Wave Rotation for Coastal Protection

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Often coastal protection works are carried out to mitigate the effects of erosion, but do not attempt to address the cause. For example, rock/concrete walls, breakwaters or groynes along the beach act to mitigate the effects or to realign the beach. However, end effects on the shoreline downstream and the environmental imperatives to retain natural character often preclude hard structures. Also, coastal re-alignment may not be possible in built-up areas where natural alignments would sweep though modern shoreline developments.

Wave rotation is a method of coastal protection that targets the cause of the erosion (i.e. longshore wave-driven currents). Offshore, submerged structures are oriented to rotate waves so that the alongshore current (and thus sediment transport) is reduced inshore. The realigned wave angle at the breakpoint (in harmony with the alignment of the beach) results in reduced longshore flows and sediment accretion in the lee of the rotating reef.

This paper considers two types of offshore reef that we describe as "dissipators" and "rotators". The former acts to break the waves and protect the coast by reducing wave energy in the lee of the reef. The latter relies on wave rotation to create the chosen wave alignment. The rotator is particularly beneficial in areas of low wave climate or large tidal range when wave breaking is difficult to achieve on a submerged structure, particularly around high tide. Numerical modelling is used to demonstrate the effectiveness of wave rotation to mitigate erosion.

1. Introduction

There are many devices that have been or are presently being used to protect the coast. These include seawalls, groynes and artificial headlands, detached breakwaters and submerged reefs, beach nourishment and dune rehabilitation, as well as training walls to stabilise river entrances (Nielsen, 2001). In broad terms, these have often been described as hard or soft, but there are several intermediate options also. Another relevant categorisation relates to the positioning, i.e. on the sandy beach or offshore (both above and underwater). There has been a negative public reaction to large structures on the beach in many parts of the world (Black, 2001). Indeed, the shoreline structures more correctly provide "land" protection rather than "beach" protection, because often the beach is severely degraded by the presence of a seawall, groyne or hard rock/concrete protection device.

The various forms of civil engineering works can be classified into different categories, depending on whether they are working with nature, against nature or have the objective of modifying nature (Nielsen, 2001). For example, beach nourishment is an option that works with nature. It feeds a natural demand of the sand transporting processes, albeit artificially, and thereby prevents further erosion of the shore. In contrast, seawalls fight nature by repelling wave action, which may have adverse consequences on other parts of the beach. Submerged reefs work with nature by modifying the natural nearshore wave transformation processes to alter nearshore currents and obviate coastal erosion processes.

Many of these measures just deal with the effect, not the cause of the erosion problem. On beaches, erosion occurs when inputs of sand are less than outputs from a region, and this arises at a series of time scales. The most serious and unsustainable are long-term loss trends, assuming that the beach is still reasonably intact and able to accommodate the shorter and neutral erosion/accretion events. The cause of long-term trends will often relate to changes to sediment supply (e.g. altered river or coastal cliff supply, upstream construction) or changes to beach orientation due to construction. The latter is prevalent in modern cities that have sculpted the shoreline with retaining walls or coastal development. The fundamental problem relates to an imbalanced alignment of the coast in relation to the average wave orientation, which leads to wave-driven longshore currents. These currents transport sand away from the site and local erosion results.

We have been involved in several of these cases in recent applied investigations. Examples are Noosa Beach (Australia), Westshore Beach (New Zealand), New Plymouth City Beach (New Zealand) and Bournemouth Beach (Southern England). In each case, the coastal orientation is out of alignment with the wave orientation, and input supply is not able to sustain the sediment losses that occur with the currents. Moreover, commercial and residential developments have precluded the option of allowing the coast to naturally re-align. Re-nourishment with construction of groynes or rock walls has been undertaken to overcome the sediment losses, but the costs have been high, and the mitigation has not been sustainable in the long term. The responsible agencies (mostly local councils) have questioned their own willingness to re-nourish and maintain the structures due to the accumulating costs.

This paper describes offshore underwater reefs that act to dissipate or rotate the waves. On a "dissipator", the reef acts to reduce the reduce wave energy at the shoreline by wave breaking. The "rotator" reduces the longshore currents to stabilise the coast. The reefs also have the important benefit of creating opportunity for incorporation of surfing and other water sports as artificial surfing reefs (ASR's).

2. Wave Dissipation and Wave Rotation

Natural offshore reefs have a beneficial impact on coastal stability. Black (2001) described offshore protection as nature's way and cites examples of coral-fringed islands, where the reef dissipates wave energy to protect the coast, and the many nearshore reefs found on beaches worldwide. Salient or tombolo growth in the lee of the reef leads to enhanced shoreline stability and protection. Nearshore submerged reefs also provide a shoreline protection solution with low environmental impact. Visual amenity is not impaired and there is often no requirement for hard structures along the shoreline. Moreover recreational and public amenity can be incorporated through surfing, diving, sheltered swimming and water games.

The effects on the shoreline of wave breaking on an offshore reef are becoming better known. There are many examples on the Australian New South Wales coast where salients have formed in the lee of offshore reefs and islands (Fig. 1). Moreover, recent studies of natural offshore reefs and islands have provided empirical relationships governing the geometry and size of natural salients or tombolos (Black and Andrews, 2001a,b).

The use of wave rotation as a method of coastal protection is less advanced but the principal of neutral alignment leading to sandy beach formation has been considered by Black and Rosenberg (1992a) and many authors have confirmed the importance of wave orientation at the breakpoint driving littoral drift (e.g. Komar, 1998; U.S. Army Coastal Engineering Research Centre, 1975). Now, with modern computer modelling and larger wave climate datasets the neutral alignment of the waves (in relation to existing beach orientation) can be more accurately determined. The same computer models are then used to design a structure to be placed offshore to achieve the required wave re-alignment in order to change the longshore wave-driven sediment fluxes.

The "rotator" is a soft option, as all construction is underwater offshore. The method is particularly beneficial in regions of high tidal range, where wave dissipation at high tide may be minimal, but it remains important to consider wave realignment in all offshore structures in relation to longshore drift. The main force that drives the currents is wave-induced radiation stress in the surf zone. The radiation stress is responsible for the well-known phenomenon of "rip currents" which transport sand offshore. The longshore currents arise when the wave crests are aligned at an angle to the beach. That is, for a given wave height, the strongest currents occur as the angle of the waves to the shoreline increases (sediment transport also increases with wave height). This results in a net movement of sand along the beach and, when the upstream supply of input sand is inadequate, the beach erodes.

In the past, there have been attempts to overcome this mismatch by realigning the beach. However, in heavily populated sites, such beach realignments are not possible because it involves destroying coastal properties and cutting a new shoreline shape. Thus, a rotation of the wave crests to deflect or stretch the waves crests will act to reduce the wave energy or spread it over a greater area, thereby reducing local wave height and coastal erosion. The rotator system is focused on a single principle, i.e. the submerged reef rotates the wave angles as they approach the beach in order to: (i) deflect and stretch the waves or (ii) to align the waves to be more shore-parallel so that the wave-driven currents along the shore are reduced. In both cases, this leads to reduction or elimination of the sediment movement responsible for beach erosion.

3. Case studies

To optimise the coastal protection in relation to construction cost and environmental goals, while also amalgamating the coastal protection with water activities like surfing, a careful design optimisation is needed. This is further necessitated because the reefs are designed to put the system closer in balance, leaving the natural erosion/accretion cycles to continue, rather than simply barricading the shoreline like a rock wall. We examine 3 case studies here, which show the basis for and benefits of the numerically determined solutions.

Figure 1. Natural coastal protection due to salient formation in the lee of offshore reefs in New South Wales, Australia. Clockwise from top left a) Sapphire Gardens to Emerald Beach, b) Toukey and Budgewoi, c) Conjola Beach and Ulladunlla, d) Woolgoola to Red Rock. (Source: Readers Digest, 1986)

3.1 Noosa

Noosa Beach in southern Queensland is greatly valued for its natural character with sweeping white sandy beaches, adjacent National Park and wooded streets. The surfing headlands in the National Park have been the mecca for surfers since the early 60's and the region remains a natural wonderland for swimmers, walkers and beach lovers. However, with coastal development, the Main Beach at Noosa is subject to bouts of severe erosion. While the expensive real estate is protected by a boulder wall and downstream rock groyne, the loss of the sandy beach leads to a major downturn in tourist numbers and a loss of natural character. With the company's unique expertise in sustainable, environmentally-sensitive solutions to coastal erosion problems, ASR Ltd, in association with International Coastal Management Ltd, were asked by Noosa Council to overcome the erosion problem.

The purpose of the Noosa study was to design a "structure" to provide coastal protection and public amenity at Noosa Main Beach. The structure had to:

- best suit the local physical system, and;
- meet strict environmental, visual and public usage requirements.

The Noosa Beach field site was investigated through historical data, aerial photographs, current and wave meters and the full suite of numerical models was adapted to the site. The analysis unravelled the complexity of the regional and Main Beach dynamics. The primary cause of the erosion was found to be misalignment of the waves and the present-day shoreline leading to dominant current patterns to the northwest. This led to an unstable beach with net erosion and depletion of sand. With the beach tucked in behind a major headland, sand arrivals in slugs coming down the headland were out of phase with the local erosion on Main Beach, which led to periods of severe depletion along the shoreline. With the rock wall in place and no buffering sand dune system, the beach was unable to recover rapidly and so nearly 1 million m^3 of nourishment had to be pumped from the estuary over two decades to artificially sustain the beach.

After considering a range of alternatives (extension of the groyne field, nourishment on an offshore bar to protect the shoreline, continued shoreline nourishment, an offshore ("surfing") reef, etc.), the most cost-effective and environmentally sound solution was an underwater "berm" that rotates the waves and changes the longshore current patterns along the shoreline responsible for the erosion was found to provide exceptional protection for the beach. Council requested inclusion of board and body surfing areas to further improve the benefit/cost ratios of the structure.

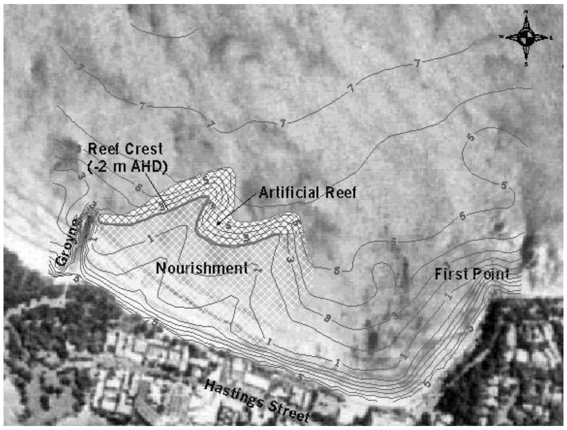

Figure 2. Plan of the wave rotation reef designed for Main Beach, Noosa.

The detailed shape and position of the berm (Fig 2.) was determined using the 3DD suite of models (Black and Rosenberg, 1992b; Black, 1995) in predictive mode (approximately 3500 model simulations), after successfully calibrating against measured movement of a large slug of nourishment placed as an interim measure on the beach and offshore bar. The offshore berm rotates the waves and reduces the current flows along the beach while also breaking the large storm waves to dissipate their energy. With the sophistication of the numerical models to optimise changes in beach set-up and radiation stress gradients, the berm will be highly efficient at the site. Nourishment will be added to initiate the new beach and eliminate short-term impacts downstream. In future, new sand will pass across the new beach profile and spill over the berm, like water spilling out of a submerged bathtub, thereby eliminating any impacts downstream.

3.2 New Plymouth City Beach

At New Plymouth, we established a time-lapse video system on a tall city building overlooking the site. The rectified images showed that the wave orientation was 20° out of alignment with the modern rock wall shoreline (Black *et al.,* 1999). Thus, while adjacent beaches with more neutral alignments were sandy (e.g. Fitzroy Beach), the main city beach had been lost and a large rock wall was required to protect the city foreshore. Interestingly, the wall eliminates the potential for fully "connecting the city to the sea", as requested by local ratepayers, and significantly reduces the various public uses of the region, leading to a negative socio-economic impact.

To create a new public beach, onshore facilities were merged with a multi-purpose structure offshore. The sedimentary impact on downstream beaches was assessed in conjunction with a large field and modelling study being undertaken on behalf of the local port (McComb and Black, 2000). Numerical modelling of the natural sedimentation within the structure was predicted to be slow, requiring beach creation by initial nourishment and a design that retains this sand. A curving rock wall, constructed of local rock, was adopted with an attached submerged surfing reef. The reef dissipates wave energy, allowing wall height to be reduced while providing recreational amenity. Interstitial rock structure was chosen to enhance shellfish habitat. Even though the main method of coastal protection in this case is a dissipator, this study demonstrated that a misaligned shoreline was the cause of erosion. In this location, a rotator device would be effective for erosion protection, but could not provide the same level of public amenity.

3.3 Bournemouth

Bournemouth Borough's ocean frontage is 12 miles of arcuate coastline linking Poole to Christchurch Bay in southern England. The Bournemouth beaches are artificially created in front of a boardwalk and stabilised cliffs (Fig. 3). The beach is presently protected by sand renourishment placed in 1975 and 1989 between a succession of wooden groynes that have a significant negative visual and amenity impact on the shoreline.

The wave approach directions relative to the shoreline orientation in Poole Bay cause the wave heights to increase from Poole to Southbourne because of the protection afforded by the headlands to the west (Handfast Point, Peveril Point and Durlston Head). Consequently, the bay has developed a spiral shape and it is believed that the net longshore transport is to the east and increases towards Southbourne (Harlow, 2000).

Cross-shore beach profiles show that the beach volumes tend to gradually and systematically diminish at decadal time scales out to the limit of the surveys at 450 m offshore of the sea wall (Harlow, 2000). The dropping beach levels in the context of the net longshore transport means that sand leaked from between the groynes is lost from the beach system, with loss rates that vary from about 80,000 m^3yr^{-1} at the west end of the borough to about 110,000 m^3yr^{-1} at the east. As such, renourishment is still required approximately every 15-20 years, which leads to a substantial cost from council revenue and MAFF grant aid.

Figure 3. An aerial view of the successive groynes in Poole Bay.

The project at Bournemouth was not undertaken for coastal protection because the primary goal was to create high quality surfing reefs along the foreshore. However, the numerical modelling undertaken for the study confirmed that the shoreline was out of alignment with the prevailing wave climate, which led to the recorded losses of sand (Harlow, 2000). Reef construction costings and numerical studies indicated that a single reef could replace two groynes, and that the construction costs would be similar. By orienting the reefs to rotate the waves to the west, the net transport could be locally neutralised, thereby acting to help stabilise the beach. A series of reefs along the foreshore would be needed to make the full adjustment, and it was proposed that construction would occur each time a groyne needed replacing. The groynes have a typical lifespan of 20-25 years and so the full replacement could be achieved in that time scale.

4. Discussion

The wave rotation concept is particularly useful in situations where long-term erosion leads to expensive or unsustainable maintenance measures. Neither the rotator nor submerged dissipator reefs attempt to stop the short-term erosion/.accretion cycles that naturally occur on beaches in response to storms and swell. Instead, these devices aim to overcome the underlying long-term trends that lead to maintenance requirements. Thus, the solutions allow the beach to retain natural character, while the natural cycles occur on a buffered, wider beach after the formation of the salient enhances beach width. A major additional benefit of the offshore solution is the capacity to incorporate water sport amenity, particularly surfing, sailboarding and diving reefs. In order to rotate the waves, the reef needs to be aligned at an angle to the shoreline (Fig. 4), and this is in synchrony with the requirements for ASR's (Black and Mead, 2001; Mead and Black, 2001a, b).

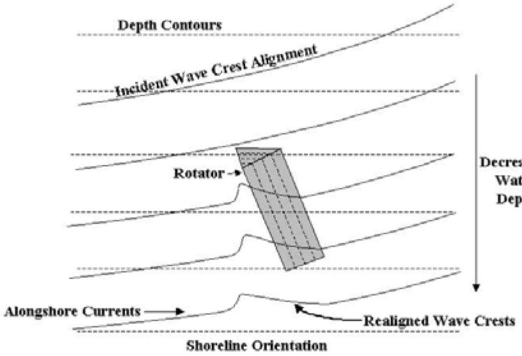

Figure 4. Idealised schematic of a rotator reef.

Offshore solutions also offer benefits through the incorporation of marine habitat, sometimes specifically for target species. Construction of a submerged reef can provide a more complex and stable habitat (than mobile sandy substrate) and will therefore increase the biodiversity and species abundance. There has been a large amount of work on ecological enhancement using artificial reefs throughout the world (e.g. Bulletin of Marine Science, 1994). From these studies it is evident that, as a general rule, species abundance and diversity are greater when the habitat is more stable (in comparison to mobile substrates – e.g. Mead *et al.*, 1998), the topographically more complex (a higher number of different niches are available) and when the reef is larger (Pratt, 1994). The reef itself provides a substrate for larval organisms in the water column to settle on and become established. Once primary producers become established, these organisms, and the reef itself, provide shelter and a food source for fish and other marine life and act as a fish-aggregating device (FAD) (Bohnsack & Sutherland, 1985). Construction of artificial reefs also provides the opportunity to create specific habitat and 'seed' specific species that may be of commercial or cultural value (e.g. Saito, 1992). In addition, a reef may also subtly alter the local hydrodynamics in a way that could increase settlement in the lee of the reef (e.g. Black & Gay, 1987). Therefore, the biological enhancement due to the construction of a multi-purpose offshore reef may include, increased environmental value (increases in bio-diversity and abundance), increased amenity in the form of a diving and snorkelling venue and enhanced fisheries by the incorporation of specific habitat.

In combination with the economic benefits of offshore coastal protection (e.g. Raybould and Mules, 1998; Gough, 1999; Black *et al.,* 2000), wave rotators provide an environmentally-sensitive solution to coastal erosion problems with potential to locally enhance ecological and amenity values.

5. Conclusions

In many practical cases, the shoreline is out of alignment with the wave climate due to coastal construction or changed sediment supply, which leads to longshore currents and sediment losses. However, an engineered re-alignment of the shoreline cannot always be achieved because of existing land structures or public use. Sometimes, shore-attached structures are implemented but these same structures can induce end effects (e.g. rock walls) or downstream effects (e.g. groynes).

As a substitute for shore-based construction, we consider wave rotation to be a useful "soft" alternative which provides a long-term reduction in net sediment losses, and thereby a more sustainable solution. The wave rotation concept is particularly useful in regions with larger tidal ranges and when net littoral drift is causing beach sediment losses. A common application of the technology is adjacent to a headland or artificial structure or along a beach requiring hard engineering or re-nourishment for its protection.

6. Acknowledgements

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