Issues Surrounding the Construction of Artificial Reefs by Detailed Examination of a Natural Headland

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ABSTRACT

Raglan, a prominent headland on the west coast of New Zealand, provides an ideal case study to understand issues surrounding the construction of surfing headlands and reefs. A number of extensive investigations have been previously undertaken at the headland related to surfing parameters, e.g. bathymetry, wave refraction and wave peel angles. However, there has been no research undertaken on the currents and sediment dynamics at the headland. Investigations have shown that both a supply of sediment around the headland due to wave-driven currents, i.e. west coast littoral supply, and importantly a recirculating transport pathway, sustain the sandy seabed adjacent to the headland's rock and reef shoreline. Surfing reef design should consider the possibility of using recirculating currents beneficially, so that potential looping sediment fluxes may be created to maintain the stability of the seabed adjacent to the structure. The results have also shown that there is a strong control on sediment transport where sandy and hard substrate interact which allowing sediment equilibrium conditions to evolve. However, despite mean bed levels remaining fairly stable, significant sand movements at the headland give insight into the potential for very large fluctuations at the toe of an surfing reef. Scour and undermining of the reef are likely to occur, which would require a protection apron to prevent collapse of the reef structure and a reduction in wave quality.

ADDITIONAL INDEX WORDS: *Sediment transport, bed stability, scour, surfing, surfing reef*

INTRODUCTION

Multi-purpose surfing reefs are increasingly being considered throughout the world as a viable option for coastal protection, ecological enhancement, and increased amenity through the creation of surfing waves (e.g. MEAD and BLACK, 2002). To better understand issues surrounding the construction of surfing headlands and reefs a case study was undertaken at Raglan, a large-scale surfing headland on the west coast of New Zealand. The scope of this study was to not only focus on the surfing aspects of the headland, but also on investigating the coastal processes in this environment. These are of fundamental importance for understanding the mechanism that maintains the stability of the seabed adjacent to the rock and reef armoured shoreline. The resulting data and insight will lead to greater scientific and engineering knowledge, of application both for coastal protection and the future development of surfing reefs.

REVIEW OF PAST STUDIES

Surfing Headlands and Groynes

The stability provided to the coast by headlands has led to the investigation and construction of surfing headlands as a means of protecting coastlines from significant erosion (Figure 1)(SILVESTER and HSU, 1997). This includes an attempt to simulate the crenulate-shaped

bays formed by nature (KLEIN *et al.,* 2002). This method of coastal protection can be termed 'headland control', where headlands are designed to minimise the effect of storm waves on the coast (SILVESTER and HSU, 1997). SILVESTER (1976) commented that the crenulate-shaped bay, either as a natural or human-made feature, can supply the variety of conditions demanded by body or board surfers. Thus, stabilisation and recreation might be served by the same headland approach. This concept of using headlands for recreation has not been embraced previously in the design of coastal protection, although groynes and breakwaters throughout the world sometimes inadvertently produce quality surfing waves following the build-up of sediment near the structure (SCARFE *et al.,* 2003).

Figure 1: Surfing Headlands on the Ibaraki Coast (Source: JAPANESE COASTS and PORTS, 1994).

On the contrary, there has been a number of surf sites adversely impacted or completely lost due to coastal construction where the quality of surf was not considered as part of the design (MOFFAT and NICHOL, 1989). An example is the Kirra Point groyne construction in 1972 on the Gold Coast, Australia, which had major impacts on the sand supply and modified the nature of sand movement in the area (Figure 2). The groyne was constructed by the local council to stop the beach erosion at Coolangatta and Greenmount beaches, due to the placement of the Tweed River training walls upstream of Point Danger, 1.5 km to the east of Kirra that interrupted the sediment supply to the headland (Figure 3). Although successful in restoring these beaches, extensive erosion ocurred downdrift on the adjacent Kirra Beach foreshore with approximately 100 m of land being lost to the sea. The surfing waves ceased breaking at Kirra until the groyne area filled with sand three years later, at which time quality waves returned to this headland. The construction in recent years of the Tweed River Sand Bypass System, where sand is continually pumped to the downstream side of the river, has significantly nourished the coastline below the Point Danger headland. This has also created what is being termed the 'Superbank' by local surfers due to the long rides that can now be achieved along the headland

Figure 2: Waves refracting around the Kirra Point groyne, Gold Coast, Australia producing a surfing break (Source: TRACKS MAGAZINE, 2000).

The value of surfing amenity to the community has since been recognised and was an integral component in the design and use of an surfing reef at Narrowneck on the Gold Coast, Australia, which was described by JACKSON and MCGRATH (1995) as the preferred method of beach protection along with nourishment and dune stabilisation. The structure was to be designed as a wide, visually unobtrusive, low profile submerged surfing headland that would enhance surfing conditions and have no adverse effect on beaches to the north (downdrift). This structure known as the Narrowneck Surfing Surfing Reef, which is essentially a large scale submerged reef or breakwater, has since been constructed and has stabilised the beach and improved surfing conditions at the site (BLACK, 2001a).

Figure 3: Aerial view of Point Danger to Kirra Point groyne at the top of the picture (left), and the 2 groynes on Kirra Point (right), Gold Coast, Australia (GOLD COAST CITY COUNCIL, 23-4-96).

Surfing Headlands

The geomorphology of a surfing headland requires a prominent coastal structure that may be a point of land or promontory, which is both exposed to swell and provides shallow water for waves to break. WALKER (1974) describes headlands or promontories as one of a number of environments where the breaking waves are surfable (i.e. where surfing waves are generated), which include reefs or shoals, beaches, and channels. An extended definition is where the seabed features of a surfing headland are configured to produce waves that refract and peel around the headland promontory, enabling maintenance of a steep unbroken wave face that creates sufficient board-speed for the surfer to perform manoeuvres (MEAD and BLACK, 2001a).

Surfing Headland Current and Sediment Dynamics

Headlands and specifically surfing headlands are regions where an abrupt change in orientation of the coast creates a variation at which the wave alignment interacts with the shoreline generating peeling waves suitable for surfing. Erosion problems in areas downdrift of the headland can potentially occur due to waves of a high oblique angle breaking along the shoreline, essentially creating a "large groyne" effect (e.g. BAQUERIZO and LOSADA, 1998). This high breaking wave angle to the shoreline leads to strong currents and significant sediment transport, especially in large surf conditions (KOMAR, 1998). The rate of transport can vary depending not only on the orientation at which the waves break relative to the shoreline, but also on the height and period of waves.

A rocky headland can also provide shelter from wave energy to its lee side, with a subsequent effect on the littoral supply and drift of sediment. The headland can act as a natural obstacle to the longshore sediment transport and the result is an accumulation of sediment on the upstream side of the headland (SHORT, 1999). The headland may also act as a cell boundary where local sediment circulation is confined into compartments. SHORT (1999) found that the bypassing of sand on medium to high littoral drift coastlines around headlands or large groynes extending beyond the surf zone has a tendency to occur in 'slugs' or pulses of sand. This transport creates phases of 'lean' and 'full' segments, with activation of the 'slug' initiated by high wave energy, due to larger or long period waves. Sand was found to pass more readily on smaller headlands such as Burleigh Heads on the Gold Coast, Australia.

CARTER *et al.* (1990) reported that currents, which had accelerated to a maximum along the flanks of a headland, decelerated on the bay beaches where the coastal alignment changed, showing that the partitioning of wave energy or power is of fundamental importance in the transport of sand at the headland. A decrease of wave energy where the alignment changed allowed deposition of sediment in this zone. Current re-circulation may also transport sediment back along the headland in the reverse direction to the dominant wave direction (BASTOS *et al.,* 2002). The presence of a re-circulating rip current at a surfing headland was identified by WALKER (1974), who found that a change in the headland orientation created a return flow seawards, allowing surfers an easier paddle back to the "take-off" point of the break. SHORT (1985) describes this as the 'end effect' where headland circulation is impacted or completely controlled by the topography where longshore currents turn and flow seaward (i.e. topographic rip). The rip intensity has been found to increase with wave height (SHORT, 1999) and can transport significant quantities of sand offshore (ROY *et al.,* 1994).

Currents at Surfing Headlands and Groynes

At coastal structures such as surfing headlands and breakwaters, currents and sediment transport may display similar characteristics to those found on natural surfing headlands i.e where waves break along the headland. Surfing waves often break along the side of breakwaters or jetties in a consistent peeling manner, similar to that of natural surfing headlands (SCARFE *et al.,* 2003). Currents and sediment transport are driven by the breaking waves, with the sediment transport enhanced in the zone closest to the seaward face, which may induce scouring at the toe of the structure (BAQUERIZO and LOSADA, 1998). Return currents may also be generated by obliquely incident waves reflecting from the rubble mound breakwaters (KOBAYASHI and ENTIN, 2001), or through wave-generated currents rotating seaward due to topographic forcing (GOURLAY, 1981; GAILLARD, 1988). FURUKAWA (2000) identified reversing tidal currents, whilst GOURLAY (1974) found in the lee of headlands or structures wave-generated current systems that often caused local reversals of the alongshore current. SAITO *et al.* (1996) reported strong rip currents along surfing headlands as well as recirculating currents in the lee of the structure, which strongly influenced sediment transport paths (see headland rips in Figure 1). Modelling for a surfing reef by MOCKE *et al.* (2003) showed similar re-circulating currents in the lee of the structure, and SHORT (1985) identified these types of rip currents as topographic (i.e. topographically controlled by headlands or reefs).

STUDY SITE AND METHODS

Investigations at Raglan, a prominent surfing headland on the west coast of New Zealand, have been undertaken to determine the mechanism for maintaining the stability of the sandy seabed in this environment (Figure 4). Raglan is well known for its consistent world class surfing waves that break along a rock and boulder lined shore (Figure 5). The naturally armoured shoreline provides an ideal case study where the stability of the headland structure is controlled, enabling an understanding to be gained into the complex wave, current and sediment dynamics at the headland.

A series of extensive investigations have been previously undertaken at the Raglan headland related to surfing parameters, including the bathymetry, wave refraction and wave peel angles (HUTT, 1997; SAYCE, 1997; SAYCE *et al.,* 1999; MEAD, 2000; HUTT *et al.,* 2001). These investigations included large-scale experiments, as part of the Surfing Reef Program at the University of Waikato (BLACK, 2001a). The surfing waves at Raglan, as well as many other high quality breaks throughout the world, have been studied (MEAD and BLACK, 2001b), so that the complex scientific issues surrounding high-quality surfing waves could be better understood. This knowledge has since been used to design a number of surfing reefs for both coastal protection and enhanced surfing amenity (MEAD and BLACK, 2002).

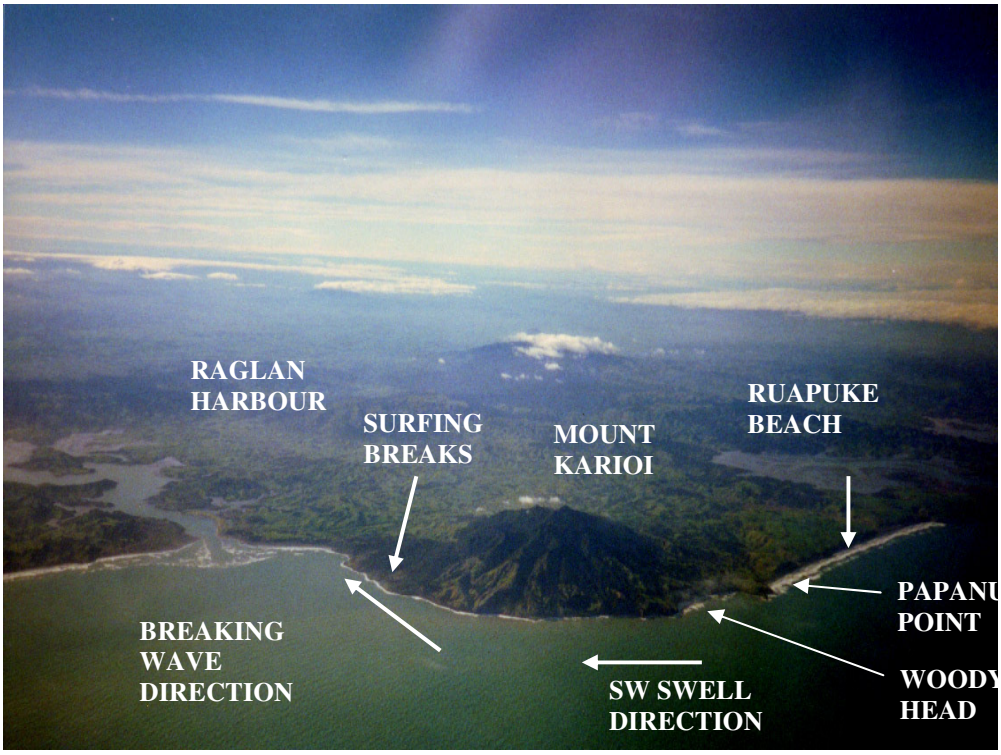


Figure 4: Locality diagram of Raglan, New Zealand (Source: HUTT, 1997)

Figure 5: Waves breaking along the rock armoured shoreline at Raglan (Source: SCOTT, 2004).

The latest field experiments at Raglan have been conducted to measure the current speeds and directions, as well as the sediment transport during moderate and large swell events at Raglan. Observations of surfers attempting to paddle through the breaking-wave zone confirm the strength of the wave-driven currents, with surfers being swept rapidly down the headland for hundreds of meters. These currents would be expected to transport significant quantities of sand from the headland, resulting in an eroded bed with scouring of the seabed adjacent to the rock/sand boundary. Bottom mounted frames were deployed from a boat along a transect and anchored to the seabed with weights, for stability and to maintain their position in the surf-zone. The frames were fitted with S4 current meters and programmed to record burst data at a set interval per hour. The retrieved data were analysed in the Matlab

programme tseries, providing burst-averaged data over the deployment period. Side-scan sonar, bathymetric surveys and numerical modelling were also utilised to determine the mechanism for maintaining bed stability at Raglan. This paper provides a summary of the study of the natural headland found at Raglan and implications related to the construction of surfing headlands and reefs.

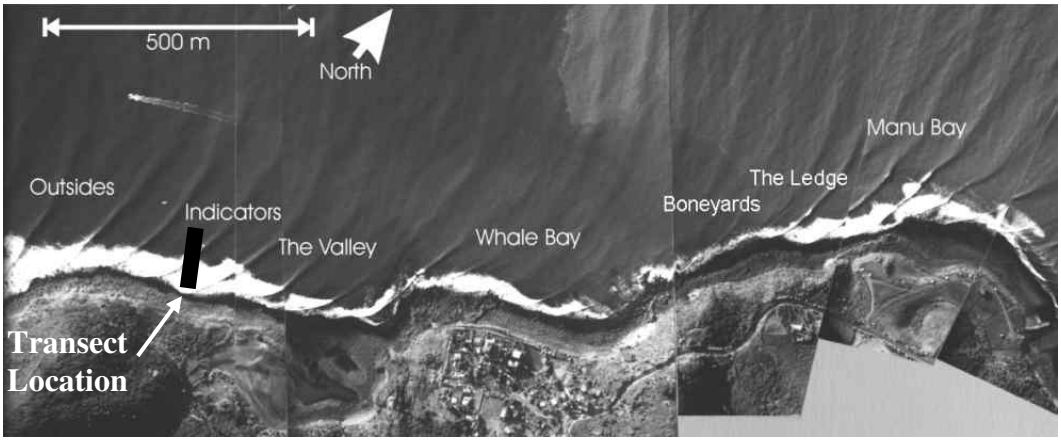
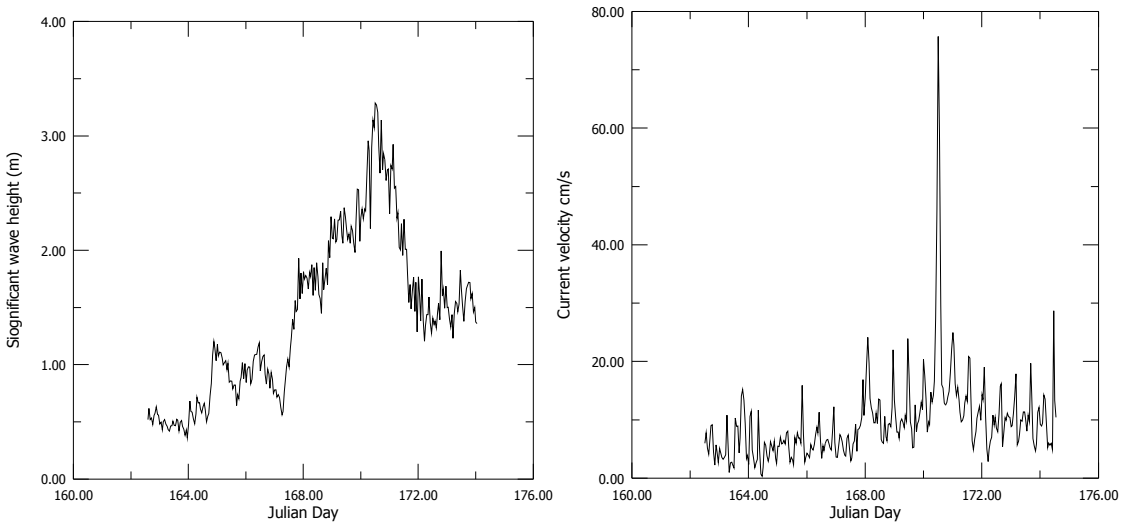


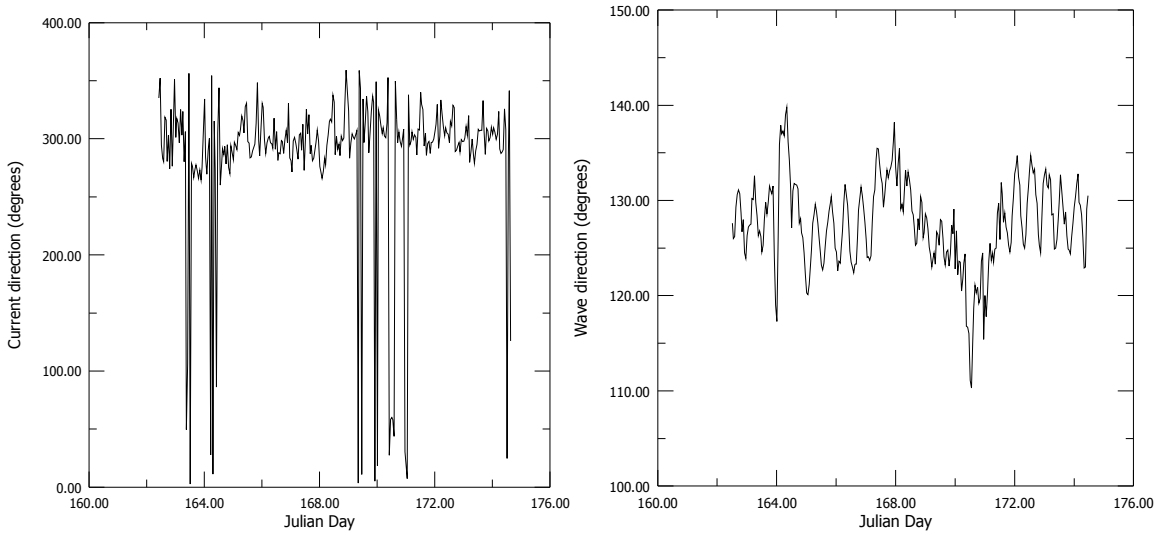
Figure 6: Aerial photo of the Raglan headland showing the fieldwork site and 7 surf main surfing breaks and transect location for instrument deployment (Source: HUTT, 1997).

RESULTS AND DISCUSSION

During large swell conditions (Figure 7a), experiments at Raglan have shown the presence of strong currents in the inshore breaking wave zone with burst-averaged velocities attaining 0.8 $m.s^{-1}$ (Figure 7b), and maximum bed orbital velocities up to 2.5 $m.s^{-1}$ (PHILLIPS *et al.,* 1999). The currents were directed down the headland in an easterly direction (50°)(Figure 7c) and increased dramatically to the maximum value, as swell wave heights peaked at over 3 m. The combination of increased swell size and a dropping tide, meant that the wave direction at the headland decreased to 110° as the waves swept straighter down the headland to the east (Figure 7d).



A) **B)**



C) **D)**

Figure 7: All data measured at Site 1 from 12-6-1998 to 24-6-1998 (a) Significant wave height; (b) Current velocity; (c) Current direction (d) Wave direction (mean).

PHILLIPS *et al.* (1999) found that further offshore the currents flow in a re-circulating gyre back up the headland to the west. This mechanism has been confirmed by visual observations of surfers in the line-up (PHILLIPS *et al.,* 2003a), with an easier paddle back to the take-off point in the re-circulating current (Figure 8). The measured currents averaged over the deployment period along the transect (3 sites) were mostly in a westerly direction (up the headland). Mean currents were only easterly (down the headland) during large swell, particularly at the most shoreward site, whilst further offshore a westerly returning current was found (PHILLIPS *et al.,* 1999). The more shoreward regions over the rocky seabed are presumably disrupted by easterly wave driven currents more often. Indeed, the location of the interface between the sand and rocky bed may relate to the location where long-term mean currents change from being directed up (west) to directed down (east) the headland. The sandy bed is winnowed away, being unable to exist over the long term where strong wave-driven flows down the headland cause strong net transport.

Seabed characteristics identified using side-scan sonar surveys with accurate bathymetric surveys showed the rock/sand boundary was fairly stable in position, fluctuating about a quasi-permanent equilibrium position (PHILLIPS *et al.,* 2001; PHILLIPS *et al.,* 2003b)(Figure 9). The sediment pathways were strongly represented in the sonagraphs with the presence of large megaripples (2.5 m wavelength and 0.5 m amplitude) adjacent to the rock/reef boundary where the strong currents sweep along the headland in an easterly direction (orientation of migration) (Figure 10), and further offshore a returning sediment pathway was evident. Shore-normal reefs were visible that appear to act as topographic boundary where currents change direction and sediment is deposited. The relative stability of the seabed also provides consistent quality surfing waves that alter very little throughout the year in breaking style and location at the headland.

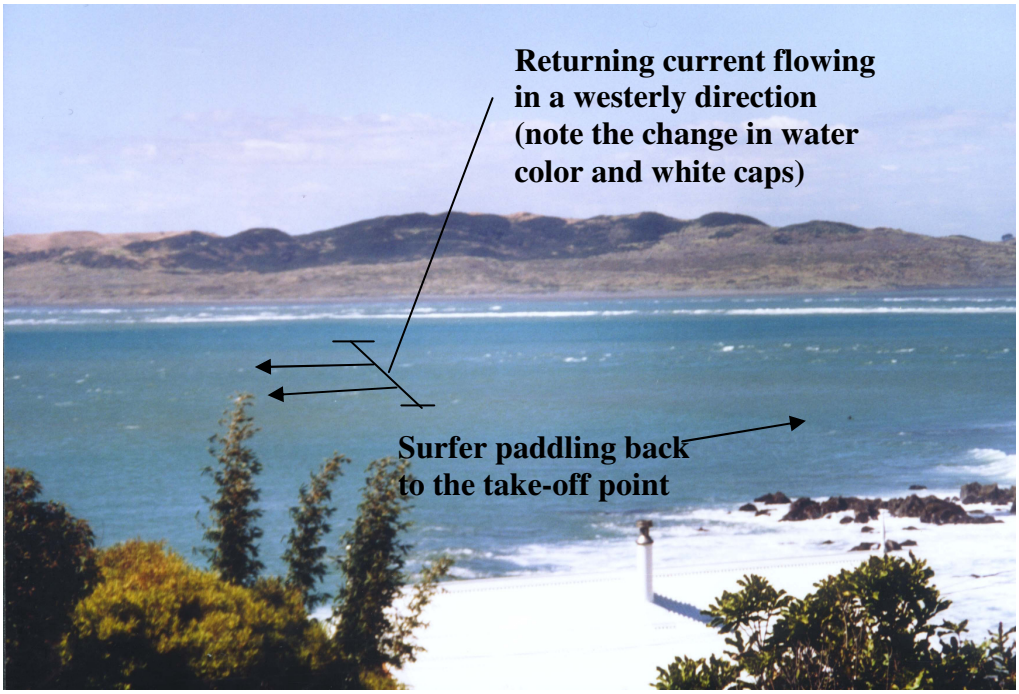


Figure 8: Current flowing in a westerly direction at Whale Bay back along the headland in a distinct band characterised by a change in water-color. A surfer is seen paddling back to the take-off point wide of the inshore wave-driven easterly flowing current (Source: PHILLIPS, 17-6-98).

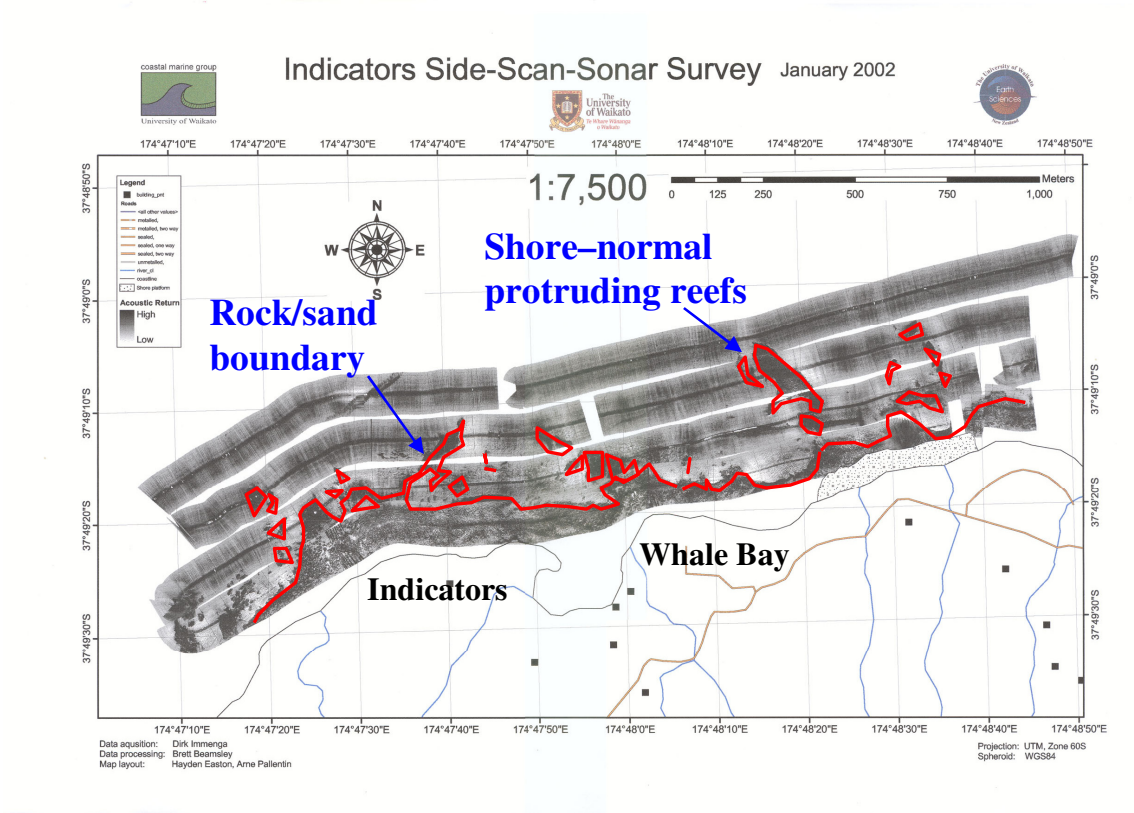


Figure 9: Side scan sonagraph on the 24-01-02 of the Raglan headland illustrating the reef location (outlined) and shore-normal protruding reefs.

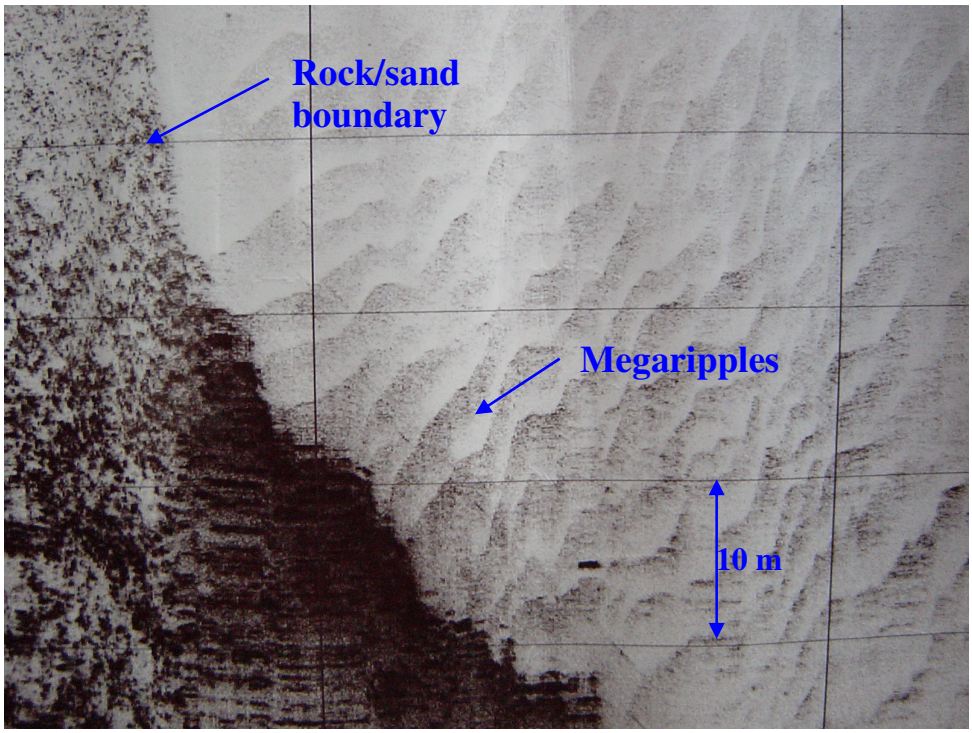


Figure 10: Side scan image (11-7-00) of large sinusoidal megaripples at Whale Bay.

The waves breaking at the headland generate strong currents that transport significant quantities of sand along the headland in an easterly direction, as part of the west coast littoral drift system (PHILLIPS *et al.,* 1999). This system transports sand on a consistent basis around the headland, due to its non-protruding nature and the consistent swell conditions from the southwest, i.e. not in a 'slug' of sand as found on other large-scale headlands. Further offshore the re-circulating sediment pathway returns sand to the headland. The re-circulating current results from topographic steering due to variation in the shoreline alignment, and radiation stress resulting in the build-up of a pressure gradient along the headland (PHILLIPS, 2004; PHILLIPS *et al.,* 2005). This is reflected in numerical modeling studies (PHILLIPS *et al.,* 2005). The model 3DD, which is part of the 3DD Suite of Numerical Models (© BLACK, 2001b), was used to simulate current flows around the Raglan headland.

The recirculating eddies can be divided into 4 cells and compare very closely to the compartmentalisation of the headland characterised by the main surf breaks (Figure 12). The combination of these mechanisms maintains the stability of the seabed where sandy and hard substrate interact, and demonstrates a complex and dynamic current and sediment system that allows sediment equilibrium conditions to evolve.

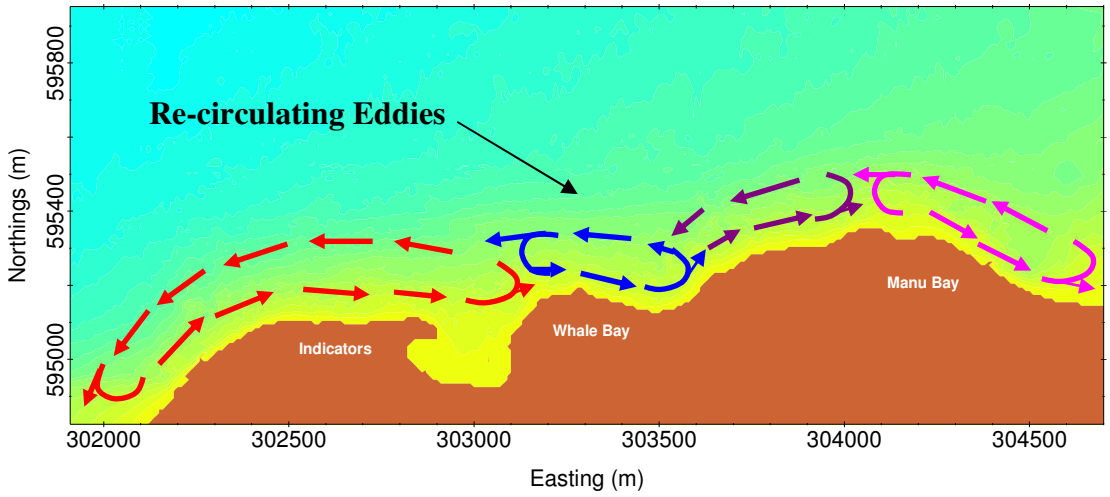


Figure 11: Idealised diagram of Raglan showing the 4 cells operating at the headland, and the low tide eddy flowing back onto the Ledge.

IMPLICATIONS FOR THE CONSTRUCTION OF SURFING HEADLANDS AND REEFS

The detailed examination of the Raglan headland has shown that analogies can be made between the mechanisms that maintain seabed stability at a natural headland to the construction of a surfing headland or reef. The seabed at Raglan is maintained by a combination of sand transport around the headland (i.e. northerly flowing littoral system), and a re-circulating sand pathway. Strong wave driven currents transport significant quantities of sand along the headland, exposing the rock boulders and reef shoreline. However, the rock/sand boundary maintains a fairly stable position, fluctuating about a quasi-permanent equilibrium position. This demonstrates that a strong control on sediment transport exists where the sandy and hard substrate interact, which allows sediment equilibrium conditions to evolve.

Similar complex currents and sediment dynamics have been found to exist at surfing headlands and reefs (e.g. SYMONDS and BLACK, 2001; MOCKE *et al*., 2003), but often scour and erosion occurs along the toe of the structure (e.g. BAQUERIZO and LOSADA, 1998). Greater stability may be provided if the dynamic sediment transport system like that at Raglan can be replicated in the construction of surfing headlands and reefs. The combination of rocks and sand at Raglan could be duplicated in geotextile and sand for an surfing reef. The field measurements at Raglan (particularly seabed characteristics, e.g. bed level variation) and sediment transport, show that there is potential for significant fluctuations in seabed level at the toe of the reef (approximately +/- 1.5 m at Raglan)(PHILLIPS *et al.,* 2003b), even if the mean bed level is not changing significantly. At Raglan this simply manifests as a mobile edge, where underlying rocks are either exposed or covered as the conditions change. In a surfing reef it would be likely to manifest as toe scour, which might undermine the reef. Consequently, scour protection may be needed (such as a scour apron) to prevent the reef from being undermined.

The upstream supply of sand to the littoral system must be maintained, but it is evident that re-circulating transport is also important in maintaining seabed stability. Re-circulation of

currents and sediment around a surfing reef has also been predicted by numerical models (BLACK, 2003). The rate of sediment transport is governed by a combination of wave heights and water depths, and the resulting wave orbital and current velocities that can vary significantly on and around the reef (e.g. LOU and RIDD, 1997; KOMAR, 1998). There is potential for local scour and deposition to occur (BLACK, 2003), so the reef design should consider the possibility of using the recirculation currents beneficially.

Conversely, interference with the local re-circulating sand transport pathways must also be carefully considered. This would include jetties and breakwaters constructed downstream of the headland, which could interfere with the current patterns and return flow of sediment to the headland (PHILLIPS *et al.,* 2004). The prominent scale of the Raglan headland and its non-protruding nature permit the consistent sediment transport around the headland, not just in 'slugs' of sand as found at many large headlands (SHORT, 1999). The headland does not act as a large groyne blocking the sediment transport pathway, which is a significant factor that must be considered in the construction of coastal protection structures so that downstream erosion does not occur. The orientation of the headland creates breaking waves and allows sediment to flow in wave driven currents, whilst radiation stress and topographic steering of currents leads to re-circulation of sediment at the headland. The large scale of the entire Raglan headland could make direct comparison to significantly smaller surfing reef structures somewhat difficult. However, each wave-driven re-circulating cell identified at the Raglan headland, can in itself be considered to be functioning in a similar nature to how a constructed reef or smaller headland may function.

CONCLUSIONS

The field investigations and numerical modelling at Raglan have shown that both a supply of sediment around the headland due to wave-driven currents as part of the west coast littoral supply, and importantly a re-circulating transport pathway, sustain the sandy seabed adjacent to the headland's rock and reef shoreline**.** Scale and orientation of the headland are important factors in this dynamic system. The transport mechanism provides bed stability and strong control where the sandy and hard substrate interact, allowing sediment equilibrium conditions to evolve. However, the measurements at Raglan show that despite the mean bed level not changing significantly, there is potential for very large fluctuations of the seabed at the toe of the reef. These sand movements provide insight into likely bed level changes at a surfing reef, which would manifest as toe scour that could potentially undermine the reef. Mitigation of this factor would require the construction of a scour apron as part of the reef structure, as any collapse of the reef may reduce the surfing wave quality. The beneficial use of re-circulating current and sediment transport pathways should be considered in the design of surfing reefs and headlands, as this investigation has shown that although the upstream supply of sand to the littoral system must be maintained, re-circulating transport is important in maintaining bed stability at the headland.

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