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Shoreline effects of vessel wakes, Marlborough Sounds, New Zealand

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ABSTRACT

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The science of vessel wake generation and propagation is well advanced, but the environmental effects of wakes are less well understood. The introduction of large vehicle and passenger-carrying fast ferries (HSC) in the 1990s resulted in numerous reports of environmental damage worldwide. In the Marlborough Sounds, New Zealand, regulatory agencies have struggled with the management of vessel wakes from both HSC and conventional vessels operating between the North Island and South Island. Gravel beaches along the route responded very quickly to the higher energy levels associated with the introduction of HSC, and there has been little change since that time, except in situations associated with geological instability. There has been no recovery of beaches towards pre high-energy conditions following HSC speed restrictions in 2000. Evidence of wake influences on very low-energy beaches in the far-field, over 7 km from the vessel path shows that long wave lengths associated with HSC can result in geomorphically significant waves and sediment transport. These findings are in accordance with other recently published results resported by other authors in the Baltic Sea.

ADDITIONAL INDEX WORDS: *fast ferries, wake wash, gravel beaches, New Zealand*

INTRODUCTION

Vessel wake waves add energy to coastal systems wherever they occur. In semi-enclosed seas and other sheltered waterways, the effects of vessel wakes can be significant. Even small boats can have significant shoreline effects in some environments (BAUER *et al.* 2002), where natural wave energy is very low. Many low-energy shorelines, particularly on approaches to ports have been influenced by vessel wakes of large displacement ships for many years, and the effects have either been negligible or accepted as reasonable. However, following the introduction of high-speed passenger ferries in the 1980s, and large and fast high-speed craft (HSC) capable of carrying passengers and vehicles, with service speeds approaching 50 knots, new and significant adverse effects were observed in numerous locations such as San Francisco Bay, Puget Sound, Washington, British Columbia, Canada, Ireland, Sweden, Denmark, England and New Zealand (PARNELL and KOFOED-HANSEN (2001). HSC were introduced with little prior understanding of the significant effects that might result, and management agencies around the world were largely unprepared for a situation that resulted in a significant increase in wave energy in the coastal environment, essentially instantaneously. Calls for management responses from affected communities were swift, and were dealt with a different ways. Denmark, for example, was the first to implement criterion-based controls (DANISH MARITIME AUTHORITY, 1997), a method that has since been applied elsewhere including the Marlborough Sounds. In almost every case, however, implementation of management regimes was hindered by the lack of baseline data derived from beach surveys and ecological studies from the period prior to the introduction of HSC. Although scientific studies quickly commenced, baselines were never able to be established, and comparisons had to rely on anecdotal or other inadequate evidence.

Different wake characteristics from vessels travelling at different speeds in confined waters are predicted by the depth based Froude number $F_{nh} = V_s / (gh)^{0.5}$, where V_s is vessel speed through the water, g is the gravity constant and h is the water depth (Figure 1). In the sub-critical range where F_{nh}<0.6-0.7, the wave system consists of divergent and transverse waves generated within a wedge +/- 19.5º from the sailing line, with the wave period being dependent on vessel speed, $T(s) = 0.27V_s$ (V_s in knots). As the vessel speed increases or water depth decreases, the waves become less dispersive, the phase velocity and wave height increases, and the angle of the wedge containing the wave increases. At the critical F_{nh}= 1 (or slightly less in practice), energy is continually added to a wave group that moves at the same speed as the vessel, at a propagation angle approaching 90º to the sailing line, and increasing its crest length away from the vessel at the same velocity. These waves can exhibit soliton-like characteristics (LI and SCLAVOUNOS 2002). Work by PETERSEN *et al*. (2003) and SOOMERE (2005, 2006), has demonstrated the significant effects of 'solitonic' waves, particularly when more than one superimpose, with localised surface elevations up to four times the amplitude of the intersecting waves. As F_{nh} increases above 1, waves can no longer keep up with the speed of the vessel, and trail behind, the longest and fastest waves being on the outside of the group and travelling at a higher angle with respect to the sailing line. Specific wave parameters will be determined by the vessel characteristics, and a myriad of other factors (MARITIME NAVIGATION COMMISSION, 2003).

Wave height is generally highest at F_{nh}~1 (KOFOED-HANSEN *et al.*, 1999). At critical and super-critical speeds the leading waves are typically much longer than waves from vessels travelling at sub-critical speeds and waves further back in the wave group.

Figure 1. A conventional ship with $F_{nh}<1$ (left) and a HSC with $F_{nh}>1$ (right) in Tory Channel (Photograph: Marlborough District Council; photographer Graeme Matthews)

Wave energy decays exponentially away from the ship's track (KOFOED-HANSEN *et al.*, 1999). Shoaling occurs as the waves move into shallow water. Close to shore, they become non-linear. Waves of long period associated with vessels travelling at critical and supercritical speeds can result in very large breakers, typical of ocean swell, and clearly differentiated from low and short period waves typical of confined waters.

Wake measurement programmes to support management (CROAD and PARNELL, 2002), and analyses based on fluid mechanics to advance the science of wake prediction, generation, propagation, shoaling and breaking now abound (MARITIME NAVIGATION COMMISSION, 2003). Many of the common practices of wave analysis, however, are difficult to apply as wake waves vary in their basic parameters over the course of a single wake event. A common feature of wave measurement programmes is the significant variability in the data records for the same vessel at different times at the same location, and at different locations (PARNELL and KOFOED-HANSEN, 2001). While there is much about vessel generated waves that is understood and predictable, it is clear that there are many other factors, both environmental (tidal currents, wind speed etc.) and operational (loading, trim etc.) that affect actual wave characteristics.

Increased wave energy caused by vessel wakes can result in beach and shoreline adjustment, including erosion, deposition and reorientation (all of which have been observed for HSC wakes). If waves approach the shore at an angle, swash motions may cause increased alongshore transport, although the transitory nature of waves mean that longshore currents caused by radiation stress gradients are not able to develop. Larger waves may reach further up the beach, possibly overtopping beach ridges. Hard shorelines may be subject to increased wave forces, and increased weathering caused by wave splash further up the slope.

This paper examines the shoreline effects of vessel wakes on the primarily gravel-beach shorelines of the Marlborough Sounds, New Zealand. Beach changes are examined in relation to changing vessel traffic, and are compared to unaffected beaches. Wake effects on shorelines in the far-field are also investigated.

WAKES IN THE MARLBOROUGH SOUNDS

The Marlborough Sounds are heavily faulted, drowned river valleys. In the study area, rocky shorelines, pocket beaches and bayhead beaches, all occur. Significant sections of the shoreline consist of 'linear deposits' forming where soft bedrock is cut back to form erosion ramps that have been infilled with weathered sediments, particularly gravels. Surficial sediments comprise sands and gravels. Most commonly, linear shorelines and pocket beaches are dominated by gravels, with bayhead beaches being mixed sand and gravel covering a range of about -7 to 2 phi, with some fine sands and muds found in deeply indented bays. Landslides form the most important source of new sediment. Most beaches are steep to below LAT, dropping steeply into the deep channel. Tides are semi-diurnal with a mean spring tidal range of about 1.5 m and a mean neap range of 0.5 m.

The Tory Channel (TC) and Queen Charlotte Sound (QSC) (Figure 2), are an important part of the National Transportation Route (NTR) for vessels travelling between Wellington (North Island) and Picton (South Island), New Zealand, and the route has been used for at least all of the 20th Century. A modern and frequent inter-island service commenced in 1962 (KIRK and NEWTON, 1978; KIRK and SINGLE, 2000). New generation HSC were introduced in the summer of 1994/95, operating alongside conventional ships. Since first introduction, 5 different HSC have operated at various times, normally only during the summer. In December 2000, a bylaw was introduced that restricted HSC speed to 18 knots while in the Marlborough Sounds. More recently, a change to the Regional Plan has been proposed that would restrict the speed of all vessels to 15 knots unless a vessel can satisfy the provisions of a 'wash rule' (CROAD and PARNELL, 2002) similar to that used in Denmark. An interim decision of the Environment Court (W38/2006) indicates that the proposal is likely to proceed.

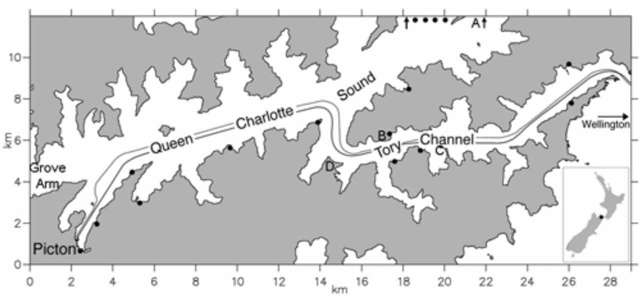

Figure 2. The Tory Channel and Queen Charlotte Sound. Profile locations are marked indicated (●), with profiles referenced in Figure 4 labelled A (Long Island), B (Ngaionui Point), C (Moioio Island) and D (Slip Beach).

METHODS

A beach monitoring programme with surveys in April and November (timed to coincide with the beginning and end of the HSC summer season) commenced in April 1996. A total of 21 profiles are surveyed, 5 in the outer QCS (off the NTR), 2 within Picton harbour (where vessels are required to travel at less than 8 knots), and 14 along the NTR with vessels travelling at normal service speed or restricted service speed in the case of HSC since December 2000. As explained above, there are no data prior to the introduction of the HSC in 1994/5. In February 2000, observations of the effect of HSC wakes on landslides on the NTR were made (PARNELL, 2000; BELL, 2000). In this paper, four profiles are highlighted (Figure 2). Long Island is in the northern Queen Charlotte Sound, and is subject to slightly higher natural wave energy but limited vessel traffic. The three sites along the NTR comprise Ngaionui Point (Figure 3) (a linear beach on the northern side of Tory Channel, very close to the sailing line), Moioio Island (a site adjacent to a significant landslide), and Slip Beach (a site that shows considerable variability, and adjacent to a position on the route where vessels are turning).

Far-field effects of vessel wakes in the Grove Arm of QCS (Figure 2) were examined by measuring waves entering the arm using a near-surface mounted pressure transducer, and with pressure transducers, capacitance gauges and InterOcean S4 current meters at a number of sites on the shoreline of Grove Arm. Modelling of wave propagation was undertaken using Mike 21 NSW software.

SHORELINE EFFECTS

Beach Profile Change

KIRK and NEWTON (1978) showed that beach changes occurred when regular inter-island services commenced in the 1960s, and although beach monitoring programmes were not in place prior to the introduction of HSC in 1994/5, it is widely believed that the beaches adjusted rapidly to the revised energy conditions (SINGLE and KIRK, 1998, KIRK and SINGLE, 2000, CROAD and PARNELL, 2002). Although some anecdotal evidence of beach erosion during this period exists, it is generally clear that most beaches adjacent to the sailing line accreted, particularly with the development and growth of supratidal gravel berms (Figure 3). In some places, particularly adjacent to landslides, the process of upper beach accretion has continued.

Profile lines (Figure 4), and associated volume data (Figure 5) expressed as a percentage of the volume of sediment under the profile (measured in m^3/m of beach) as at April 1997 are provided.

Sites that are not affected by regular large vessel traffic, represented by Long Island, have shown very little change. When all 5 profiles in this category are considered together over the period since surveys began, beach volumes range between 94% and 103% of the commencing volume.

Figure 3. Supratidal gravel berm at Ngaionui Point, probably placed or enhanced by the introduction of HSC in 1994/5

The linear shorelines and pocket beaches along Tory Channel and Queen Charlotte Sound (represented by Ngaionui Point), are a very important shoreline type. For the 6 cases for which other factors causing beach change can not be identified, there has been very limited change over the survey period with beach volumes ranging between 94% and 112% of original volume. No significant changes in trends were observed following the slowing of the HSC in December 2000.

Five of the profiles along the NTR have had sediment additions from landslides immediately adjacent to, or within the same embayment as the profile line. An example of this type is the Moioio Island profile, which is a convex beach immediately adjacent to a significant landslide. An increase in the rate of sediment accumulation on this profile occurred at about the time HSC were slowed in December 2000. There is little doubt that vessel wakes increased the rate of sediment supply from the landslide on Moioio Island, and the landslide was observed to be particularly active when HSC were operating (PARNELL, 2000; BELL 2000). The continued accretion of this profile is likely to be the result of continued landslide activity.

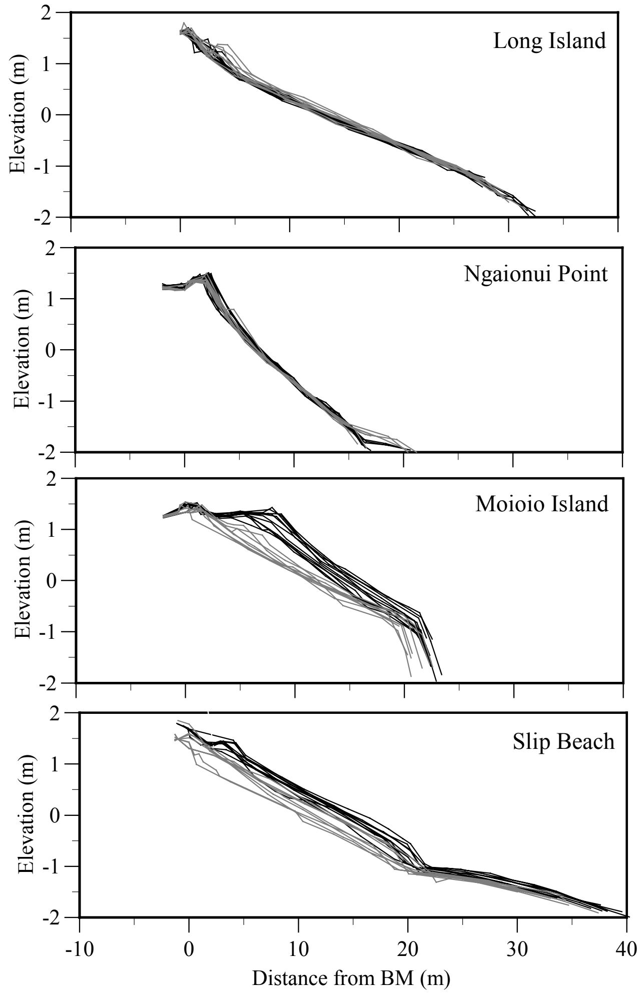

Figure 4. Beach profiles from 4 of the 21 study sites. Lines plotted in grey are from prior to December 2000, after which time HSC were slowed to 18 knots.

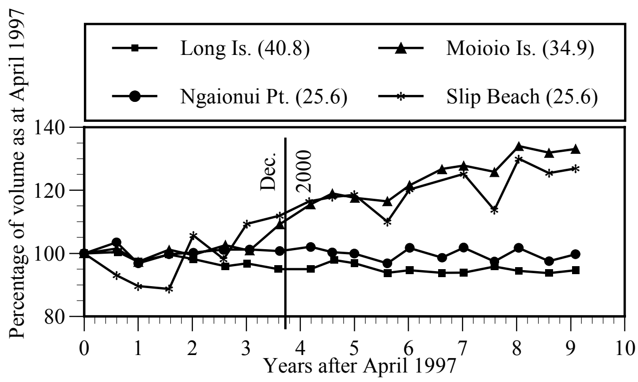

Figure 5. Beach volumes for selected profiles, expressed as a percentage of the volume at April 1997. Numbers in brackets are the initial volumes (m^3/m).

A number of the 21 profiles are considered to be "special cases". Two of these sites are within Picton Harbour where vessels are travelling slowly. One of these profiles is demonstrating very significant beach erosion, the cause of which remains unknown. A site at Picton Point, is demonstrating erosion as a result of the deep water channel moving closer to the beach. The influence of vessel wakes on this process is also unknown. A site in an embayment off the NTR was stripped of sediment to bedrock during the period of HSC operation. With no current source of sediment, low wave energy and a steep slope into deep water, this is unlikely to be reversed.

Slip Beach is an interesting special case. It is adjacent to an old landslide, that has not been contributing large quantities of sediment to the beach in recent times. Slip Beach is on the outside turning curve of vessels travelling in both directions. During the period of HSC operation, the profile exhibited significant variability, in sediment volume, profile shape and surficial sediment composition, with significant volumes of sand moving on and off the beach. Wave recordings from this site showed generally high wave energy, with considerable variability, but with wake events continuing for significantly longer periods than at all other sites, likely to be the result of vessels turning. A trend of accretion has continued since HSC were slowed in December 2000, but with considerable variability.

Far-field effects

While HSC were operating at service speed, reports were received of significant waves and shoreline effects from over 7 km up the Grove Arm (Figures 2 and 6) of QCS. Grove Arm is the western extension of QCS, beyond the approach to Picton Harbour. Reports were of a long period surge, significant wave shoaling, erosion and beach lowering (evidenced from before and after photographs from Lissaman's Bay (Figure 6)), and ecological effects associated with HSC travelling towards Picton. These reports were largely ignored, with most attention focused on the significant effects along the NTR. Observations of this phenomenon were commenced about the time that HSC operation ceased in December 2000, but were then abandoned due to the inability to collect further field data. However, due to the fact that such far-field effects had not been previously reported and it was apparent that even conventional vessel wakes could be seen, a series of experiments were undertaken in February 2002 to measure far-field effects.

Wake measurement at a number of sites (an example of which is shown in Figure 7) clearly showed that wakes travelled the length of Grove Arm, although they lost considerable height. The duration of the wake events was surprisingly long, suggesting that they are, at least in part, the result of the transverse wakes breaking free from the track of the vessel as it turns into Picton. Because HSC were not operating at the time of measurement, the MIKE 21 NSW model was used in an attempt to determine HSC effects (McDonald, 2003). The wave parameters measured at the entrance to Grove Arm (Figure 6) were used for the offshore boundary conditions, and the model was verified for 9 wake events where predicted wave heights were compared to measured values at two sites in Grove Arm (McDonald, 2003). At a site less than 2 km into Grove Arm, the model under-predicted significant wave height, possibly the result of wave diffraction that was not represented in the model. At Lissaman's Bay there was much better agreement, although wave heights were small (<0.08 m). A simulation of long period (20 second) HSC waves, typical of the leading waves in the group, was undertaken, using data collected by Parnell (2000). These waves in deep water are not normally significantly greater in height than conventional ferry waves. The most significant effect of increased period was increased refraction around headlands, due to the long period waves being affected more and earlier due to their longer length, meaning that wakes could reach further into some sheltered bays. At the shoreline, however, the much higher wave period leads to increased shoaling and a larger breaking wave. Although not able to be modelled with Mike 21 NSW, shoaling was clearly observed and photographed at sites in the upper reaches of the Grove Arm, and can account for reported and photographed shoreline change.

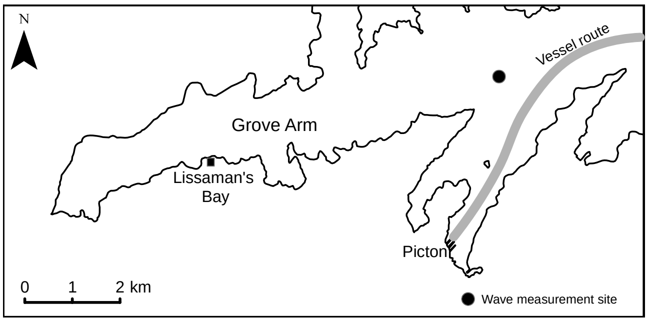

Figure 6. Grove Arm, showing the measurement sites for data illustrated in Figure 7.

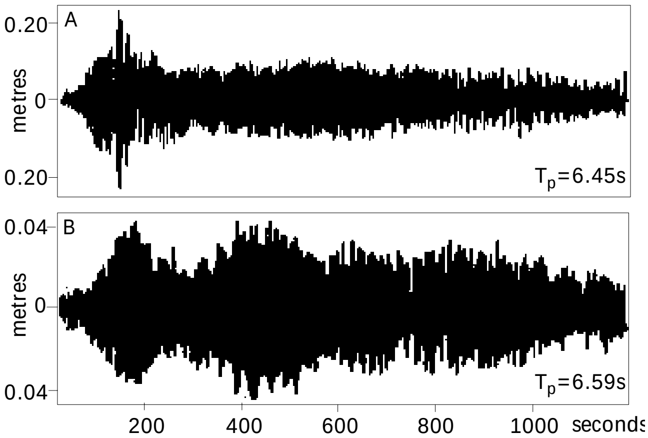

Figure 7. (A) Conventional vessel wake (Aratere, travelling towards Picton), measured in deep water near the sailing line (Figure 6); (B) the same wake measured at site Lissaman's Bay (Figure 6), commencing 19m21s after the start of the wake at the site near the sailing line.

DISCUSSION

The beaches of the Marlborough Sounds are naturally very stable, illustrated by beach profiles that are not impacted by vessel wakes. The paucity of baseline data from shorelines affected by HSC wakes is unfortunate, and this study is no different. However, there is reasonable evidence, and agreement amongst those working in the Marlborough Sounds, that HSC caused rapid change to beaches after they were first introduced. The nature of this change was primarily accretion of gravel on the upper beach. This study demonstrates, however, that there has not been a return to pre-HSC beach morphology following their slowing in late 2000. Current energy levels are not sufficient to move gravel sized sediment in supra-tidal berms. These features are now essentially relict (and quite stable), and will take a long time, or increased energy, to become active again. Beaches on the NTR show somewhat more variability than others even with conventional ship wakes only. Beaches that receive sediment from landslides are continuing to accrete, and there is some evidence that vessel wakes, particularly HSC can hasten landslide processes.

Far-field effects of vessel wakes have, until recently, been substantially overlooked. Anecdotal evidence from the Grove Arm of QCS suggested that HSC were having a significant erosive effect on beaches at least 7 km from the sailing line. Wake events from conventional ships and HSC travelling at 18 knots were recorded and longer period HSC wakes were modelled to show they reached the upper reaches of the Grove Arm. When shoaling of long waves occurs, substantial waves result that clearly can have the reported impacts. Interestingly, waves in the Grove Arm have extended duration, and at least for vessels travelling slowly, are likely to be transverse waves that have broken free from the vessel track as the vessel turns. The conclusions on far-field effects support findings recently published by SOOMERE (2005), who described the leading long period waves of HSC wakes as being "practically non-dispersive compact entities carrying a massive amount of energy", with shoaling causing "violent plunging breakers far from the ship lane and a long time after the ship has passed" (SOOMERE, 2005, p319).

CONCLUSIONS

Vessel wakes can cause significant change to beach morphology, particularly in confined coastal waters with low natural wave energy. Even conventional vessel wakes result in more shoreline variability than that which occurs under natural low energy conditions. On the gravel beaches of the Marlborough Sounds, the introduction of HSC in the 1990s generally caused initial rapid and significant accretion, which continued in many places for the duration of HSC operation. Sediment supply, likely to be affected by wakes in the case of landslides, is a particularly significant factor in the magnitude of beach change caused by vessel wakes. To the present time there has been no return to likely pre-HSC beach morphology following HSC being slowed to 18 knots in 2000. Under current energy conditions, beaches modified by HSC wakes are likely to remain essentially relict.

This study has demonstrated that vessel wakes, particularly those generated by HSC can have significant shoreline effects in the far-field, 7-10 km from the sailing line, a conclusion supported by considerable anecdotal evidence. This conclusion supports results obtained from the Baltic Sea by SOOMERE (2005).

The generation and propagation of vessel generated wakes is now well understood, but the environmental effects are frequently supported by anecdotal information only. This study shows that HSC do not generally cause erosion on the primarily gravel beaches of the Marlborough Sounds adjacent to the vessel route, but can have this effect in the far-field. However, slowing HSC does not result in the return to shoreline conditions that existed prior to their introduction.

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