Artificial Surfing Reefs for Erosion Control and Amenity: Theory and Application

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ABSTRACT


The logic and benefits of offshore, multi-purpose, coastal protection structures are addressed through example, theory and application. From a series of basic principles, the offshore reef philosophy is explored. The benefits are emphasised by summarising relevant NZ coastal research and by using a series of natural examples, case studies and numerical model simulations, including the large Gold Coast Reef designed for coastal protection and surfing. Offshore reefs with recreational amenity are shown to have three important “MOA” qualities (Multi-purpose, Offshore and Adjustable), which makes these structures more versatile and adaptable than sea walls, breakwaters or groynes. However, with the amalgamation of multiple purposes, the designed reef needs more sophistication than that required for coastal protection only. High-quality computer modelling, field datasets on surfing reef behaviour and advances in construction technology make these elegant and scientifically complex coastal protection solutions achievable.

ADDITIONAL INDEX WORDS: Offshore reefs, coastal protection, salient, breakwater, rockwall, wave refraction.

INTRODUCTION

Addition of environmental and recreational amenity to coastal protection facilities provides a range of benefits, and these come at a critical time when shoreline modification is accelerating. The beach (and coral reefs in the tropics) are being mined, built upon, bulldozed, modified and, in some countries, stolen at night. Shoreline construction will always be required for ports, marinas and some coastal protection problems. However, this paper challenges the need for so much coastal protection placed on the beach itself, which is the section of public property that is most valued for its visual, recreational and natural character.

In Asia, and all along the equator, beach sand and coral is used ubiquitously for construction. Ironically, if the extraction rate is too fast, foreign loans are needed to pay for groyne and rock wall protection that costs more than the small gains accrued by the cottage extraction industry. Moreover, as the problem is often just the “lack of sand”, the “protection” structures unnecessarily change the character of the beach permanently.

The impact on human lifestyle has been irreversible, with people unable to launch small boats, fish with nets, promenade or maintain a long cultural relationship with the sea when waves are present; in many cases they are now separated from the sea by a dangerous rock wall (Figure 1). In Bali, Indonesia, local residents are split over the need for rock walls and groynes along the world-famous Kuta Beach. In England, thousands of groynes abound along the coast and totally change its character to one of human control (Figure 2). In Japan, much of the coastline has been barricaded, both for wave protection and tsunami protection. There are numerous other examples worldwide, in Australia, New Zealand and California for example, and the human, social and monetary cost of all this shoreline construction is gigantic.

The cultural attachment to the natural character of the beach in Australia and New Zealand is particularly strong. In synchrony with this, powerful Management legislation through the Resource Management Act (1991), the unification of an international group of coastal scientists, planners and legal advisers, plus strong cultural support by Maori for protection of natural resources, has led to the establishment of the “Artificial Reefs Program” in New Zealand (NZ) (BLACK et al., 1997a). A series of associated developments including the Cam-Era coastal video monitoring system (http://yorick.eco.cri.nz/camera), government-funded beach research and strong university/industry links have further fostered NZ coastal research.
The demand from funding agencies for science that maximizes commercial benefit while improving human living conditions, and the need to reduce the burden of construction costs, is met by the Reefs Program. On Australia’s Gold Coast, where a large submerged reef for coastal protection and surfing has been constructed, the cost-benefit analysis showed that the reef and shoreline re-nourishment could return 60 times the project cost in increased tourist revenue (RAYBOULD and MULES, 1998).

With offshore protection, visual amenity is not impaired and there is no requirement for rock emplacement along the shoreline. Salient growth in the lee of the reef leads to enhanced shoreline stability and protection, and “the barricades” isolating people from the sea are removed (Figure 3). The designed size of the salient is adjustable during the design stage by changing reef size, distance offshore, orientation and elevation. Recreational and public amenity can be incorporated through surfing, diving, sheltered swimming, water games, fishing and marine habitat.

This paper addresses the need for and the benefits of offshore coastal protection through example, theory and application. The benefits of multi-purpose, offshore reefs are emphasised by summarising relevant NZ coastal research and by using a series of natural examples, case studies and numerical model simulations, including the large Gold Coast Reef designed for coastal protection and surfing (BLACK et al., 1998, 2000a; BLACK, 1999).

**OFFSHORE REEFS**

**The Hiatus Principle**

The use of sensitive solutions in coastal protection uplifts natural character to its proper priority. As such, offshore reefs emerge to overcome the current-day “Hiatus” in coastal protection which is exemplified by the appearance of the “planned retreat” management strategies. Planned retreat involves sacrificing property that is eroding to prevent the placement of hard engineering structures along the shoreline.

The hiatus arises because of public recoil against shoreline “barricades” made of rock or concrete, or the long-term cost of beach management. Moreover, in many cases, coastal erosion management solutions have only exacerbated existing problems, with serious “end-effects” adjacent to rock walls, changes to the natural processes that sustain a sandy beach and the well-known cases of downstream erosion behind breakwaters (Figure 4). Often these changes, which occur solely in response to the coastal protection structure, support the management consensus that “one piece of coastal protection leads to another”.

The “Hiatus” in New Zealand is both cultural and economic, brought on by well-founded environmental regulations through the Resource Management Act (1991). The cultural association with the beach during summer holidays (or the more serious surfer, fisher or recreational user) results in a strong demand for natural character. This is strengthened by local Maori who collect shellfish and wish to maintain the “gathering” culture.

In parts of Asia, the economic realities, such as maintaining subsistence fishing and coastal housing, make it essential that coastal protection be undertaken.
Indeed, space to relocate people simply may not be available. However, inadequate solutions have often resulted in expensive foreign loans, continuous maintenance of the protection and severe loss of amenity, particularly with rock walls (Figure 1). As such, a hiatus has emerged in these countries as well.

In this context and as offshore reefs can be much more sophisticated than simple rock walls and groynes, the design process needs to amalgamate complex computer modelling with an “architectural” and “social” perspective. In addition, with positive cost:benefit ratios through tourism and land protection (e.g., RAYBOULD and MULES, 1998), the offshore reef can actually “pay its own way” and this leads to opportunities to overcome the perpetual economic burden of coastal construction and maintenance. Accordingly, with the incorporation of highly developed multi-purpose perspectives that go beyond the simple aim of protecting a stretch of coast, opportunities emerge for cost-effective and environmentally-sensitive solutions that provide broader public benefit.

The principle of “People’s way and Nature’s way”

Often “people’s way” in coastal protection has been heavy handed and defensive. Drawing a parallel with a trench war is not unreasonable. The ocean enemy is attacking on the other side of the rock wall and a victory is won when the sea cannot get across the wall. However, the casualties in this war are public good, natural character and loss of positive opportunity.

New Plymouth is one of New Zealand’s best placed central business districts overlooking the Tasman Sea, but the city is isolated from the sea by an imposing and dangerous rock wall. There are many other well-known cases where the wall is collapsing, the beach is lost and there is no public amenity.

While the wall can be repaired, the loss of the beach has broad implications, including elimination of the natural protection that the surf zone and beach provide, and this would inevitably explain the cause of the wall’s collapse. Similarly at Noosa, southern Queensland where the rock wall has been slowly replaced after a series of coastal projects, including long-term nourishment of the beach (Figure 5).

Figure 4 shows a case where the coast is protected and a renourished sandy beach has stabilised. However, natural character is still not being considered, particularly as the large offshore breakwaters dominate the view out to sea and the benefit of incorporating recreational use into the breakwaters has not been realised. This series of offshore breakwaters has been constructed recently in East Anglia (England). The consequence of causing total blockage to longshore transport has been severe erosion of the beaches downstream. The coastline is presently suffering from a sediment deficit and so major blockages to transport are expected to lead to downstream deficits, unless additional sediment is provided to the system. Although the potential for offshore reefs to provide a complete solution in this case has not been explored, subtlety, rather than heavy-handedness, plus sophistication, rather than simplicity, is generally needed to optimise the sediment budget for the most cost-effective outcomes. As the reefs are smaller and much less expensive to construct, a more cost-effective management strategy potentially could be developed.

“Nature’s way” is very different. Figure 6 shows a small island on the exposed Great Barrier Reef perched on a coral reef in the Pacific Ocean. The waves are large at the site but the island requires no coastal protection because nature provides protection through the presence of the offshore fringing reef that dissipates the wave energy. The reef in many cases provides a world-class surfing break, there is a lagoon used for fishing and swimming etc., and the shoreline is protected.
Some tropical islands with fringing reefs require coastal protection because of rising sea levels or impacts of human construction, but the protection requirement is often small, compared to an open coast beach. However, for a range of reasons, including misinformed attempts to transfer temperate protection solutions into the tropics, large coastal protection structures are still common there. In an Indonesian case, small, long-term erosion problems are exacerbated by the local use of beach sand for construction and the placement of accommodation hotels too far seaward. One solution recommended by international consultants was a very large series of groynes. The initial cost for construction and loan repayments to the Indonesian economy would be substantial. Moreover, this development lacks subtlety, fails to consider natural character, the small longshore transport rates or the very important local social issues associated with beach use. Indeed, the local people were strongly opposed to the planned development.

The concept of offshore protection through breakwaters is not new (e.g., LEE and BLACK, 1978), but the development of a more subtle approach to offshore coastal protection has only become achievable with the appearance of sophisticated computer modelling to support the design process. Several other important factors have played fundamental roles and four of these are the rise of the “Hiatus Principle”, the demand for better cost:benefit ratios, the appearance of datasets collected specifically to understand the surfing reef characteristics through the Artificial Reefs Program (MEAD and BLACK, 1999a; MEAD et al., 1998; HUTT, 1997; SAYCE, 1997; ANDREWS, 1997) and the utilisation of less expensive geotextiles for reef construction (JACKSON, 1987).

Undoubtedly, the world-wide interest in surfing and the growth in recreation has led to strong support for incorporation of surfing. Surfers require new breaks to generate new challenges (Figure 7) and to alleviate over-crowding of existing breaks (Figure 8). It is estimated that the surf industry is worth several billion dollars worldwide.

The MOA Principle

Offshore reefs embody three fundamental characteristics described by the acronym MOA, i.e. Multi-purpose, Offshore and Adjustable. (Interestingly, a Moa is a flightless Kiwi bird that went extinct in the late 1800’s). The word adjustable is used to describe the design phase, not to imply that offshore reefs are adjustable after construction.

The “multi-purpose” reef incorporates recreational and public amenity through surfing, diving, sheltered swimming, water games, fishing and marine habitat. Being “offshore”, the coastal protection is no longer on the beach itself which eliminates the loss of natural character, removes the protection from the shoreline, and allows the natural processes which link the offshore sand banks to the sand dune to continue to operate.

The Lever Principle

It is informative to liken coastal protection structures to machines with levers, with each lever providing an adjustment.
capacity. A designer of a shoreline structure will “adjust the levers” to suit the local environment. The sophistication of the machine is, of course, related to the number of levers. The following section compares shore-parallel rock walls, groynes, offshore breakwaters and offshore submerged reefs on open, sandy beaches.

The shore-parallel rock wall is a machine with one major lever. While the height, rock size gradient etc. are varied, this is done primarily for the stability and over-topping aspects, which depend on wave climate. The one free major lever is the adjustable horizontal position of the wall across the beach, although, in most cases, this lever is not used when the wall is simply placed at the position of the erosion scarp, or on a legal land boundary.

A shore-normal groyne is a machine with two major levers. The first free lever is the length of the groyne and this is the most varied design characteristic. The other lever is groyne orientation, but the common orientation is parallel with the alignment of the dominant wave direction. Occasionally, the groyne height will be varied cross-shore or the groyne will be made semi-transparent, but the main lever is still the cross-shore length, as most groynes are above water level and solid. Note that while the gap between groynes is varied, the lever principle is being applied to a single structure, not a field of groynes.

A single offshore breakwater arguably has 2 levers, which are the breakwater length and the distance offshore. Orientation has always been longshore (e.g., Figure 4), partly to minimise construction costs per unit length of coast, and height is set to prevent over-topping.

A single offshore, submerged reef incorporating multiple use has many levers. For coastal protection, there are at least 8 which are: distance offshore, depth of the reef crest below the surface, placement in relation to natural water depth at the reef site, longshore reef length, cross-shore reef width, length/width ratio, orientation and wave refracton/diffraction characteristics. Surfing amenity creates many more levers (at least 6) including surfing wave difficulty, take-off design, section size and number, and paddling access. And each of these is different for the 6 different water sports of surfing, windsurfing, body surfing, bodyboarding, swimming or jet skiing. Additional complexity for swimmers includes elimination of rip currents and degree of shelter. Other positive benefits such as net fishing on the reef, development of tourism around the reef and association of the reef with land-based facilities need to be adjusted and incorporated. Marine habitat quality and suitability will also vary with wave size, wave exposure, suspended sediment concentration, complexity of the substrate, etc., and all of these have a dependence on reef design and can therefore be adjusted. Factors such as currents, sheltering and habitat can be adjusted in relation to the optimisation of scuba or snorkel dive trails. The offshore submerged reef therefore has the capacity to be a very sophisticated structure with many adjustment factors.

Offshore reefs can be permanently submerged, emergent or inter-tidal. In each case, the depth of the reef, its size and its position relative to the shoreline determine the coastal protection level provided by the reef. This ability to vary the protection level as part of the reef design cannot be achieved with hard rock structures like rock walls or groynes and breakwaters, as these latter structures cannot be easily adjusted to the environment because they form impermeable barriers. On the contrary, offshore reefs allow sand to pass over their crest and between the reef and the shoreline.

**Confirmation of the coastal protection capacity of offshore reefs and prediction of salient size**

While considerable research has been published on shoreline response to emergent offshore breakwaters (e.g., HSU and SILVESTER, 1990), very little qualitative work has been done on the effect of submerged offshore reefs, particularly in the natural environment. For this purpose, aerial photographs seeking natural cases of offshore reefs and islands were examined (ANDREWS, 1997; BLACK et al., 1997a; BLACK and ANDREWS, in press). The coast of New Zealand experiences very different wave climates between the North and South Islands and between the east and west coasts and the sand grain sizes, sediment densities and beach slopes also vary. Thus, all New Zealand cases were considered and supplemented with cases from the eastern Australian coast in New South Wales (ANDREWS, 1997). Several hundred shorelines were scanned and digitised. Supplementary topographic charts were used for scale checking and to place the smaller shoreline features in the regional morphological context. A myriad of outline shapes were identified, such as multiple tombolos, complex salients behind island chains and symmetrical and asymmetrical forms arising from combinations of offshore features in a variety of coastal settings (Figures 3 and 9).

From these data, a classification scheme for salients was
developed. By regression curve fitting to the digitised shorelines, non-dimensional variable analyses were used to derive geometrical relationships and subsequently develop predictive methods for determining shoreline adjustment to the presence of offshore reefs and islands. The data were broken into sub-categories relating to the presence of multiple offshore features and particular emphasis was placed on the analysis of cases for a single obstacle (Figure 3).

Average salient apex position in the lee of offshore islands and submerged reefs was found to be given by,

\[
\frac{X}{B} = 0.422 \left( \frac{B}{S} \right)^{1.37} \quad \text{(islands; average } r^2=0.96) \quad (1)
\]

\[
\frac{X}{B} = 0.498 \left( \frac{B}{S} \right)^{1.27} \quad \text{(submerged reefs; average } r^2=0.96) \quad (2)
\]

where \(X\) is the distance from the obstruction to the tip of the salient, \(B\) is the width of the obstruction in the longshore direction and \(S\) is distance from the undisturbed shoreline to the obstacle. Island data suggests similarities to breakwater research with salients forming with \(B/S\) ratios of less than 1, whereas limiting parameters for reef data are a function of wave transmission, and thus full numerical simulations are needed in some cases. Equation (2) reduces to the form \(X=0.498\cdot S^{1.27}\cdot B^{-0.27}\), and \(S\) is expected to play the dominant role.

Responses of salient amplitude and basal width to size, type and positioning of offshore obstacles showed that natural salients are predicted to be larger than salients created in the lee of breakwaters. Previous breakwater and laboratory data suggested a coefficient of 0.678 and a power of -1.22 (HSU and SILVESTER, 1990) compared with 0.422 and -1.37 in equation (1). The ratio of salient amplitude (\(Y_{\text{off}}\)) and the full basal width (\(D_{\text{tot}}\)) were found to maintain a constant ratio given by,

\[
\frac{Y_{\text{off}}}{D_{\text{tot}}} = 0.125 \pm 0.020 \quad (3)
\]

Together, the above formulae allow prediction of the geometry of shoreline features in the presence of offshore emergent or submerged obstacles. The analysis also confirms that coastal protection associated with offshore reefs occurs in the natural environment. Further analysis is needed to identify the importance of reef width that will be significant in relation to the wave energy reduction performance of the reef. Reef depth, of course, will also be important. However, the cases considered here are those which could be identified on aerial photographs which meant that the reefs were close to the surface, as would be normally required for coastal protection and surfing reefs. Further research into these aspects is continuing.

**Other developments in New Zealand**

The Artificial Reefs Program is a specific and focused application of coastal research in New Zealand. Direct supporting research has included a series of surveys and studies of surfing breaks (e.g., HUTT, 1997; HUTT et al., 1998; MEAD et al., 1998; MEAD and BLACK, 1999a,b among others). These have formed the basis for prediction of surfing reef outcomes. Within this direct category, considerable attention has been given to application of numerical models (BLACK et al., 1998, 2000a; BLACK, 1999). Similarly, the planning and social aspects have been examined (SMITH, 1997; RENNIE, 1998; RENNIE et al., 1998a,b; LANCASTER, 1988; GOUGH, 1999) and the legal issues considered (MAKGILL, 1999). The other direct studies relate to the engineering construction aspects and the application of geotextile technology to the surfing reef application (JACKSON, 1987; JACKSON et al., 1998). The Gold Coast City Council’s demand for incorporation of coastal amenity in offshore protection has also been of direct importance (JACKSON, 1997; JACKSON et al., 1998; MCGRATH et al., 1999, 2000).

While many research programs have not focused on offshore reefs, they have indirectly helped through refinement of our understanding of wave and sediment dynamics. These include studies of port, harbour and marina dredging issues (HEALY et al., 1997; MCCOMB et al., 1997). Sediment dynamics studies have led to a better understanding of sedimentary processes (HUME et al., 1992; BELL et al., 1997; GREEN, 1999; GREEN et al., 1999, 2000; GREEN and BLACK, 1999) and the refinement and further development of computer models (BLACK et al., 1997b). The broader-scale geomorphological programs have led to an understanding of the interactions between the circulation and the seabed (HUME et al., 1997). The establishment of wave and sediment research projects (funded by the Public Good Science Fund of the Foundation for Research Science and Technology) have led to micro-scale measurements of sediment suspension (GREEN et al., 1999) (Figure 10) and the use of novel experimental techniques (FORSYTH, 2000), some at the continental shelf scale (BLACK and OLDMAN, 1999; BLACK et al., 2000b). Estuarine studies of sediment and mud suspension, often with supporting numerical models, have been very informative (GREEN et al., 2000; BLACK et al., 1999). Our understanding of beach processes and shoreline development has been supported by numerical modelling and with the assistance of permanent computer-controlled video systems, such as the Cam-Era Program (BOGLE et al., this issue).

**Case Study: the Gold Coast Reef**

A new “structure” to complement a 1.3 million m³ beach renourishment project at Narrowneck on Australia’s Gold Coast was requested by the Gold Coast City Council which set two goals for the project: (1) to provide a control point for the widened beach and dunes at Surfers Paradise; and (2) to use the structure to improve the surfing conditions. Although the shape and size of the structure was not pre-specified, the City Council wanted to maintain the amenity value of the beaches and did not want a rocky groyne or breakwater above water level to detract from the long, white-sand, beach panorama at Surfers Paradise. Thus, the City Council requested that the structure should be submerged, if feasible. Their own data indicated that the beach had a high commercial value by attracting tourists to the region, and that any increase in amenity would increase tourism (Figure 11).
Environmental and recreational amenity value was confirmed when, after completion of the design, an economic assessment indicated that the project would return more than 60 times the project cost, some $Aust 300-500 million (RAYBOULD and MULES, 1998).

There were no precedents, as existing submerged, offshore reefs had been crudely-rectangular and oriented longshore to maximize protection. Moreover, the potential to deliberately incorporate surfing and associated recreational amenity had not been considered previously. Thus, the novel structure had to be designed to be multi-functional. In addition, the Gold Coast region is known to experience up to 500,000 m$^3$ of net longshore transport (Figure 12). Any structure in this “river of sand” could have serious impacts downstream. It was necessary to trap some sand, but not all. The City was able to sustain a downstream renourishment program of around 80,000 m$^3$, which meant that the structure should allow free passage of more than 80% of the total littoral drift, while still providing a coastal control for the widened beach profile upstream and a “reef” for surfing.

A suite of design studies was established, including on-site field measurements (HUTT et al., 1998), surfing reef design using numerical wave modelling (BLACK et al., 1998, 2000a) and sediment transport modelling (BLACK, 1999). Because the reef had to simultaneously meet potentially-exclusive surfing and sediment transport design criteria, the wave and sediment modeling studies were conducted concurrently and iteratively (BLACK et al., 1998).

To develop the design, the natural bathymetry, wave breaking characteristics and peel angles of 33 (now 43) world-class surfing breaks were recorded at sites in Indonesia, Hawaii, California, Brazil, New Zealand and Australia (MEAD et al., 1998). The bathymetries of these reefs provided considerable insight into the characteristics of quality surfing reefs.

In addition, the reasons why the natural sandy headlands on the Gold Coast provide world-class surfing waves were only intuitively understood, as no surfing studies of these breaks had been previously undertaken. Knowledge of their sediment dynamics and surfing character was crucial for predicting the impacts of the new reef within the same coastal environment. Thus, two world-class “headland” surfing breaks on the Gold Coast (Kirra Point and Burleigh Heads) (Figure 8) were scrutinised to seek commonalities within this coastal system that experiences large net littoral drift.

Guided by these measurements and using a range of hydrodynamic, refraction, beach circulation and sediment transport models from the 3DD suite (BLACK, 1995; 1996), several hundred different designs were numerically simulated to examine surfing reef characteristics and the impact of the reef on net littoral drift. The design presented here was the optimal choice for the site, having the required impact on longshore drift, while providing surfing waves over a broad range of wave heights, wave periods, swell directions and tide levels.

**Gold Coast Reef Shape**

A unique characteristic of the Gold Coast Reef is its shore-
normal orientation (Figure 13a,b). Moreover, the reef shape is not a simple rectangle, but consists instead of concave and curved isobaths, with large offshore focusing segments. These form a “double-sided underwater headland” (BLACK et al., 1998). The reef has a long northern arm, with a beginner’s surfing segment at the inshore end, and a shorter southern arm. The short arm has no beginner’s segment, but is identical to the long arm otherwise. The long arm extends over 400 m offshore from the natural 2 m depth out to 10.4 m depth.

The two arms both incorporate a large, focusing segment on the offshore tip. By refraction, this sets up the wave orientation along the surfing ride and creates a pronounced wave peak that maximises breaking wave height at the take-off. Surfing ride length is 200 m for the most common wave height of 1 m. However, rides are shorter for larger wave heights, but remain as much as 120 m long for the largest design height of 4 m.

The two arms have been separated and this is designed: (i) to eliminate wave interference on the take-off zones and main part of the wave; (ii) to provide the space needed to create the peak at the take-off and (iii) as a paddling channel to give surfers access during moderate and large wave conditions when the adjacent beaches are closing out.

The reef crest was set to be as shallow as possible, without emerging, to ensure that the minimum design wave (Hs=1 m) breaks at high tide. Accordingly, the reef crest was set to 0.25 m depth at mean low water spring tide. After wave climate analysis, the structure’s overall orientation was set to 95°T which rotates the reef 5° south of the shore-normal to face into the cyclone swells which are best for surfing.

Wave interference patterns due to diffraction and refraction provided an inshore segment of “wedge-like” waves at the cross-over points for water games and all forms of surf craft (Figure 14). A lagoon shoreward of the reef provides sheltered paddling and, at low tide, sheltered swimming for beach-goers. This is the only sheltered beach location at Surfers Paradise and should therefore be highly valued by beach-goers.

### Sedimentation Patterns

In developing the final shape, the patterns of sedimentation around the reef and effects on adjacent beaches were numerically simulated for 17 different cases of wave height, wave direction and tidal level to assess the reef’s impacts on local and regional sediment dynamics (BLACK, 1999). For these, the non-linear Boussinesq model 3DD (BLACK, 1995) of wave propagation (incorporating refraction, diffraction, bed friction and breaking) was coupled with the Lagrangian sediment transport model POL3DD (BLACK, 1996; BLACK et al., 1999) to predict sedimentation patterns and the effect of the reef on littoral drift.

The modelling showed highly variable sedimentation patterns between the different weather cases. In addition, with the high longshore sediment transport on this coast, the modelling predicted the need to place the inshore end of the reef on the 2 m depth contour in order to leave a gap between the reef and beach for sediment by-passing. Detailed sedimentation patterns after averaging of all of the modelled cases showed a “rhythmic” distribution and the general results (BLACK, 1999) were:

- Sedimentation will occur in the paddling channel between the two arms, along the outer rim of the reef, in the lagoon and on the inshore tip of the northern and southern arms;
- Sedimentation trends run both longshore and cross-shore. For example, there is a tendency for a longshore bar to form but shore-normal sand bars are common, so that the longshore bar is sometimes rhythmic in the longshore direction;
- Flow convergence leads to scour through or near the narrow cross-section between the reef and beach;
- There is no accretion on most of the reef crest.

After adjustments of the reef characteristics were completed with the numerical models, the designed reef was found to...
provide an effective coastal control point, without causing a total blockage to littoral drift. This design met the requirement to trap approximately 80,000 m³ of the net movement of approximately 500,000 m³ yr⁻¹ moving along the Gold Coast (BLACK, 1999).

As required, the reef remains relatively transparent to interruption of natural littoral drift. This is due to: (a) penetration of waves into the lee of the reef which has a narrow aspect ratio in relation to the wide distribution of wave directions at the site; (b) the submerged nature of the reef which allows waves and sediment to pass over the reef crest; and (c) the placement of the most-shoreward part of the reef on the 2 m isobath to allow longshore transport to pass between the reef and the beach. Notably, this narrow aspect ratio relates to the sediment transport design criteria for the site and so the shape will not be the same at all sites.

The southern arm was shortened to make a major saving on construction costs when the models predicted that the arm would be buried by encroaching longshore drift. The ratio of cross-shore to longshore reef dimensions and the wave penetration into the lee of the reef determined the size of the predicted salient in the lee.

Construction

With the reef design completed, an undistorted-scale, laboratory model of the reef was constructed, which confirmed the numerical modelling (TURNER et al., in press), and the reef construction was then approved.

The reef is made of ReefBags© which are “TerraFix mega” geotextile bags, filled with natural sand (JACKSON et al., 1998). The bags are filled in a split-hull hopper dredge after being pre-sewn in the supplier’s factory. Once filled, bow and stern satellite positioning on the dredge is used to find the release location and the bag is dropped to the seabed.
(Figure 15). Construction is undertaken offshore and so there is minimal impact on beach users. The bags are 160-300 tonnes, being typically 20 m long and up to 5 m diameter. These are predicted to be stable in the 8-10 m waves that occur during cyclones (A. JACKSON, pers. comm.). 300 bags are being used to make up a total reef volume of approximately 110,000 m³.

The Outcomes

Reef monitoring is being undertaken, both formally and informally through university projects and remote video (www.wrl.unsw.edu.au/coastalimaging/).

Ecology

Prior to construction, the seabed was covered in mobile loose sand, supporting a very limited diversity of marine organisms. With the presence of the reef however, a bio-diverse marine ecosystem has developed. The geotextile bags attracted small fish within hours of their placement. Within 2 weeks, the bags became overgrown with marine organisms and plants (Figure 16). After several months, a complete eco-system developed, including sightings of sharks (at the top of the food chain) feeding on recruited fish. As such, the reef has met its purpose of creating new habitat and of supporting a broad range of marine life.

Surfing

At the time of writing this paper, the reef was still incomplete, as the top layers of the reef had not been placed. This means that the smaller swells are not breaking and the long surfing rides are not yet possible. However, when the swell is large enough to break, the reef is providing high-quality surfing rides and is fully meeting its design criteria (Figure 7 and 17). The usage by surfers has been exceptionally high, and the comments being placed on the associated public world-wide-web sites (http://www.burleighcam.com.au) have been positive. The following quotation comes from the site on May 13, 2000 which refers to the new reef as “Nazz”:

“You want the bomb waves, you go to Nazz. That's the story today. It's going sick up there. Light westerly winds and a 1.5 metre SE swell is making Narrowsneck and the northern beaches find some wicked form. Heaps of crew knew it too, they were all too keen for the early offshore sesh. The bulk of the pack is hanging around the artificial reef, but the banks north, south or anywhere in the nearby vicinity are just as good. The barrel show will hold till those westerlies swing later through the day. Tomorrow should see the offshore last longer. Check the pics and work out why the hell you're not there.”

Thus, although not yet fully complete, the surfing characteristics of the reef are now beginning to meet or exceed surfers’ expectations.

Beach Dynamics and the Salient

As the top layers of the reef have not yet been placed, the development of the salient at the shoreline is continuing. However, the prediction of a rhythmic pattern of sand banks shorewards of the reef has been confirmed. These banks are highly popular with surfers, as they offer better surfing rides, than the less reliable sand banks on the open beach (Figure 15b).
Offshore reefs alone will not stop all beach erosion and so the public needs to consider their value as a structure to systematically modify and control the shoreline changes, rather than acting as a total barricade, particularly when natural character remains a high priority. Natural character includes shoreline oscillation. In many cases, as at the Gold Coast, shoreline nourishment will accompany the reef during the construction phase. On-going nourishment may be required after construction, but the reef in most cases will reduce the extent of the shoreline movements and the long-term volumes of nourishment required.

**DISCUSSION**

Because offshore reefs have so many “adjustable levers” during the design phase, issues of sediment movement, trapping rates, salient size and amenity criteria such as surfing conditions need to be pre-specified as design criteria. The design criteria can include the type of surfing reef, degree of difficulty, length of ride and other surfing factors.

Secondly, each reef needs to be adapted to the physical environment. Each design case has proved to be absolutely different and the physical setting has played a strong role. For example, a reef designed for the rocky shoreline at...
New Plymouth in New Zealand with a rocky reef attached to the shore by a wall and pier, has very different characteristics to one designed for a beach adjacent to a large headland at Noosa in Queensland, Australia where the reef was similar to a submerged berm made of geotextile ReefBags©. Both are of these are very different to the Gold Coast Reef. The variations have been inspired by the local sediment transport conditions and some of the variation will come with the surfing requirements.

We are now able to numerically define the degree of surfing difficulty on the reef (HUTT et al., 1998). This opens opportunities for developing reefs for beginners or for experts, and to modify the design for the different surf craft. For example, the Gold Coast Reef was ranked “6-7” on a degree of difficulty scale from “1-10”. The “9-10” rankings are essentially unsurfable, and so the Gold Coast Reef is providing world-class waves and challenging the top amateurs (Figure 9). We are also able to change the nature of the surfing ride from “trick riding” to “tube riding” or to incorporate both aspects into one large reef.

With the development of sophisticated computer modelling, optimisation of the reef designs for coastal protection and surfing is now achievable. Thus, the future for coastal protection looks set to focus on elegant, scientifically-complex and environmentally-friendly solutions, rather than the simple defensive barricading that we have witnessed in the past.

CONCLUSIONS

A summary of the uses of offshore coastal protection amalgamated with recreational amenity was presented. With (i) the adaptation of high-quality computer models, (ii) the collection of datasets and development of knowledge about surfing reefs; and (iii) the reduction in construction cost with geotextile ReefBags©, more sophisticated coastal protection solutions are achievable. These complex structures will replace the simple rock wall, groyne or offshore breakwater construction that has been the feature of coastal protection in the past.

With offshore protection, visual amenity is not impaired and there is no requirement for rock emplacement along the shoreline. Salient growth in the lee of the reef leads to enhanced shoreline stability and coastal protection, and “the barricades” isolating people from the sea are removed. The size of the salient is adjustable by changing reef size, distance offshore, orientation and elevation. Recreational and public amenity can be incorporated through surfing, diving, sheltered swimming, water games, fishing and marine habitat.

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