 60° than with an internal reef angle of 0°. The rip currents through the breakers are decreased as well for increasing internal reef angle.
Considering the previous simulations, it was found out that an internal reef angle of 60° and a cut reef fitted best to the design demands. Therefore in the next simulations, where the internal reef slopes were varied, the optimum internal reef angle and the cut reef were used, thereby reducing the number of required simulations. The simulations were started with a mild internal slope of 1:6. The mean current velocities are shown in Figure 3.10.

\[ \text{Figure 3.10 Absolute mean current velocities averaged over 40 minutes for different internal reef slopes, colour bar is in m/s.} \]

It is obvious from the numerical simulations that with reducing the reef in $y$ direction the rip current through the channel decreases. The rip current through the channel is weaker with an internal reef slope of 1:1 then with an internal reef slope of 1:6. The rip currents through the breakers are decreased as well with a steeper internal reef slope, although the difference in strength between the 1:3 and 1:1 situation is negligible. Considering the design demands the best internal reef slope is 1:1.

The previous simulations showed that the optimum internal reef angle is 60°, the optimum internal reef slope is 1:1 and the reef should be cut. In the next simulations the width of the rip channel was varied, using the optimum values for the internal reef angle and slope. The mean current velocities are presented in Figure 3.11.
Figure 3.11 Absolute mean current velocities averaged over 40 minutes for different rip channel widths, colour bar is in m/s.
From figure 3.12 it is evident that by reducing the rip channel width, the rip currents through the breakers reduce in strength and the rip current in the rip channel increases in strength. However, for a rip channel width of 5 m or smaller no rip current through the rip channel exists yielding much stronger rip currents through the breakers. The rip currents through the breakers are the smallest for rip channel widths of 10 m and 15 m.

During the simulations it became evident that the width of the rip channel not only influences the strength of the rip currents, but the stability of the currents in the rip channel as well. One can understand that a meandering current which sheds eddies is not favourable for surfers. Therefore the standard deviation of the absolute velocities for each channel width is plotted in figure 3.12 to find the effects of the width of the rip channel on the stability of the current.

**Figure 3.12** Absolute mean standard deviation of mean current velocities averaged over 40 minutes for different rip channel widths, colour bar is in m/s.
The currents over the reef with a rip channel width of 10 meter are more stable than the currents over the reef with a rip channel width of 15 m. Therefore a rip channel width of 10 meter is the optimum value.

The final ASR design has an internal reef angle of 60 degrees, an internal reef slope of 1:1, a rip channel width of 10 meter and is cut just behind the breaker line at the end of the reef.

A simulation was done with a conventional ASR to determine the differences in strength of the currents through the breakers with respect to the integral ASR design. This simulation was done with the ASR designed in section 3.2. Figure 3.13 shows the results of the simulation for the conventional surf reef and Figure 3.14 shows the results of the integral artificial surf reef design.

![Figure 3.13](image)

**Figure 3.13** Conventional artificial surf reef design, solid lines denote depth contours of the reef (left) and arrows denote mean current directions averaged over 40 minutes (right) with absolute mean current velocities, colour bar is in m/s.
The rip currents through the breakers over the conventional ASR are about 1 m/s. Considering the integral ASR design, the maximum current velocities through the breakers are about 0.6 m/s and through the channel about 1 m/s. The simulation of the final ASR design shows that, the rip currents through the breakers are decreased about 40%. It can be concluded that the design meets the objectives: the currents through the breakers are minimized and the rip current through the channel is relatively stable.

**Figure 3.14**: Integral artificial surf reef design, solid lines denote depth contours of the reef (left) and arrows denote mean current directions averaged over 40 minutes (right) with absolute mean current velocities, colour bar is in m/s.
3.4 Artificial surf reef design with a Boussinesq model

3.4.1 The Boussinesq model

This section is partly rewritten from Kirby et al. (1998). The propagation of waves over the ASR and the ambient currents were simulated with the Boussinesq model (Funwave2D, www.coastal.udel.edu) as described in Kirby et al. (1998). This section provides a small overview of the theory in the numerical Boussinesq model.

Boussinesq-type equations provide a general basis for studying wave propagation in two horizontal dimensions. At their core, the equations are the linear shallow-water equations for non-dispersive wave propagation. This basic foundation is extended by the addition of terms which include the lowest order effects of nonlinearity and frequency dispersion.

The assumption of weak frequency dispersion effects makes the standard Boussinesq equations invalid in intermediate and deep water. The corresponding dispersion relation of the standard Boussinesq equation only matches well in shallow water areas. Extended forms of Boussinesq equations have been derived by Nwogu (1993). Nwogu (1993) used the velocity at a certain water depth as a dependent variable and pursued a consistent derivation of the governing equations using this non-standard dependent variable. In the end, the choice of the representative depth was constrained by the goal of obtaining the most accurate possible dispersion relation.

Despite their improved dispersion relation, the extended Boussinesq equations are still restricted to situations with weakly non-linear interactions. Moreover, as shown by Chen et al. (1998), the sets of equations introduced by Nwogu (1993) are not applicable to combined wave-current motions which are often encountered in near-shore regions.

Adapting the approach of Nwogu (1993), but making no assumptions of small non-linear effect, Wei et al. (1995) derived a new set of Boussinesq equations which include additional non-linear dispersive terms. Not only can the equations be applied to intermediate water depth as the extended Boussinesq equations with improved dispersion relation, but are also suitable for simulating wave propagation with strong nonlinear interaction. The inclusion of full nonlinearity also leads to a correct form of doppler shift in the equations when an ambient current is present.

To enable the Boussinesq model to simulate surf zone hydrodynamics, energy dissipation due to wave breaking is modelled by introducing an eddy viscosity term into the equations, with the viscosity strongly localized on the front face of the breaking waves.

For the simulations in this chapter bichromatic waves were used to give a good estimate of the wave-driven currents. The original model however, was only capable of simulating monochromatic waves. Waves in the model are generated by a source function. To model bichromatic waves, the author superimposed a second wave at the source function in the code of the model through personal communication with Q. Chen.
The surfability parameters were estimated using the output files of the wave model. The output of the wave model consists of data files containing the surface elevation at all time steps and velocity components in $x$ and $y$ direction averaged over an integer multiple of wave periods. The wave angles, the wave heights and whether or not the wave breaking condition is met at each grid point, had to be computed out of the time series of the surface elevation before the surfability could be determined.

The wave height is defined by the highest wave height of the wave group (set-wave) and was computed as the difference between the highest surface elevation in the group and the preceding smallest surface elevation. Hereafter the information whether the wave breaking condition is met at the grid points was determined with the breaking criterion $H = 0.8 \ h$, using the computed maximum wave heights at the grid points. The wave angles at each grid point for the set-wave were computed using the following equations.

$$\eta(x, y) = a \cos(\chi) \quad (3.2)$$

where $\chi = k_x x + k_y y - \omega t$ and $a$ is the wave amplitude, $k_x$ and $k_y$ are the $x$-component and the $y$-component of the wave number respectively, $\omega$ is the radian frequency and $t$ is time.

The derivatives to $x$ and $y$ are

$$\frac{d\eta}{dx} = -k_x a \sin \chi \quad (3.3)$$

and

$$\frac{d\eta}{dy} = -k_y a \sin \chi \quad (3.4)$$

respectively.

Squaring and averaging over one wave period gives:

$$\left(\frac{d\eta}{dx}\right)^2 = k_x^2 a^2 \sin^2 \chi = \frac{1}{2} k_x^2 a^2 \cos 2\chi + \frac{1}{2} k_x^2 a^2 = \frac{1}{2} k_x^2 a^2 \quad (3.5)$$
The wave angle can be defined as:

\[
\theta = \arctan \left( \frac{k_y}{k_x} \right) = \arctan \left( \frac{\sqrt{\left( \frac{d\eta}{dy} \right)^2}}{\sqrt{\left( \frac{d\eta}{dx} \right)^2}} \right)
\]  

(3.7)

The numerical approximation for the derivatives to x and y are:

\[
\frac{d\eta_{i,j}'}{dx} \equiv \frac{\eta_{i,j+1}' - \eta_{i,j-1}'}{2\Delta x}
\]  

(3.8)

and

\[
\frac{d\eta_{i,j}'}{dy} \equiv \frac{\eta_{i+1,j}' - \eta_{i,j-1}'}{2\Delta y}
\]  

(3.9)

The numerical approximation of the wave angle can be defined as:

\[
\theta_{i,j} = \arctan \left( \frac{1}{T} \int_0^T \left( \frac{\eta_{i+1,j}' - \eta_{i,j-1}'}{2\Delta y} \right)^2 \right)
\]  

\[
\int_0^T \left( \frac{\eta_{i,j+1}' - \eta_{i,j-1}'}{2\Delta x} \right)^2 \right)
\]  

(3.10)

When the wave angles, the wave heights and the information as to whether or not the wave breaking criterion is met were known, the surfability could be determined.
3.4.2 Modelling results and interpretation

Before determining the effects of the wave-driven currents on the surfability for the conventional ASR and the integral ASR design, the wave-driven currents were calculated (averaged over 10 minutes) with the Boussinesq model. Figure 3.15 shows the results which agree well with the results of the surf-beat model, the currents over the integral ASR are approximately 40% decreased compared to the conventional ASR. In the surf-beat model, the currents were averaged over 40 minutes and were further developed towards the boundaries of the computational domain than the currents computed with the Boussinesq model averaged over 10 minutes. The average velocities with the Boussinesq model however are near-stabilizing after 10 minutes and will only further develop towards the boundaries of the computational domain when simulated longer. This does not affect the surfability as the averaged velocities through the breakers remain nearly the same. When simulating a longer time with the Boussinesq model reflections in the surface elevations occur due to boundary effects, therefore the surfability is determined after 10 minutes.

Figure 3.15 (a) and (b) show the absolute current velocities and directions averaged over 10 minutes for the conventional ASR and the integral ASR respectively, arrows denote current directions and the colour bar is in m/s.
To determine the improvement of the surfability taking the wave-driven currents into account for the integral ASR, the effects of the currents on the surfability of the conventional ASR and the integral ASR design had to be determined. Therefore the surfability for each reef was computed for two cases: the first set-wave over the reef when the currents are not developed yet and after ten minutes when the currents are developed. By comparing these two cases the effects of the currents on the surfability for each reef were quantified. By comparing the quantified effects of the currents on the surfability for each reef, the improvements of the integral ASR are determined. Figure 3.16 shows the surfability of the first set-wave and of a set-wave after 10 minutes over the conventional ASR.

In general, according to section 2.3.1, a rip-current through the breaker will increase the wave heights thereby moving the breaker line offshore potentially resulting in lower peel angles, which can be too low to be surfable. In Figure 3.16 the wave heights are decreasing monotonically along the breaker line; the peel angles are more or less constant and the breaker line is almost straight for the first set-wave. However, the peel angles are about 10 degrees higher than in the computations with

Figure 3.16 (a) is the reef shape where thin solid lines denote depth contours (grayscale bar is in m) and the thick lines denote the breaker lines; (b), (c) and (d) are respectively the Wave heights $H$, Peel angles $\alpha$ and Iribarren numbers $\xi$ along the breaker line projected on the $y$-axis; the dashed lines denote the first set-wave and the solid lines denote a set-wave after 10 minutes.
the spectral model in section 3.2.3. When the currents are taken into account (set-wave after 10 minutes) the wave heights are not decreasing monotonically but increase at the location of the currents (Figure 3.16b), the peel angles are decreased from 50 degrees to 40 degrees (Figure 3.16c) and the breaker line is moved offshore at the location off the rip currents. The simulations do not show that the wave is not suitable for surfing at the location of the rip channel, but do indicate that the rip current is affecting the surfability somewhat.

The other effects of the currents on the breakers (breaking irregular, sectional and with a rough water surface) can not be determined using the numerical model. Currently these effects can only be determined by laboratory experiments.

In the next figures the surfability, of the first set-wave and a set-wave after 10 minutes for the integral ASR are determined. Figure 3.17 shows the surfability of the first set-wave and of a set-wave after 10 minutes for the integral ASR.

Figure 3.17 (a) is the reef shape where thin solid lines denote depth contours (grayscale bar is in m) and the thick lines denote the breaker lines, (b), (c) and (d) are respectively the Wave heights $H$, Peel angles $\alpha$ and Iribarren numbers $\xi$ along the breaker line projected on the $y$-axis; the dashed lines denote the first set-wave and the solid lines denote a set-wave after 10 minutes.
Figure 3.17 shows that in both cases, the peel angles exceed the design demands at the first part of the wave ride. The other design demands are met; the Iribarren numbers range between 0.7 and 0.9 and the wave heights are greater than $H_0 = 1.5m$. The wave heights are decreasing along the breaker line, the breaker line therefore is not moved offshore, it is however not a straight line.

From the numerical simulations we can conclude that for both ASR designs, the peel angles are on the high side. The simulations of the conventional ASR indicate that the rip currents slightly affect the surfability.

### 3.5 Conclusions

One objective is to design a reef shape optimized for surfing purposes, taking into account both waves and effects of wave-driven currents by means of numerical wave and wave-current models. First a conventional ASR was designed without taking the currents into account. From experiments by Henriquez (2004) it is known that approximately 20% of the wave ride is negatively influenced over a conventional reef by rip currents. Therefore an integral ASR was proposed and dimensionally optimized with a surf-beat model taking into account the wave-driven currents. The main objective was to minimize the rip currents through the breakers and stabilize the currents as much as possible. This was done by varying the reef shapes as mentioned above. The final design showed a decrease of the rip currents through the breakers of approximately 40% in comparison with the conventional ASR design. Hereafter the conventional design and the integral ASR design were simulated with the Boussinesq model to determine the improvements of the surfability of the integral ASR in comparison to the conventional reef. The simulations showed that in both ASR designs the peel angles are slightly too high. The spectral model, which is used to design the reef without taking the currents into account, is underestimating the peel angles (Henriquez, 2004). Although, it seems that the Boussinesq model gives better predictions of the peel angles, the experiment should give a decisive answer.

Determining by means of numerical modelling if the integral ASR design produces better breaking waves, considering the irregular and sectional breaking of the wave as well as the rough water surface, is not possible. Therefore laboratory experiments should were conducted. These laboratory experiments are presented in the next chapter where comparisons are made between the numerical and experimental results.
4 Experimental study

The last objective is the verification of the design (and thus numerical predictions) by means of a laboratory experiment, specifically designed to obtain measurements of currents and surfability parameters. The laboratory experiment was conducted in the Fluid Mechanics Laboratory of the TU Delft on scale 1:15. Wave-driven currents, surface elevations and down-line velocities were measured to compare the experimental and numerical results. The Iribarren numbers could not be measured; instead snap shots of the breakers were taken to qualitatively determine the breaking regimes.

4.1 Experimental set-up

The experimental set-up is shown in Figure 4.1. The wave basin is approximately 30 m long and 16.5 m wide. Three piston-type wave generators are located at the offshore end of the wave basin. The wave board width of each wave generator is 5 m, resulting in a total span of 15 m. The limited height of the wave board resulted in a maximum water depth of \( h = 0.40 \) m. On one side, the wall of the basin serves as a wave guide, on the other side a wave guide was built. Opposite to the wave makers, a plane 1:20 slope over the whole width of the wave basin functions as a beach. The smooth bottom of the wave basin ensures minimal frictional dissipation in the flat part between the wave generators and the plane slope.

The prototype reef has a symmetrical shape, but the wave-driven currents through the rip channel are influenced by both sides of the reef. Therefore the whole reef was superimposed on the middle of the plane slope. The reef itself has the shape according to Figure 3.12. The reef is submerged and its crest is at \(-10\) cm with respect to the still water level.

![Figure 4.1 Top view of the wave basin](image)
4.2 Test conditions

The test conditions were obtained by scaling down the wave conditions used for designing the integral ASR in Section 3.3.2, namely bichromatic waves with $H_0 = 1.5$ m, $T = 8$ s. For the correct reproduction of both refraction and diffraction in a Froude-scaled, short-wave hydrodynamic physical model, the model should be geometrically undistorted (Stevens et al. 1942). The deep water wave steepness was scaled using:

$$\left[ \frac{H_0}{L_0} \right]_{pr} = \left[ \frac{H_0}{L_0} \right]_m$$  \hspace{1cm} (4.1)

in which the subscripts $pr$ and $m$ denote prototype and model, respectively. Replacing $L_0$ with $\frac{2\pi}{T}$ in equation 4.1 results in:

$$\frac{(H_0)_m}{(H_0)_{pr}} = \left[ \frac{T_m}{T_{pr}} \right]^2$$  \hspace{1cm} (4.2)

A restriction to the wave conditions results from the requirement, that Stokes second-order wave theory should be valid at the given wave maker. A measure for the relative amplitude of the bound super harmonic is given by the Ursell number, $U_i$:

$$U_i = \frac{HL^2}{h^3}$$  \hspace{1cm} (4.3)

where $h$ is the water depth, $H$ the wave height and $L$ the wave length at the wave maker. Stokes second-order theory is no longer valid for Ursell numbers larger than 25. The laboratory experiments were conducted with unidirectional bichromatic waves. The two frequencies of the bichromatic wave field were chosen such that the group consists of 7 waves. Second-order wave board control was used to generate second-order Stokes waves and to minimize spurious second-order free wave generation (Madsen, 1971). The bichromatic wave conditions are presented in Table 4.1.

<table>
<thead>
<tr>
<th>Waves</th>
<th>$H$ (m)</th>
<th>$f_1$ (Hz)</th>
<th>$f_2$ (Hz)</th>
<th>$U_i$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bichromatic</td>
<td>0.10</td>
<td>0.518</td>
<td>0.448</td>
<td>23.1</td>
</tr>
</tbody>
</table>

Table 4.1 Wave conditions used in the experiments. $H$ presents the maximum wave height in a group. And $f_1$ and $f_2$ represent the two frequency components with equal amplitude of the bichromatic waves.
4.3 Instruments

Measurements were conducted with three electromagnetic flow meters (EMF), three resistant-type wave gauges (WHM) and a camcorder. One WHM was placed approximately 3 m from the wave maker to measure the generated surface elevation. The two other WHMs were placed on a carriage to measure the wave heights at break point of the waves on the reef. The WHMs can slide over the rails and were visually positioned at the break point of the highest wave of the wave group. On the carriage also the three EMFs were placed to measure the current velocities at various depths in the rip channel. See Figure 4.2 and 4.3 for a visual impression and the locations of the instruments over the reef. The camcorder was used for three types of measurements: 1) the camcorder was placed just above the water level to film the shape of the breaking waves; 2) the camcorder was placed at an elevated position over the reef to record the wave transformation over the reef; 3) finally, also from an elevated position, float positions were filmed which were processed with Particle Tracking Velocimetry (PTV) software to determine the currents over the reef and its vicinity.

All the measurements took place after a quasi-stationary situation was reached (approximately one minute) in the small scale currents close to and over the reef. After approximately 5 minutes a large eddy developed, which is expected a boundary effect. In the prototype no such boundary effects are expected, therefore the measurements were conducted between the first and fifth minute after turning on the wave generator.

Figure 4.2 Carriage equipped with a WHM and an EMF positioned at the breakpoint and in the rip channel, respectively.
4.4 Experimental and numerical data

This section compares the laboratory measurements to the numerical values obtained with the Boussinesq model. The data for the currents are compared with the surf-beat model as well.

4.4.1 Wave-driven currents

To measure the wave-driven currents over the reef with the PTV technique, approximately 1000 white floats where distributed in the wave basin and filmed from an elevated position. The reef was divided in three parts to film the floats; the right, the left and the middle. The following analysis had to be repeated for each part. In the first minute of the measurement approximately 700 floats were thrown into the field of view the camera. After the first minute the actual measurement started. The remaining floats were placed outside the view of the camera in such places that they flowed into the field of view by the wave induced basin circulation. The latter was done to ensure that the number of floats in the field of view of the camera remained This was done, to make sure the amount of floats remains more or less constant throughout the duration of the measurement and therefore getting more accurate results. The measurement took three minutes.

![Diagram of the reef with measurement points and directions](image-url)

**Figure 4.3**: Top view of the reef. The carriage is denoted by a dotted line, the numbers indicating various positions. The EMF positions are denoted by the circles. The WHMs are positioned at the break point of the highest wave of the wave group somewhere along the dotted lines.
Measuring velocities in the rip channel was initially problematic. The rip current in the channel was not strong enough to carry continuously floats through the breaker zone. This only happened when floats were locally added to the rip current, to ensure sufficient floats in the rip channel after each set of waves. In this manner only about half of the time the density of floats in the rip channel was sufficient. Therefore complementary measurements were conducted with the EMFs in the rip channel.

The frames of the film were stored as RGB bitmap images. This means that the image is stored as an m-by-n-by-3 data array that defines red, green and blue colour components for each individual pixel. The wave basin was also filmed from the same position when no floats were distributed and no waves were generated. One frame of this film was stored and is referred to as the ‘zero image’. From the images that contain the floats and waves, the ‘zero image’ was subtracted. This yield images where only changes, with respect to the ‘zero image’, are visible. In these images the floats and the white water from the breaker can be seen. The images are referred to as the ‘enhanced images’.

The enhanced images were processed with an advanced PTV program. The enhanced pictures have a frequency of 25 Hz, but the PTV program uses 5 frames per second because the movement of the pixels in 1/25 s is too small to get accurate results. In the PTV program the floats were distinguished from the white water by applying a threshold on the colour components of the pixels. The floats have a high value for the colour component relative to the white water on the ‘zero image’. The PTV program computes for each frame (1/5 sec.) the velocity components for the pixels where the movement of a float is recognized by finding correlations between the present and the previous frame. The output of the PTV program consists of files, containing the velocity components in pixels per 1/5 sec. on pixel coordinates for the corresponding floats. With some post-processing the mean currents were acquired from this data.
The measured mean current velocities and directions for each part of the reef are plotted in (figure 4.4 b). Because the currents were measured in three parts, the figure shows some spurious discontinuities at the boundaries between the parts.

**Figure 4.4** The absolute mean current velocities and directions averaged over 3 minutes for the computed currents (a) and the measured currents (b), respectively; arrows denote current directions and the colour bar is in m/s.

Overall, considerable differences exist in the measured and computed current fields:
- A large asymmetry occurs in the current field, the current velocities on the left are almost half that of the velocity on the right.
- The (rip) currents in the numerical model are directed parallel to the shore, while in the measurements they are directed more offshore.
- The rip current through the channel is smaller in the measurements.
- After 4 minutes a big eddy forms in the observations on the right side of the reef.

In order to try to explain this asymmetry, the bathymetry of the reef was measured with a grid size of 0.5 m. This measured bathymetry was used as input in the surf-beat model and the Boussinesq model. However, both models did not show the asymmetry occurring in the measured current fields.
The cause of the difference in the directions of the currents (alongshore and more offshore) is not understood at present. Figure 2.10 shows that at the sides of the reef the wave set-up is smaller than the wave set-up at the uniform shore next to the reef. This gradient in the mean water level forces the rip currents to flow offshore. The calculations with the surf-beat model do not show this set-up gradient (Figure 4.5) at the sides of the reef. Therefore the currents might not be forced to flow offshore.

The cause of the smaller rip-currents in the rip channel can be explained by the problem of the floats in the channel discussed in this section before. The EMFs positioned in the channel give mean velocities of approximately 0.13 m/s directed straight offshore at -5 cm with respect to the still water level averaged over three minutes (Table 4.2), which agree well with the numerical results.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>0.05</td>
<td>0.11</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The eddy on the right side of the reef is probably the result of the asymmetry in the strength of the currents on the left side and right side of the reef together with the influence of the boundaries.

**Figure 4.5** Expected wave set-up (upper panel) and calculated wave set-up (lower panel) for a cross section at $x = 5$ m, respectively.
4.4.2 Wave heights

The wave height $H$ is defined as the height of the highest surface elevation (wave crest) above the preceding lowest depression (wave trough). The wave heights measured in the flat part of the basin were used as input for the wave model. All the numerical simulations were done with bichromatic waves consisting of two frequencies. Instead of comparing the wave heights at the wave gauges the time series of the surface elevation is compared as it better shows the accuracy of the model. The surface elevation is compared by plotting the measured time series on the computed time series with the wave-current model for each wave gauge number at the right and the left (see Figure 4.3).

From Figure 4.6 it is evident that the computed time series of the surface elevation agree very well with the measured time series at the wave maker.

Figure 4.6 Comparison of computed (dashed line) and measured (solid line) time series of surface elevation $\eta$ at the wave maker.
In Figures 4.7 and 4.8 comparisons are made for the wave gauges at the right and the left side of the reef (see Figure 4.3).

**Figure 4.7** Comparison of computed (dashed lines) and measured (solid lines) time series of surface elevation $\eta$ at 6 different locations along the breaker line.
Figure 4.7 and 4.8 show that the computed and measured surface elevations (and thereby the wave heights) agree very well for the different locations. And no differences are noticeable between the left and the right side, although the currents on the right are much stronger.

Figure 4.8 Comparison of computed (dashed lines) and measured (solid lines) time series of surface elevation $\eta$ at 6 different locations along the breakerline.
4.4.3 Down-line velocities

During the experiment the waves breaking over the reef were filmed from an elevated position. This film was converted into bitmap images to determine the down-line velocity $V_s$. Figure 4.9 shows how this was accomplished. The position of the surfer (see the asterisk in Figure 4.9) was followed across a great number of images. The position of the surfer is where the crest starts to overturn, at the transition of the broken to unbroken wave along the crest. Knowing the coordinates of the positions and the frame rate, the velocity of the ‘surfer position’ can be determined. This estimate is compared to the estimate obtained with the numerical model.

![Figure 4.9 Measuring the down-line velocity $V_s$. $\Delta S$ is the distance a surfer travels between the frames.](image)

Figure 4.10 (a) and 4.10 (b) show that the trend in the numerical data agrees well with the laboratory data of the down-line velocity $V_s$. The agreement is much better for the left side of the reef than the right side of the reef. This is probably due to the stronger rip currents at the right side. The figures show also that at the end of the wave ride the laboratory data is scattered. The scattering is a result of the rip currents travelling offshore through the breakers which affect the waves. When a breaking wave encounters a rip current the wave will break in sections; hence the high down-line velocity $V_s$ observed in the laboratory data. The scattering is larger at the right side than at the left side of the reef, due to the stronger rip current.
Figure 4.10 Down-line velocity $V_s$ along the breaker line projected on the $y$-axis for the right (a) and the left (b) side of the reef.
4.4.4 Breaker shapes

The waves in the laboratory were small and strongly curved during breaking. Henriquez (2004) showed that, the error in predicting the breaker regime due to attendant scale (1:12.5) effects is about 2.5 %. In this experiment the scale effects should be slightly bigger, but still small. According to the numerical model, the Iribarren numbers of the waves breaking over the reef are in the plunging regime and more or less constant (Figure 4.11). At the start of the wave ride the Iribarren number is lower indicating a gentle plunging breaker.

![Figure 4.11 Iribarren numbers along the breaker line projected on the y-axis.](image)

The snap shots in Figure 4.12 and Figure 4.13 show that the waves were all breaking in the plunging regime and are more or less constant along the wave ride. It is not noticeable from the snap shots that the waves at the start of the wave ride break in a less plunging manner than during the rest of the wave ride.
Figure 4.12 Wave shapes at the different wave gauges at the right.
Figure 4.13 Wave shapes at the different wave gauges at the left.
Remarkable is that the wave at gauge number 6 at the right of the reef was breaking in an almost spilling manner. This is due to the fact that the currents on the right were much stronger than on the left. The experiments showed that the waves at the right located at the rip current were breaking very irregular. They were breaking further offshore, sometimes in a spilling manner and sometimes in a plunging manner. The water surface was also very rough. At the left side however, where the rip current was almost twice as weak, these effects were not noticeable and the waves were breaking constantly in a plunging manner without a rough water surface.

Waves meeting an opposing current of which the velocity increases in the upstream direction can meet a point where the local opposing current velocity equals the wave energy transport velocity relative to the water (the intrinsic wave group velocity), so that relative to the fixed bed the wave energy transport vanishes. This is called wave blocking. Wave blocking occurs when $U + C_g = 0$ or when the ratio $U/C_g = 1$, where $U$ is the velocity of the rip current and $C_g$ is the intrinsic wave group velocity. $U/C_g$ within the shallow water limit of linear theory is equivalent to $U/\sqrt{gh}$, referred to as the Froude number. Rip current velocities are often non-dimensionalized by $\sqrt{gh}$. Thus the Froude number determines the importance of wave-current interaction, which can be used to differentiate rip current systems based on hydrodynamics (Reniers et al., under review).

The Froude number located at the break point of the waves in the rip current on the left side (weak rip current) was around 0.10 and the Froude number on the right side (strong rip current) was around 0.20 (Table 4.3).

<table>
<thead>
<tr>
<th>Rip Current</th>
<th>Rip Current velocity $U$ (m/s)</th>
<th>Waterdepth $h$ (m)</th>
<th>Froude number (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Right</td>
<td>0.20</td>
<td>0.10</td>
<td>0.20</td>
</tr>
</tbody>
</table>

It seems that rip currents with a Froude number of 0.1 or smaller do not affect the surfability on a negative manner and rip currents with a Froude number of 0.2 or bigger do affect the surfability on a negative manner (Table 4.4). The values between 0.1 and 0.2 are recommended for further research. It should be noted that this is only valid for typical swell conditions in the Netherlands; the effects of rip currents on the surfability of e.g. choppy waves can be larger as they can be smaller on more solid swells.

<table>
<thead>
<tr>
<th>Froude number</th>
<th>Influence on surfability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr ≤ 0.1</td>
<td>Negligible effect</td>
</tr>
<tr>
<td>Fr ≥ 0.2</td>
<td>Negative effect</td>
</tr>
</tbody>
</table>
4.5 Summary

The last objective is the verification of the design (and thus numerical predictions) by means of a laboratory experiment, specifically designed to obtain measurements of currents and surfability parameters. In this chapter the design is verified by comparing the numerical and experimental results. The PTV technique used to measure the currents gives good estimates of the velocities of the rip currents through the breakers except for the rip current through the rip channel. This rip channel is not strong enough to get the floats from inside the breaker zone outside the breaker zone. This was leading to estimates of the velocities in the rip channel which were too low, because only about half of the time floats were in the rip channel. Therefore EMF measurements were conducted in the rip channel which results agree well with the numerical results.

The currents however are in the numerical results perfectly symmetrical, but in the measurements a large asymmetry occurs. Due to the asymmetry in the currents a relation is found which shows whether a rip current will affect the surfability in a negative way or not for typical Dutch swell conditions. This was done using the Froude number to non-dimensionalize the rip currents. The strong rip current affects the surfability negatively and the weak rip current does not negatively affect the surfability. Another difference is the difference in the direction of the computed and measured (rip) currents. The computed directions are alongshore and the measured directions are offshore. Further research is needed to explain the differences.

The measurements of the surfability parameters: the time series of the surface elevation at the breakpoints of a bichromatic wave field, the peel angles and the breaker types agreed all very well at the side of the reef where the rip current was weak. At the other side, where the rip current was strong, the surface elevations agreed, but the peel angles and breaker types were very irregular and the water surface was rough. The spectral wave model underestimates the peel angles (Henriquez, 2004) but the Boussinesq model gives very good results (at the side where the rip current was weak).
5 Conclusions and recommendations

5.1 Key findings and conclusions

In the design a rip-channel was applied in the middle of the reef, where surfers do not surf, to minimize the rip currents through the breakers (Figure 5.1). In the rip channel no wave breaking occurs and the cross-shore set-up gradients in the channel are thus smaller. The alongshore variations in wave set-up produce feeder currents to the channel and to the sides of the reef. The rip currents through the breakers are therefore smaller than in a design without a rip channel.

![Diagram of reef with rip channels and currents]

**Figure 5.1** bathymetry of the reef where solid lines denote depth contours, white vertical arrows denote the feeder currents, white diagonal arrows denote the alongshore currents and the black diagonal arrows denote the rip currents.

Three important topographic features affect the wave-driven currents. The first one is the rip channel width; this is the distance between both halves of the reef. By decreasing the rip channel width, the rip current through the channel increases and the rip currents through the breakers over the reef decrease. This is valid down to a certain width at which the rip current through the channel does not exist anymore and the rip currents through the breakers increase again. The width of the rip channel does also have a significant influence on the stability of the rip currents.
The two other topographic features are the width of the reef perpendicular to the shore and parallel to the shore. The internal reef angle and reef length are the reef variables used to influence the width of the reef perpendicular to the shore. The internal reef angle again and internal reef slope are the reef variables used to influence the width of the reef parallel to the shore. In general, the rip current through the channel and the rip currents through the breaker decrease with decreasing reef widths in any direction.

The numerical study showed that for the final reef design, the rip currents through the breakers are approximately 40% decreased in strength in comparison with the conventional reef. The Boussinesq model is not able to show that the waves are unsurfable when a rip current is travelling through the breakers, but does slightly indicate that the rip currents affect the surfability. The breaker line is moved offshore, the peel angles decrease and the wave heights increase when a strong rip current is flowing through the breakers. In the final design this indication is not noticeable and in the conventional design it is. The sectional and irregular breaking of the wave and the rough water surface could not be determined numerically.

The measurements and the numerical results agree very well. The flow field is measured using the Particle Tracking Velocimetry (PTV) technique and gives a good estimate of the currents occurring around the reef. For the rip current through the channel an Electro Magnetic Flow meter had to be used as it was impossible to get accurate results of the currents in the channel with the PTV technique. The measurements showed that the rip currents were very asymmetrical. The current through the breaker at the right of the reef is almost twice as strong as the current on the left.

The measurements of the surfability parameters: the time series of the surface elevation at the breakpoints of a bichromatic wave field, the peel angles and the breaker types agreed all very well at the side of the reef where the rip current was weak. On the other side of the reef, where the rip current was strong, the surface elevations agreed, but the peel angles and breaker types were very irregular and the water surface was rough. The spectral wave model underestimates the peel angles (Henriquez, 2004) but the Boussinesq model gives very good results (at the side where the rip current was weak).

A primitive relationship was proposed for the effect of rip currents on the surfability. This was done by non-dimensionalizing the rip currents with $/\sqrt{gh}$ where $g$ is the gravitational constant and $h$ is the water depth. If the non-dimensionalized current velocity (Froude number) is equal to or smaller than 0.1 the rip currents through the breakers have a negligible influence on the surfability. And if the Froude number is equal to or larger than 0.2 the rip currents through the breakers are affecting the surfability negatively.
### 5.2 Recommendations

By decreasing the rip channel width, the rip current through the channel increases and the rip currents through the breakers over the reef decrease. This is valid down to a certain width at which the rip current through the channel does not exist anymore and the rip currents through the breakers increase again. Research is needed to find out why this happens.

The experimental study showed that the rip currents through the breakers are very asymmetrical. Further research is needed to find the cause of the asymmetry. Research is also needed to find out, if the rip currents remain very sensitive to small asymmetries in the boundary conditions, when the rip channel width is changed.

The floats used in the Particle Image Velocimetry measurements were not suitable to give accurate results of the current velocities in the rip channel. Alternative floats should be considered.

Further research is needed to find out why the (rip) currents through the breakers in the numerical study are directed alongshore, while in the experimental study they are directed more offshore.

Further research is needed to find the exact transition value for the Froude numbers, used to indicate whether the surfability is negatively influenced by a rip current or not. And, more important, a relation of the effect of the currents on the surfability for different waves e.g. longer wave periods should be investigated.

The surfability parameters were estimated using bichromatic waves. A wave spectrum can be used to determine the surfability of irregular waves as these represent reality even more (but not so much for very good surfing conditions).

Before constructing an artificial surf reef on a beach, research should be done to the effects of sediment transport induced by the locally induced wave-driven currents and e.g. the alongshore currents.
Bibliography


