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Wave-focusing surfing reefs - a new concept

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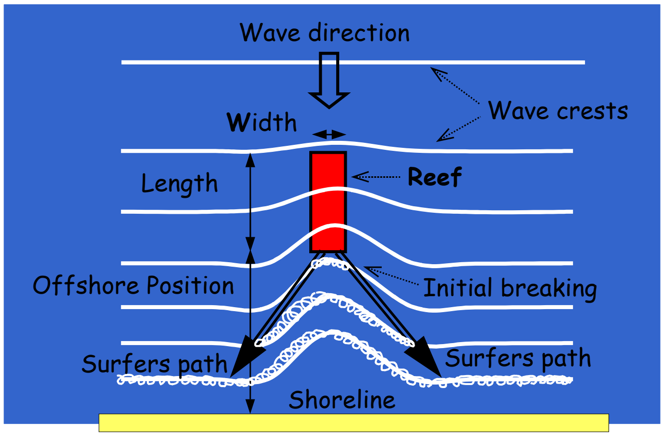
Introduction

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

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

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



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

Figure 1: Concept of a wave-focusing reef

When the wave has passed over the structure, the whole length of the wave crest resumes travelling further over the plane sloping beach. If a wave's approach to the shore is uninterrupted, it will break along its entire crest equidistant from shore. Because the reef can slow down a section of a wave (Figure 1) and also amplify the wave height, it is expected that the wave will start to break at the peak. After the initial breaking of the wave at the highest point along the wave crest, the wave on either side of the peak will break causing the wave to peel to both sides of the peak. The overall mechanism can be regarded as inducing added instability in the wave crest in the region of the peak. Thus in effect, a small-scale submerged artificial reef can convert a close-out wave to a peeling wave. However, the purpose of this type of reef is not only to create a peeling wave but also to allow a surfer to "take off" earlier than would otherwise be possible, this is analogous to tow-in assistance. By taking off earlier, a wave with a high peel rate can be ridden successfully. Therefore, the aim is to influence waves with a spilling to plunging character which would be otherwise suitable for surfing if they did not close out. Thus, by delaying wave breaking at the take off zone with a reef, these waves would be made more surfable.

This study was carried out in order to address the following questions that have not been studied up until now:

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

Definition of parameters

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

Parameters describing amplification of wave height: Wave transformation at the centre of the reef crest and induced breaker patterns were compared with the same situation without a reef. This is referred to as the plane case. The relatively shallow water over the reef causes a wave to shoal earlier. Therefore the wave height will be expected to reach its maximum further away from the coast than in the plane case. In addition, the alongshore variations in water depth will cause the wave to focus. The wave on the reef will reach its maximum height earlier and subsequently break further away from the coast. Thus due to wave focusing, the breaker height with the reef is expected to be greater than the breaker height without the reef. The relative wave-focusing effect caused by the reef (K_{focus}) is determined by the ratio of the breaker height with a reef (H_{reef}) to the breaker height without a reef, (H_{beach}):

$$K_{focus} = \frac{H_{reef}}{H_{beach}} \qquad (1)$$

Where K_{focus} is the wave-focusing factor. Thus, a value of 1 for K_{focus} means that the reef has not had any focusing effect and that the breaker height would be equal to that without the reef. A value of K_{focus} larger than unity means that there is a focusing effect. When comparing the plane case with normally incident waves where only shoaling has effected H_{beach} to the case with reef, the relative wave-focusing effect (K_{focus}) can be written as:

$$K_{focus} = \frac{H_{reef}}{K_S H_0} \qquad (2)$$

Where K_s is the shoaling coefficient at the breakpoint and H_0 the offshore wave height.

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

$$K_{axis} = \frac{H}{K_S H_0} \quad (3)$$

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

Parameters describing increase in breaker distance: The parameters defining the degree of wave focusing are shown in Figure 2.

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

$$X_{beach} = \frac{K_s H_0}{\gamma \tan\alpha} \quad (4)$$

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

In order to determine the relative contribution to earlier wave breaking of the forced effect of the shallower water over the reef and of wave focusing, these effects need to be separated. Because the water depth over the reef is the same as that at a point further onshore, it would be expected that the waves would break at a distance further offshore. This distance (X_γ) defined as the gamma effect, which is the effect of a shallower water depth over the reef, is the ratio of the reef height (D) to the tangent of the angle (α) of the beach slope (see Figure 2).

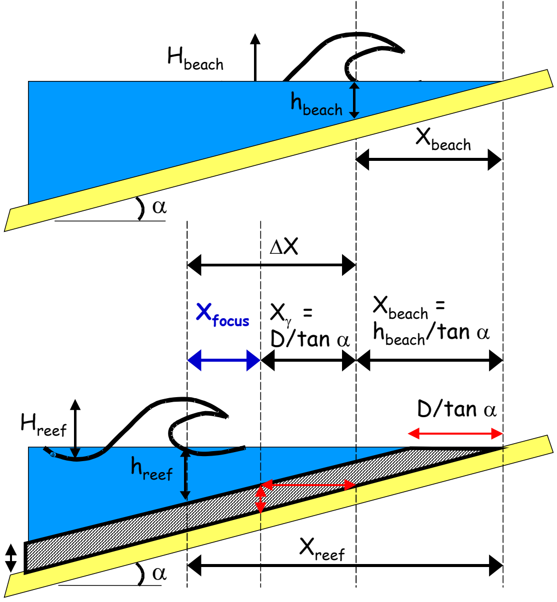


Figure 2: Breaker distance on the reef compared to the breaker distance for the plane case.

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

$$\Delta X = X_\gamma + X_{focus} \quad (5)$$

Where X_{focus} is the distance that can be attributed to wave focusing (see Figure 2) and is the augmented breaker distance:

$$X_{focus} = X_{reef} - \frac{D + h_{beach}}{\tan\alpha} \quad (6)$$

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

$$A_{focus} = \frac{X_{reef}}{X_{beach} + X_\gamma} = \frac{X_{reef}}{\left(D + h_{beach}\right)/\tan\alpha} = \frac{X_{reef}\tan\alpha}{\left(D + \frac{K_S H_0}{\gamma}\right)} \quad (7)$$

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

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

Wave height and breaker distance are influenced not only by reef height but also by reef width. A very narrow reef, such as a paling fence (a fence made from stakes) or a vertical sheet placed perpendicular to the shoreline, will have practically no effect. The question is how much wider than a paling fence does a reef need to be in order to have sufficient influence on waves, i.e. what is the minimum reef width required to focus waves. In contrast, there is also possibly a maximum reef width beyond which no further effect on wave focusing would occur. A very wide reef would not produce a wave peak but rather would result in an extended section along the wave crest with a maximum wave height.

The optimum reef width would be a trade off between the minimum possible (for economic reasons) and as effective as possible for wave focusing. The minimum and maximum widths of the reef are most likely to depend on the wave length. Wider reefs that focus waves more than do narrow reefs would cause waves to break at a greater distance from shore where the wave length is also greater. The ratio of reef width (W) to wave length at breakpoint (L_{reef}) is the relative reef width (W_{rel}). As waves propagate to shore, they start feeling the seabed at a certain water depth, depending on the wave period and thus the wave length. The longer the reef is the earlier the waves will be influenced by the reef. A reef that extends further offshore is expected to influence waves more than a shorter reef of the same height and width. The ratio of the reef length (Λ) to the wave length at breakpoint (L_{reef}) is the relative reef length (Λ_{rel}).

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

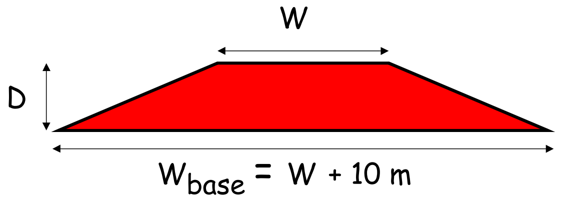
$$S_{RF} = \frac{D}{h_{reef}} \frac{W}{L_{reef}} \qquad (8)$$

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

Methods

Wave-focusing reefs are designed to focus incoming waves in order to increase wave height locally and to induce waves to break further offshore. Thus, the dimensions required for such a reef were determined including, height, width, length, optimum position of the reef offshore, and the profile of the reef relative to the seabed. Simulation studies were carried out to establish the required dimensions of a wave-focusing reef and to assess the effect of varying reef dimensions on wave breaking patterns. From a practical and economic point of view, a reef should be as small as possible.

The wave breaking on the reefs was simulated with Ref/Dif [Kirby and Dalrymple 1994], which is a combined refraction and diffraction numerical model that predicts wave behaviour over an irregular seabed. Ref/Dif is a phase resolving model, which predicts wave patterns when waves are affected by refraction, diffraction, shoaling and energy dissipation.



The total area of the bathymetric grid was a square with sides of 995 m, comprising 199 by 199 grid blocks, each of 5 m by 5 m. The water depth at the offshore boundary was therefore 50 m.

The base width (W_{base}) of the reefs was 10 m wider than the crest width (W), and thus the side slopes of the reef varied (Figure 3).

Figure 3: Cross-section of reefs

Different shaped reefs were superimposed on a constant seaward sloping beach with a bed slope of 1:20. For most simulations, the hydrodynamic conditions were kept constant at a wave height of 1 m and a wave period of 8 s. The Iribarren number for this is 0.5, which characterises the transition between spilling and plunging breakers: such waves are preferred for surfing [Walker 1972].
In order to establish the effect of reef height and width on waves, simulations were conducted with reefs of infinite length but varying in width and crest height. An infinite length was chosen initially so that changes in the wave field attributable to differences in cross section could be examined in the absence of effects of reef length. To establish the effect of reef length on waves, simulations were done with reefs of various lengths but with a fixed height and width. Simulations were also carried out with finite length reefs placed at different distances from shore in order to establish the role of reef position. The sides of the reefs were inclined making the cross-section trapezoidal. In reality, such a relatively simple shape probably would be chosen because it would be practical to construct and to deploy in the surf zone.

Initially, the reefs were subjected to the same regular waves in order to compare wave transformation over reefs of different shapes. Then, wave conditions were varied to study the performance of a few reefs. Finally, the output data was used to find the relationships, in dimensionless parameters, between reef dimensions and wave breaking patterns.

The range of reef dimensions that produce a significant effect on wave focusing were evaluated. This involved determining the minimum dimensions of an effective reef and the dimensions above which there is only a marginal influence of a reef on wave height and consequently on breaker distance.

Results

A plot of the water surface elevation for an infinitely long reef with crest width (W) of 10 m and reef height (D) of 1.5 m is given in Figure 4. As the wave travelled to shore over the reef, a peak in the wave crest formed that increased until the wave initially broke at 75 m from shore (i.e. $X_{reef} = 75$ m). On the reef where the wave first broke at the peak, the breaker height (H_{reef}) was greatest at 1.61 m. The gap in the wave crest nearest to shore, was due to the reef not being submerged from the shore to 30 m offshore.

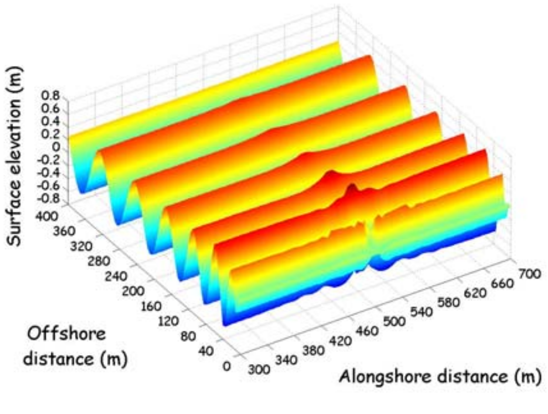


Figure 4: Water surface elevation for an infinitely long reef with width of 10 m and height of 1.5 m. As the wave travels to shore the peak in the wave crest increases until the wave breaks at 75 m from shore

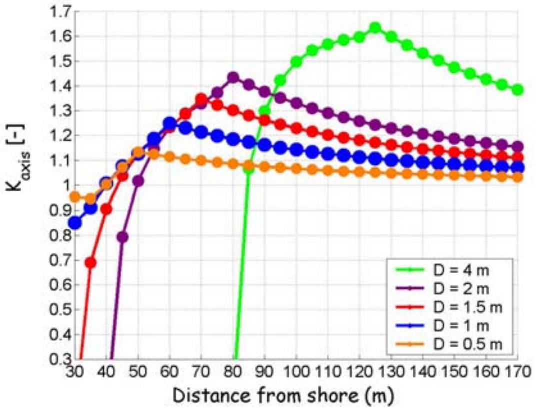


Figure 5: Wave factor along reef axis (K_{axis}) related to distance from shore, for infinitely long reefs with reef width of 5 m and reef heights (D), varying from 4 m (top) to 0.5 m (bottom).

In order to find out how wave focusing varies as waves travel towards shore, the wave height along the reef axis has been compared for infinitely long reefs with different heights and widths. In Figure 5, the wave factor along the reef axis ($K_{axis} = H/K_sH_0$) was related to the distance from shore (x). The influence of reef height (D) on wave height along the reef axis was compared for reefs with W = 5 m and D = 0.5 m, 1 m, 1.5 m, 2 m and 4 m. Above the reef, waves were affected by the reef from the start ($K_{axis} > 1$) and K_{axis} increased as waves travelled to shore (Figure 5). The peaks in the lines in the graph show where breaking occurred (i.e. X_{reef}). Closer to shore K_{axis} decreased because of earlier wave breaking caused by the reef. Up until wave breaking, K_{axis} increased with D (Figure 5) and also dK_{axis}/dx increased with D. For the lowest reef D = 0.5 m, the wave-focusing effect was marginal.

The influence of varying reef height and reef width on increasing breaker height, for infinitely long reefs, is shown in Figure 6. For constant W, the wave-focusing factor (K_{focus}) increased with increasing relative reef height ($D_{rel} = D/h_{reef}$). For wider reefs the effect of increasing D_{rel} on K_{focus} was greater (Figure 6, left). However, for smaller W the effect of further increasing D_{rel} in order to increase K_{focus} were minimal.

K_{focus} increased linearly with increasing relative reef width ($W_{rel} = W/L_{reef}$) for all reefs of constant D (Figure 6, right). The value of dK_{focus}/dW was greater for higher D (Figure 6, right).

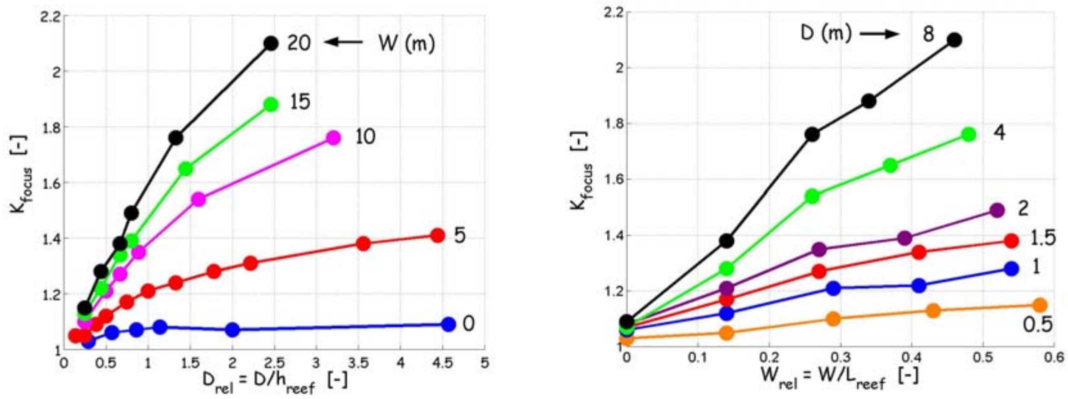


Figure 6: Relationship between wave-focusing factor on the reef (K_{focus}) related to relative reef height (D_{rel}; left figure) and relative reef width (W_{rel}; right figure) for infinitely long reefs. Each line represents reefs of constant width (W) or constant height respectively, the values of which are given by the numbers at the end of each line.

The increased wave height due to the focusing effect of the reef can be related to the reef dimensions, which may be expressed in a dimensionless relationship. The wave-focusing factor (K_{focus}) increased with the relative reef height (D_{rel}) for constant reef width (W) and that K_{focus} increased with the relative reef width (W_{rel}) for constant reef height (Figure 6). Therefore, a relationship was sought for K_{focus} with D_{rel} and W_{rel} combined. The wave focusing factor (K_{focus}) increased proportionally with the West-Cowell surfing reef factor (S_{RF}) (Figure 7).

Because S_{RF} is the product of D_{rel} and W_{rel}, this means that waves are focused proportionally to the area of the cross-section of the reef. There was a close correlation between K_{focus} and S_{RF} for $S_{RF} < 0.4$. However for $S_{RF} > 0.4$, the correlation was not as strong. There were fewer points for these higher values of S_{RF} because only few simulations were conducted with very large D, such as 4 m and 8 m. These large reef heights were not regarded as realistic for a surfing reef, because such heights would not be economically or logistically feasible.

The influence of varying reef height and width on increasing the breaker distance due to wave focusing is shown in Figure 8.The augmented breaker distance (X_{focus}) has been related to the product of D and W (i.e., DW), which is not the cross-sectional area of the reef (i.e., DW + (5 m)D). However, there is a large scatter of the points in the graph X_{focus} increases with DW.

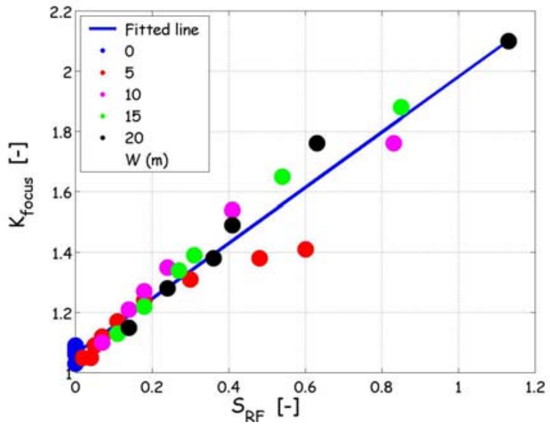


Figure 7: Wave focusing factor (K_{focus}) related to the West-Cowell surfing reef factor (S_{RF}) for infinitely long reefs.

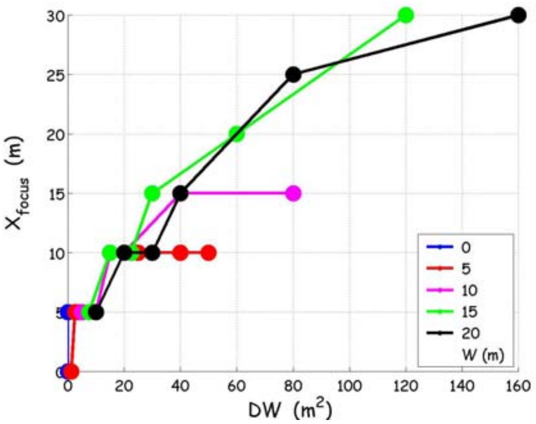


Figure 8: Augmented breaker distance (X_{focus}) related to the product of reef height (D) and reef width (W) for infinitely long reefs. Each line represents reefs of constant width (W), which are given in the legend.

For a reef with an offshore position (X_{OP}) of 35 m a plot of the instantaneous surface elevation has been presented in Figure 9. For this case where the wave starts breaking on the side of the reef, the peel rate (α) is approximately 40 degrees.

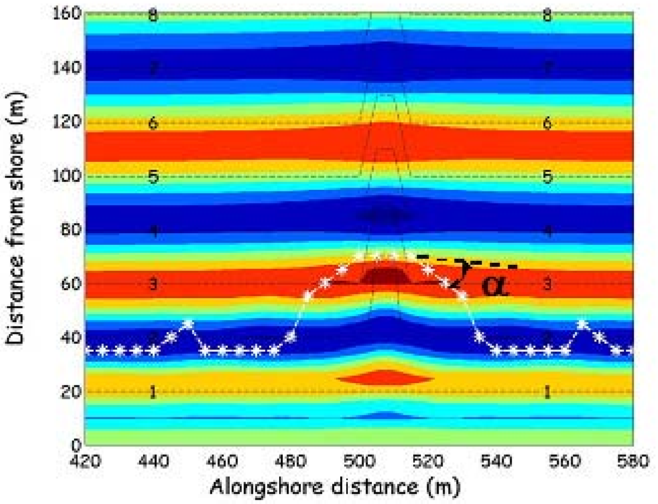


Figure 9: Instantaneous surface elevation for a semi-infinite length reef positioned 35 m from shore with reef height of 1.5 m and crest width of 5 m. The black dashed lines are depth contours where the numbers denote the local water depths. The white dashed line is the breaker line, where the calculated breakpoints are given by a *. On either side of the reef the peel angle (α) is 40^0. At an alongshore distance of 450m and 570 m, the breaker line is not straight for an unknown reason.

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

Discussion

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

Using the West-Cowell surfing reef factor derived in this research, the cross-section of the reef required for the wave focusing effect can be calculated. With increasing reef height and width, the wave focusing increases resulting in an increase in the breaker height and breaker distance (i.e., surfzone width) on the reef. The reef should be longer than the reef height and longer than the reef width. Such a reef would be positioned just beyond the breaker zone.

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

Reef dimensions: A reef can be characterised by its cross-section, length and position from the shore. Wave focusing, which is a function of an increased breaker height and breaker distance, increases with increasing reef height at constant reef width, and similarly with increasing reef width at constant reef height. The combined influence of reef height and width on wave focusing is described by the West-Cowell surfing reef factor derived in this research. The factor, which is the product of the relative reef height and relative reef width, is related to wave focusing in an almost linear way (see Figure 7).

With respect to conventional reef design, dimensionless relationships describing reef dimensions have not yet been developed. However, large-scale reef components of natural surfing reefs have been classified [Mead 1999]. Certain combinations of these components were found to produce high quality surfing waves and the reef component most resembling the concept of a wave-focusing reef was named the 'Focus' [Mead 1999]. Another study on natural surfing reefs related breaking wave characteristics such as breaking intensity and 'wave hollowness' (shape of plunging breaker) to the bathymetry [Sayce 1999]. These studies of natural surfing reefs described breaking wave characteristics but did not relate reef dimensions to wave breaking.

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

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

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

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

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

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

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

The primary aim when designing and placing wave-focusing reefs is to influence waves in order to improve their surfability. However, reefs need to be designed also to enhance beach protection and to reduce coastal erosion. Thus, if a reef is placed and is shown to have negative effects on the coast such as erosion or the formation of a salient, it could be removed. The interaction of the altered hydrodynamic conditions with the submerged reef may cause scouring around the reef that may endanger its stability and cause problems such as subsidence of the reef. These aspects should be taken into consideration in reef design.

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

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

Cable Station Reef was built using rock to enhance an existing reef by placing large rocks on a stable rock bottom. The construction, involving the placement of 11,000 tonnes of granite armour stone, began in February 1999 and was completed in December 1999 after an interruption of work during the winter months [Pattiaratchi and Bancroft 2000]. The coast is stable due in part to the presence of rocky cliffs, no coastal stability problems would be encountered at this site [Pattiaratchi 1999]. Because of the size of the reef and because construction could only take place during calm weather, the time to complete the construction of Cable Station reef was 11 months. As for the sand-based Narrowneck Reef, a wave-focusing reef would be much smaller.

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

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

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

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

Conclusions

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

However, more attention will need to be given to construction methods and to refining the relationships of reef dimensions to wave-breaking patterns.

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