

Surf reefs – Physical modelling results, not pipe dreams

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Abstract

This paper discusses the diverse needs for near-shore reefs required to serve for both coast protection and to improve surfing, and how they impact on each other when a multi-purpose reef is designed. Two case studies using extensive physical modelling are discussed. At Borth, the modelling looked at optimising the design of two offshore multi-purpose reefs as part of a wider coastal defence scheme. Initial designs were changed to a single multi-purpose reef after the physical modelling showed that wave interactions between the reefs reduced their overall surfability, further contribution to coast protection were provided by an additional low crested breakwater. At Jumeirah, the modelling tested a single multi-purpose reef and its effect on the shoreline position in its lee. The modelling showed that the reef was able to produce a degree of surfable waves and also had an impact on the coast protection behind it. The authors of this paper believe that the physical modelling of the reefs allowed beneficial design refinement of the multi-purpose reefs to increase their effectiveness for both surfing and coast protection.

Introduction

A lot of excitement (and perhaps even hype) has been born from the idea of merging requirements to protect the coastline and creating an increase in the surfing amenity of a coastal area. Named by some as 'multipurpose reefs' (MPR), these near-shore structures require a lot of design (and supporting modelling) to ensure that they both protect the coastline behind, and are capable of producing surfable wave conditions under the wide variety of sea-states and water levels that are likely to impact on a given site.

Multi-purpose reefs are likely to need compromises to satisfy the different requirements for the different purposes. For surfing, the infrequency of ideal waves and tidal conditions make it difficult to manage the reality of performance and expectations. Coast protection, requires appropriate control of waves and currents, and sediment transport, even under relatively rare storms. Analysis and/or modelling of the complex wave and sediment transport processes involved make it difficult to explain easily why and how these compromises are needed.

Coast Protection

An offshore breakwater required to offer coast protection needs to be at a suitable depth during design morphological conditions so that it is effective in reducing the wave energy behind the structure and thereby reduce littoral drift potential. An optimal offshore breakwater or breakwater system will create salients in their



lee, building up the beach protection behind it, but not creating a tombola which can stop the net transport of sediment. The optimum design of the offshore breakwaters in forming a salient is given as a function of the width of the structure (I_s) at the still water line and the distance to the original shoreline position (Y). General guidance suggests that there will be minimal response of the shoreline if I_s /Y is less than 0.17-0.5 (CEM, 2002).

A breakwater that is normally emergent, but becomes submerged at high tide levels, can pose a risk to small boats which may strike the breakwater. Sets of offshore breakwaters can also pose danger to swimmers due to the strong currents that may be formed when overtopping water sets up behind the breakwater and flows back out to sea through the gaps in the breakwater system. This same process can also reduce the breakwaters performance in protecting the shoreline as suspended sediment can be removed from the system by these out-flowing currents, leading to local erosion.

It is also important that the beach is replenished to a suitable width when the breakwaters are designed / constructed. This is because the shoreline between the salients is likely to retreat as the system becomes stable (erosion balancing accretion).

Surf Reefs

A surf reef works by reducing the depth of water and shoaling up an unbroken wave, ideally causing it to become a (tubular) plunging breaker. To create a long surfable ride, the reef needs to be configured to continue this shoaling along the wave crest. The plunging breaker should progress along the wave at a speed that allows the surfer to ride the wave. The angle, relative to the wave crest, at which the wave needs to break is defined as the peel angle (see Figure 4). For recreational surfers the peel angle needs to be between 45°-65° (Mocke *et al*, 2004). Typically, this means a surf reef will benefit from being longer and narrower, and be orientated strongly oblique to the predominant wave direction. This is illustrated by Mocke *et al*, (2004) who found the best surfing performance for a delta type surf reef, was obtained using a narrow half nose angle (see Figure 11) of only 10°, rather than a wider reef that was more parallel to the incoming wave crests. There is very little limitation in the physical modelling of these plunging waves that would have an adverse effect on the peel angle measurement.

The reef will need to be at a suitable elevation relative to the tidal cycle to allow for maximum 'working' times. If the crest level is too high, the reef will be exposed and the waves will break on to it. If the crest level is too low, the reef won't cause the waves to shoal enough to break. The depth of water over the reef to allow it to be operational will therefore depend on the height and steepness of the waves, and the minimum depth of water required for the surfboard not to impact on the reef. In areas where strong tidal currents occur, the times at which the reef is able to generate surfable waves are best suited to either high water or low water tide levels where the typically slack water will create less currents and be safer for users. If the reef is required to protect a high water level shoreline, then it is likely that it will only be able to produce surfable waves during high tides.

One method of supporting the design of the multi-purpose reefs is the use of large scale physical modelling. This allows the local coastline to be modelled, covering not only the MPR but also the adjoining shoreline. The multi-purpose reef needs to be reproduced accurately in the model so that the surfing potential can be assessed under a variety of incoming sea-states. The wider coastal area needs to be included in the model to assess the effectiveness of the multi-purpose reef in protecting it and controlling littoral drift, wave run-up and overtopping. The design of a multi-purpose reef is a difficult exercise because the most effective forms of the single components are very different (Mocke *et al*, 2004). A shoreline protection reef is most effective



as a wide shore-parallel breakwater. Artificial surfing reefs tend to be longer narrow structures placed oblique to the waves.

Two such physical models have been carried out in HR Wallingford's modelling facilities, and these have been given as case studies below looking at the study findings of both the surfing potential of the multipurpose reef and also its ability to protect the shore line. These models were for the Borth (Wales) coastal protection scheme and the Jumeirah (UAE) coastal zone management plan.

Borth Coastal Protection Reef

Purpose

Borth is a small tourism-driven village on the west coast of Wales in Cardigan Bay, Figure 1. The multi-purpose reef at Borth has been built as part of a wider coastal protection scheme. That scheme (now completed), consists of a shingle beach nourishment, two near-shore fish-tailed breakwaters, two rock groynes and the offshore multi-purpose reef. The multi-purpose reef was designed with the key principle of reducing erosion to the shingle ridge berm width behind it, without the need for an intrusive near-shore structure and allowing a net transport of material to pass, thus ensuring natural replenishment of sediment to the north of Borth. There was previously a natural surf break at the south end of

the Borth frontage and the multi-purpose reef was designed to complement this and the wider beach break, and encourage more surfers to visit the bay.



Figure 1 Location of Borth, UK (courtesy Google Maps)

During extreme sea-states and storms, the frontage becomes heavily overtopped and houses are damaged by overtopping water and shingle propelled into the town by the waves. The extensive (but ageing) timber breastwork that protected the frontage had depreciated to a low standard of protection, increasing the chances of the shingle ridge overtopping and the potential for a breach. A strategic appraisal report, by Royal Haskoning in 2006, recommended that the frontage should be protected by the phased replacement of the breastwork, re-nourishment of the beaches, and building a series of beach control structures incorporating a multi-purpose reef at the southern end of the frontage. The scheme as constructed, is described in more detail by Johnson *et al* (2011) and the morphological and hydraulic performance testing by Obhrai *et al* (2011).

Designs and Alterations

The multi-purpose reef at Borth was designed and built as part of a wider coastal protection scheme. The original design concept was for two surfable reefs, a northern reef and a southern reef, but this was changed to a single surfable reef and a shore parallel breakwater (SPB). The original and final designs for the southern part of the scheme are shown in Figure 2. The original design consisted of reefs A and B. The final design removed reef B and replaced it with C. The reefs tested consisted of a single arm providing a single break to either the left (A) or right (B). A small hook was included on the near side to prevent the



incoming waves from wrapping around the rear side and interfering with the breaking wave as it peels along the arm. For the Borth project, it was estimated that it would cost an additional £300,000 for the additional surfing amenity benefit over a sole coast protection scheme.

Three different designs / layouts for the Northern reef were tested in the model and the initial design for the Northern reef is shown in Figure 3. The truncated delta shaped reef was originally constructed in the model using cement mortar to represent the profile of a reef constructed from geo-tubes. For the second design, the model reef was extended and grooves were cut into the cement mortar surface to further replicate the roughness of the geo-tubes. For the final design, the same extended reef layout was used, but constructed out of rock.



Figure 2 General layout of Phase 1 of the Borth Coastal Protection Scheme. A) Northern reef, B) Southern reef and C) shore parallel breakwater (SPB)



Figure 3 Initial plan view layout and side profile of the Northern reef

Modelling Methodology

The multi-purpose reef was modelled at a scale of 1:45 at HR Wallingford as part of the large model discussed by Obhrai *et al* (2011). The large model represented 1.5km of the local shoreline and bathymetry to ensure the modelled sea-states were an accurate representation. The model used two different scaled sediments to represent the shingle ridge and sandy foreshore. Further detail on the sediment grain size and scaling can be found in Obhrai *et al* (2011). A 3D laser scanner was used to measure the sediment before and after each tests to assess coastal protection performance of the reef. The shingle ridge was modelled to reproduce the morphological impact of the reef on the net movement and width of the shingle ridge. The sand sediment indicated patterns of erosion / accretion of the sandy foreshore, particularly around the reefs. Finally, anthracite tracer was used to determine sediment transport directions around and behind the reef.



Figure 4 Overhead video shot of the Northern reef and parameter definitions

The surfability of the reef was assessed both quantitatively and qualitatively with advice from surf specialists. The quantitative results consisted of measuring the peel angle and break rate of the waves, tested using 16 monochromatic waves ($H_s = 1.0$ -2.0m, $T_p = 8$ -12s WL = 0.86-2.36mOD increasing in 0.5m increments). The definitions of these parameters are given in Figure 4 and were recorded using overhead video cameras. Four random wave conditions ($H_s = 1.0$, $T_p = 8$ -12s, WL = 1.36-1.86mOD increasing in 0.5m increments) were used to give an estimate of the number of surfable waves in realistic seastates.

The qualitative results were based on subjective surfing assessments from surfers who assessed the waves for the look and feel and rated them for each condition out of 5 (1

being a poor quality and 5 being a high quality wave). The waves were assessed from a video camera placed on the shore looking out towards the reefs. An example image from this video showing a breaking wave can be seen in Figure 5.





Figure 5 Example frame from video of 'wave quality', showing plunging wave breaking along reef

Coastal Protection Results

Behind the MPRs, salients started to form after frequently occurring morphological conditions run for 108 hours (H_s =3.5m T_p=10.2s, SWL=1.81mODN). The multi-purpose reef reduced wave heights in its lee and allowed the salient to build up in the shingle ridge (in lee of the wave direction) where the littoral drift was reduced. This is shown in Figure 6 where the waves direction was from 255°N. Up-shore to the south of the structures, the beach remained stable and little accretion or erosion occurred. This demonstrates that the slimmer reef (which is better suited to provide a surfing amenity) was able to provide coastal protection, and to assist stabilising the shingle ridge. This is demonstrated in Figure 6 which shows a comparison between the pre-test and post-test plan shapes of the shingle ridge and an extension of the ridge in the lee of the reefs. Figure 7 gives a photograph of the post-test salient.





Figure 6 Difference plot after 108 hours of frequent low return period waves (H_s =3.5m T_p =10.2s, SWL=1.81mODN, mean direction=255, dark=erosion, light=accretion)



Figure 7 Final shoreline position after 108 hours of frequent low return period waves (H_s =3.5m T_p =10.2s, SWL=1.81mODN)

With incoming waves from 285°N, a salient was again formed in the shingle ridge in lee of the incoming waves. However, the accreted material that made up the salient came from down-shore and caused erosion where the 255°N salient had previously formed. This is likely to have been caused by a lack of

replenishment material bypassing the groyne down-shore. Changes to the still water line after 108 hours of morphological waves from 255°N and 108 hours of morphological waves from 285°N are shown in Figure 8.



Figure 8 Shoreline difference plot after 108 hours of frequent waves (H_s =3.5m T_p =10.2s, SWL=1.81mODN, dark=erosion, light=accretion) with waves from 255°N and 285°N

A direct comparison has been made between the effectiveness of the Southern multi-purpose reef reef and the shore parallel breakwater. The shore-parallel breakwater created a wider berm width in the shingle ridge with waves from 255°N. The shore-parallel breakwater would therefore provide a more resource-efficient method of improving the defence capabilities of the offshore submerged structures but does not offer the amenity benefit of the multi-purpose reef. A comparison between the final SWL after 108 hours of morphological conditions from 255°N with the dual multi-purpose reef reefs and the single Northern multi-purpose reef and shore parallel breakwater is shown in Figure 9.

Figure 9 Difference plot after 108 hours of frequent waves (H_s =3.5m T_p =10.2, SWL=1.81mODN, dark=erosion, light=accretion) for the dual multi-purpose reef and the single multi-purpose reef and shore parallel breakwater layouts

As demonstrated by Obhrai *et al* (2011), the anthracite tracers showed that the reef did not stop the transport of sediment to the north behind the structure. A large, artificial tombola was constructed behind the reef and the test showed that even with this artificial tombolo in place, the sediment was able to bypass the reef and continue north. This is shown in Figure 10 which illustrates the direction and movement of the tracer material around the tombola and along the shingle ridge behind.

Surfability Results

During testing, observations were made that the original dual multi-purpose reef layout was not feasible due to interference of cross waves between the reefs. This lead to the removal of the Southern reef and a focus on improving the surfing conditions for the Northern reef. The Northern reef was extended to try and increase the ride time, but this had little impact on the ride time which stayed the same. The ride time for the rock reef was however shorter than for the geo-tubes due to the later breaking point of the waves from the

Figure 10 Laser scan showing movement of anthracite tracer from initial locations $\mathsf{A}-\mathsf{D}$

permeable nature of the rock construction. The less permeable geo-tube structures tended to reduce breaking at lower water levels, possibly due to the reduced roughness of the structure (compared to the rock surface) reducing the friction felt by the bottom of the wave.

The peel angle of the waves for all three reef designs was between 72-85° with the rock reef angles being marginally smaller than those for the impermeable reefs.

For the original Northern reef design, the larger wave heights, longer period and higher water level waves tended to score higher with a maximum wave quality rating

of approximately 3.5 seen most frequently for waves at SWL +2.4mODN. For the extended ridged design, only three conditions scored higher than 3.0 in terms of

wave quality. These again tended to be the larger waves at the higher water levels. For the rock structure, six conditions scored a wave quality higher than 3.0 with the higher quality waves appearing in the middle to lower water levels and for the highest wave heights.

Jumeirah Reef

Purpose

The Jumeirah multi-purpose reef was designed to help coastal defence by achieving accretion of sand in the lee of the reef and to create wave breaking conducive to surfing. The reef was to be built as part of the Immediate Action Plan for the Jumeirah seafront in Dubai.

Designs and Alterations

The Jumeirah reef underwent many design iterations in numerical modelling before the final design was tested in the physical model (Mocke *et al*, 2004). A total of 36 different reef variations were tested to assess their performance for both coastal protection and surfability in the numerical model. The final reef design combined a lens shaped reef with a part-depth shelf around the seaward end of the reef. Two options of this reef were tested in the physical model and Option 2 elongated the nose of the reef, shown in Figure 11. The

reef was designed to be made out of geo-tubes. The tip of the reef was constructed approximately 250m from the still water line of the beach.

Figure 11 Jumeirah reef design and local bathymetry

Modelling Methodology

Two sets of test were run in the physical model at 1:35 scale. The first was to test the reef's morphological effect. The second set of tests were to test the reef's surfing performance. The model reef had an impermeable mortar surface and the shelf was made out of rock.

Two types of test were used to define the morphological response of the scaled beach material behind the multi-purpose reef and to test its performance in producing surfable waves. A series of long random wave sea-states were used to test the morphological response and were run for 47 hours to allow a stable beach plan to develop. During testing, there was a build-up of material down-drift of the reef and erosion of the material up-drift. To combat this model effect, a scheme of sediment recycling was employed. Shorter monochromatic wave tests were used to measure the surfability of the reef. The monochromatic waves used wave heights ranging from 0.8-2.0m and periods between 5-7s. The water levels ranged between +0.4mDMD and +1.75mDMD to cover the extent of the tidal range.

Coastal Protection Results

The significant Shamal sea-state (H_s =2.25m, T_p =6.86s, SWL=1.13mDMD) from 310°N caused an asymmetric salient behind the reef, extending out approximately 40m from the original still water line. A stable beach plan was achieved after approximately 30 hours. The progression of the salient is plotted in

Figure 12. When the wave direction was changed to 295°N (perpendicular to the coast line), the salient reduced in width to only 10m from the original SWL. From this wave direction (almost head on to the reef) the currents produced behind the reef were almost identical up-shore and down-shore of the reef.

Figure 12 Progression of salient development (H_s =2.25, T_p =6.8s, SWL=1.1mDMD)

Surfability Results

From 310°N, the peel angle on the reef started at about 35-45° with a break rate of 4.2m/s. This break rate then accelerated to 8.6m/s as waves refracted towards the centre of the reef from the rock shelf. At the end of the reef, the peel angle went up to 80° as wave breaking did not progress along the crest. As the wave height and water levels increased, peel angles became greater, and the initial break rate increased. An example of the waves breaking on the reef is given in Figure 13.

Figure 13 Example of waves breaking over the Jumeirah reef (H_s =0.8m, T_p =5.0s, SWL=+0.4mDMD) – view looking seaward

From 295°N the initial break rate was higher, between 50°-60° and the break rate of the later stages of the reef were also higher. The break rate stayed at a similar speed of between 5-9m/s except in the largest 2.0m condition where the speeds hit 22.0m/s giving a wave that would be difficult to ride.

The modified reef gave a more complex breaking pattern to the waves compared to original reef. The elongated nose appeared to give an initial fast break along the nose and a peel angle that was mostly seen later on in the break the previous design. The same high peel angles were observed in the later stages. As the wave height increased, the initial break improved, but a close-out of the wave (wave breaking instantaneously along the entire crest) was observed as the break reached the main lens of the reef. The shelf caused waves to refract and interfere with the breaking on the reef.

Conclusions

This paper outlines some of the potential difficulties that come from designing a multi-purpose reef that provides both coastal protection and an acceptable level of surfing amenity. Inherently, the design of a structure to achieve one of these goals would be rather different. A coastal protection reef needs to dampen the waves, and its design is very much dependant on how the waves interact with the shoreline behind it. A surf reef however, attempts only to shape the waves within its vicinity to provide a clean plunging breaker that a surfer can ride.

This paper has given two examples where multipurpose reefs have been used. In both cases, some level of coastal protection was provided by the reefs and salients formed in the lee of the structures. In the Borth model, a higher level of protection might be given by a standard shore parallel breakwater (smaller and simpler) in its design than the original surf reef. The Northern reef which was left in place to provide a surfing amenity did provide some medium quality surfable waves but only during some of the sea-states tested.

The Jumeirah reef also provided surfable waves, but the wave breaking process was complex, and varied with the different sea-state. The front shelf of the reef, built to increase the reefs ability to protect the coast, interfered with waves breaking along the reef and lowered the surfing amenity potential of the reef.

In both cases, a level of both coastal protection and surfing amenity were provided by the multi-purpose reefs. The studies show that the surf reef designs were able to provide some level of coastal protection. It is probable that a specifically designed shore parallel reef would have been able to improve the coastal protection using less resource, but without the amenity benefit. A surf reef needs to be placed where it will be able to catch and transform the waves, possibly placing it rather too far off-shore for salient and shore-line responses to be observed. These compromises did not however prevent the reefs from being able to perform their multi-purpose role.

Further work would be beneficial to assess the surfability performance of the Borth reef on site once it has been operational for longer. Presently it has only been operational for one winter surfing season.

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