Wave Deformation in the Vicinity of a Long Ocean Outfall at Wanganui, New Zealand

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Abstract
This paper investigates wave deformation at South Beach, Wanganui and the relationship with an 1800 m long marine outfall pipeline. The study included wave comparisons between a control beach to the northwest of the Wanganui Rivermouth and South Beach, examination of aerial photography and analysis of a high-resolution bathymetric survey. The aerial photographs indicated very deep water on the southeastern side of the pipeline and wave focusing on the northwestern side. The bathymetric survey confirmed the presence of a large seabed depression. This depression, caused by current-induced scour around the pipe, appears to spread wave energy leading to reduced wave height in its vicinity. In turn, waves converge on either side of the depression, concentrating energy and increasing in height. Due to the depression's offset angle to the predominantly westerly approaching swell, more intense wave focusing occurs on the northwestern side. Wave comparisons show period to be the primary variable influencing the extent of wave focusing. Conceptual modelling supports this, as longer period waves interact to a greater extent with seabed features. This conceptual model was subsequently verified by numerical wave modelling, which confirmed wave period as the controlling variable with wave direction also playing an important role. Results of this study were consistent with findings for natural canyons at La Jolla, California, and pipeline-induced depressions at Ashkelon, Israel.

1. Introduction

Whenever a large 'clean' swell reaches the Wanganui coast, surfers flock to South Beach (Figure. 1). The waves are bigger and of better shape for surfing than those at other beaches, approaching the South Beach as large 'A-frame' peaks (Figure. 2). The general thought amongst local surfers is that this difference is caused by the ocean outfall pipeline. This outfall was constructed in the early 1980's to discharge Wanganui's wastewater. However, it was unlikely the pipe was interacting directly with the waves. But that the pipe may influence the underwater topography, which in turn could deform the incoming waves.

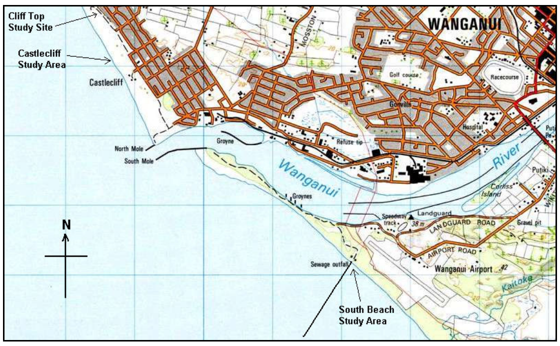

Figure 1: The study site at Wanganui, New Zealand.

The aim of this investigation is therefore *to investigate the possible influence of the South Beach outfall on both the seabed and wave deformation.*

The following objectives were used to achieve the study aim:

To quantify wave deformation in the vicinity of the South Beach outfall by comparing wave parameter values at a 'control' site at Castlecliff Beach (Figure. 1) with the South Beach outfall site. Site observation suggested a relationship between wave period and the wave height difference at the two beaches. And to use aerial photographs to identify where waves break, as well as showing wave-crest deformation patterns. This gives an indication of underwater topography.

To determine the bathymetry of the study site by carrying out a detailed survey of the area. And to empirically and numerically model wave propagation in the vicinity of the pipe using wave and seabed information collected during this study. This exercise attempted to replicate site observation and qualitatively identify deformation characteristics.

This paper is structured as follows; The environmental conditions and background of the study area are described in section 2. A summary of the research design is outlined in the methods section (3). Results are presented in section 4 and discussed in section 5. Finally, conclusions are made about the cause and nature of wave deformation in the study area (section 6).

Figure 2: Waves 'peaking' and breaking to the northwest of the pipeline.

2. Background

2.1 Study Site

Wanganui is a city of 40,000 people and is situated on the southwest coast of New Zealand's North Island. Jetties were constructed at the mouth of the river between 1884 and 1940 and have been responsible for substantial accretion on the northwestern side and erosion on the southeastern side of the entrance (Burgess, 1971). This erosion and accretion appear to have reached a dynamic equilibrium in the past few decades.

The Wanganui coastline has a northwest - southeast orientation. It is characterized by an ebb tide delta at the Wanganui Rivermouth, which is offset toward the southeast. Castlecliff Beach is multi-barred and generally dissipative (Shand, 1999). South Beach is influenced more by the river delta and has less pronounced sandbars. The mean wave height is 1.3 m and the 5% excedence value is 2.5 m. Long period swell waves occur ~33% of the time with period ranging up to about 18 seconds. Most waves approach from the westerly quarter resulting in a predominant NW to SE longshore drift.

2.2 Outfall Background

The outfall was constructed in 1982 by Downer Construction. The pipe originates from a treatment station on the western side of the river. It then passes under the river, through a surge chamber and extends 1800 m out to sea. The pipe crosses the beach approximately 2500 m southeast of the river. The steel pipeline, offset 17° southeast of shore-normal, is 150 mm thick, and has a diameter of 1800 mm. It was constructed in sections on land, moved out to sea along a temporary pier and then lowered into cradles located at the then bed-level. The pipe supports vary with distance out to sea.

3. Methodology

3.1 Wave Measurement Comparisons

Most wave measurements reported in this section were based on observational methods used by the Beach Protection Authority of Queensland and documented in Patterson and Blair (1983). This paper describes methods for determining wave height, period, breaker depths and surf width.

Measurements at South Beach were taken offshore from the surge chamber, where the pipe crosses the foreshore. The site on Castlecliff Beach used to measure wave properties is located 1500 m northwest of the river mouth.

Measured properties include wave direction, wave period (T), travel time across the surf zone and maximum wave height, $(H_{los})_{max}$. The latter was determined using a graduated staff placed approximately at still water level according to Patterson's line-of-sight method (Figure 3). This measurement could then be converted to a significant wave height at breakpoint, $(H_b)_{sig}$, using corrections for wave set-up, the earth's curvature and an empirical relationship between maximum and significant wave heights.

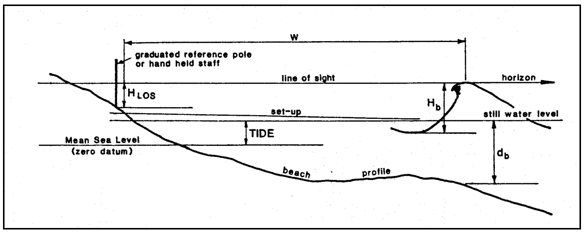

Figure 3: The line-of-sight (LOS) method of measuring breaking wave height. (Patterson and Blair, 1983)

Properties derived theoretically and/or empirically from these wave measurements include deep-water wavelength (L_d), the surf-zone width (W), breakpoint depth (d_b), wavelength at breakpoint (L_b) and the Irribarren Number (ζ).

The final calculation was the difference in corresponding wave height at Castlecliff (H_{Cas}), and South Beach, (H_{Sth}), using Equation (1).

$$HtDiff = \frac{H_{Sth} - H_{Cas}}{H_{Cas}} \qquad (1)$$

This gives a relative height difference between the control beach and the beach of interest.

3.2 Aerial photography

Vertical aerial photographs are well suited for qualitatively and quantitatively identifying wave deformation as a length scale can be applied. Vertical aerial photographs from the Wanganui District Council archive were used, together with aerial photographs taken during this study. The later photographs were taken during a very large swell event on the 5th May, 2003 when waves in excess of 6 m were recorded breaking at South Beach.

Some oblique aerial photographs were also used; these were rectified to map co-ordinates and the output image to show wave-crest lines more clearly.

3.3 Bathymetric Survey

The Wanganui Port Company carried out a detailed bathymetric survey of the study site. The sounding equipment consisted of a Hydrotrack sounder with both digital and analogue (trace) outputs. Depth accuracy is estimated at ± 2 mm. Position fixing was achieved using a Ashtech differential GPS system (accuracy ± 0.2 m) which is integrated with the depth measurements.

Once the boat's computer had recorded depths along each run, the data was tide-adjusted, reduced to chart datum and presented as a contour map. This detailed map was subsequently combined with the larger scale Royal New Zealand Navy Charts.

4. Results and Analysis

4.1 Wave Measurements

Significant wave height ranged from 1.9 to 2.9 m at Castlecliff, and 2.5 to 4.7 m at South Beach, and wave period ranged between 8.1 and 17.0 sec.

Relationships between variables were investigated using Pearson correlation analysis. For 10 observations (n=10), the correlation becomes significant at the 5% level when r is greater than 0.632. As expected, wave period is strongly related to the wave height increase between Castlecliff and South Beach with r = 0.917 (Figure. 4). The best-fit curve for this plot is exponential with r^2 = 0.932. Other variables showing significant associations were: surf zone width with wave height at both Castlecliff (r = 0.619) and South Beach (r = 0.924), and the wave height at Castlecliff with wave height at South Beach (r = 0.717).

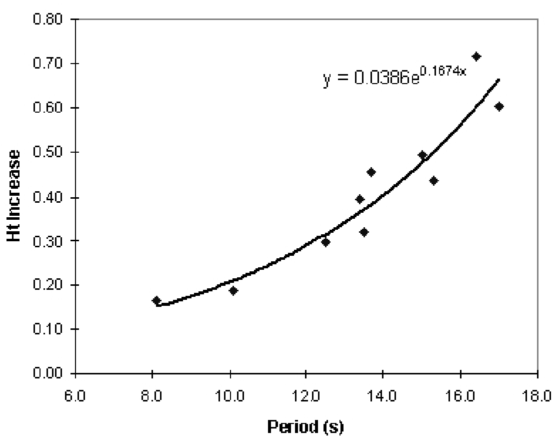

Figure 4: Best-fit relationship between wave period and wave height increase at South Beach relative to the wave height at Castlecliff.

4.2 Aerial Photographs

An example of a rectified aerial photographs illustrating wave-crest patterns in the vicinity of the South Beach outfall area is shown in Figure 5. Wave deformation and irregular wave breaking indicate uneven bottom topography.

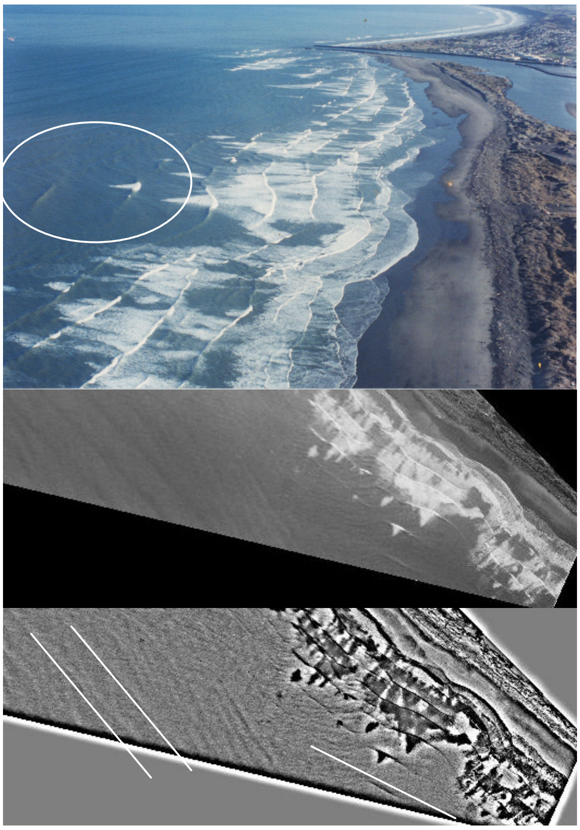

Figure 5: Oblique aerial photograph of outfall area (A) taken on 25 July 1993 then rectified and enhanced in B and C. Waves can be seen peaking and changing direction as they approach the central part of this photo (shown in ellipse). An area of deep water can be seen to the right of the pipe in B, with unbroken waves bending into it.

On the rectified images waves can be seen breaking a long way out to sea on the north-western side of the pipe, but almost nothing is breaking for ~300m on the south-eastern side of the pipe. This would suggest the existence of a seabed depression located southeast of the pipe. This agrees well with shore-based observation in which large waves peak (local height increase) and break just northwest of the pipe, but not to the southeast.

4.3 Bathymetric Survey

In the detailed bathymetric map of the site, a depression approximately 300-400 m wide is evident (Figure 6). Contours, which are usually relatively parallel to shore, move landward more than 600 m. This depression is ~4 m deep and has an average side slope of ~0.01. However, nearer the pipe, the slope increases to ~0.03. The pipe is located just northwest of the depression base. This is consistent with land-based observation and the aerial photographs.

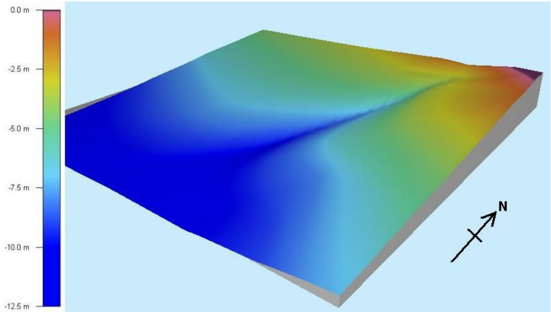

Figure 6: Contour model of the South Beach depression

5. Discussion

The most dominant relationship evident in the wave height comparison was that of period and wave height increase between Castlecliff and South Beach. This relationship was predicted to be important at the beginning of the study.

Conceptionally, this is logical as wave interaction with the seabed depends on wavelength, and this is directly related to period. Waves of greater period start to interact with the seabed further offshore i.e. in deeper water. Irregular seabed topography therefore has more effect on longer period waves than on shorter period waves, and any deformation should be more evident.

The longest period waves recorded in this study were 17 seconds. However, waves with periods up to 20 seconds have been observed at Wanganui. The observed exponential relationship noted earlier, suggests that very large increases would be expected for these very long period waves. Waves at South Beach could be approximately twice the size of those at Castlecliff during these events.

Some of the relationships which were expected to be strong, turned out to be very weak. These include the wave height at Castlecliff and the height difference between Castlecliff and South Beach (r = -0.113). This indicates that wave height does not play a role in the amount of wave focusing occurring.

Since this part of the study involved a comparison, and provided the errors at each site were similar in nature and in magnitude, errors in the measurement methods were not as critical as they would have been if the focus had been on absolute values.

Wave direction was not included in the correlation as not enough variation in wave direction occurred during the study to accurately assess its effect. However, on two occasions (15/01/03 and 17/04/03), measurements were made of swell with a greater southerly component and relatively low periods (8 and 11 seconds). There was no wave height increase at South Beach, in fact there were virtually no waves breaking at all for 300 m either side of the pipeline. It appears that waves travelling shoreward with crests perpendicular to the orientation of the pipe, behave different to waves approaching at an angle to the pipeline. This phenomenon will be further considered later in the discussion.

From aerial photographs, waves were observed to refract and bend near the outfall. This appears to be related to changes in water depth. Wave velocity (c), is expressed in terms of the Airy Wave Theory formula in Equation (2).

$$c = \frac{gT}{2\pi} \tanh \frac{2\pi d}{cT} \qquad (2)$$

This relationship between c and water depth (d) for a fixed wave period (T), shows wave velocity increases with water depth. The difference in water depth between the margin and base of the depression is ~ 4 metres. The associated difference in wave velocity causes the wave to move faster in the depression and hence to bend out towards either side. When the wave-crest length is reduced, the energy per unit length is increased (Figure 7). As wave height is directly related to the energy, any local increase will result in a corresponding local height increase.

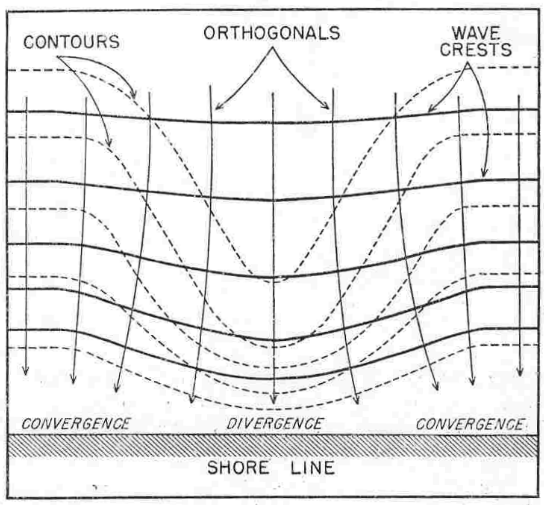

Figure 7: Wave crests moving over a perfect canyon. Note the wave orthogonals diverge over the canyon and converge to either side. (Source: Munk and Traylor, 1947)

It cannot be assumed however, that the difference in wave height between Castlecliff and South Beach is due entirely to the depression. These beaches face different directions and have different geometry. The South Beach has a lower gradient than Castlecliff due to effects of the Wanganui River delta. Effects of wave refraction due to these differences have not been included in this study. However, the dominant angle of wave approach in the data is from the western quarter. This means that waves must bend (refract) more to align with the South Beach. Because wave height decreases when waves bend in this way (due to an increasing wave-crest length), slightly reduced wave heights would be expected at South Beach.

A good example of the phenomenon of wave refraction around underwater canyons occurs at La Jolla, California, were two canyons, La Jolla and Scripps dominate the offshore topography. Incoming waves refract and defocus over the canyons leading to increased wave height on either side (Shepherd, 1951). The Scripps canyon in particular has a very similar angle to incoming swell as the South Beach depression. Here, an intense concentration of energy and therefore increase in wave height occurs: similar to occurrences at South Beach. As was observed at South Beach, studies at La Jolla (Munk and Traylor, 1947) indicate more intense focusing results from longer period waves.

An empirical refraction diagram was constructed for the South Beach study site (Figure 8). This method, contained in the US Hydrographic Office Publication 605 (1949): "Graphical Construction of Wave Refraction Diagrams", shows that a 14 second wave results in intense focusing about 500 m from shore and on the northwestern side of the pipe. This is approximately the location that large waves were observed to break (Figure 2). The actual pattern of wave-crests also closely resembles those observed in aerial photographs.

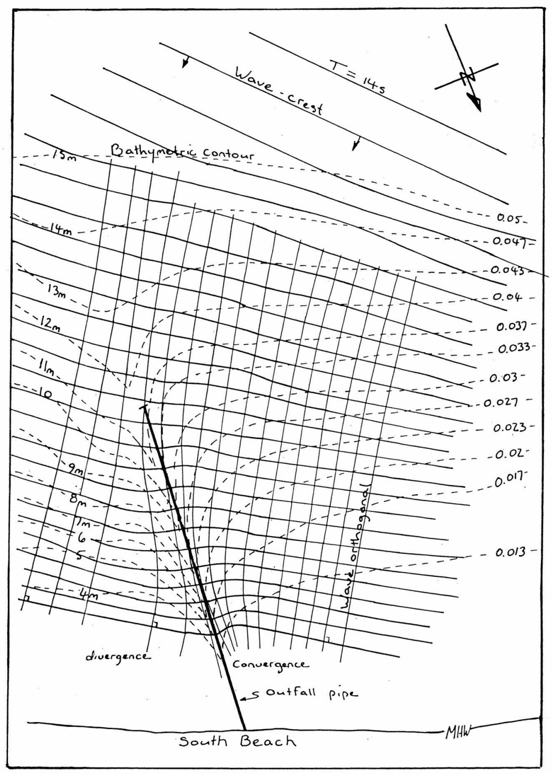

Figure 8 Empirical refraction diagram depicting wave focussing occurring to the northwest of the pipeline, approximately 500m offshore

Numerical modelling was undertaken using the combined refraction/diffraction model REF/DIF 1 (V2.5). This model uses a mild slope equation to model monochromatic wave movement over irregular bathymetry. Mild slopes are theoretically defined as having a gradient of less than 1:3. The South Beach depression satisfies this requirement. The computational grid of 2km by 2km was used with a 20m resolution. A range of wave heights, periods and directions were modelled. All wave types showed a local increase in wave height to the northwest of the depression and decrease to the southeast. The extent of this deformation varied with input wave properties. An example of the model output is shown in Figure 9.

This numerical modelling is very preliminary and qualitative. Quantitative modelling would require use of a larger model area and instrumention for calibration and verification. In spite of this, results were in very good agreement with observation and with results of the empirical modelling.

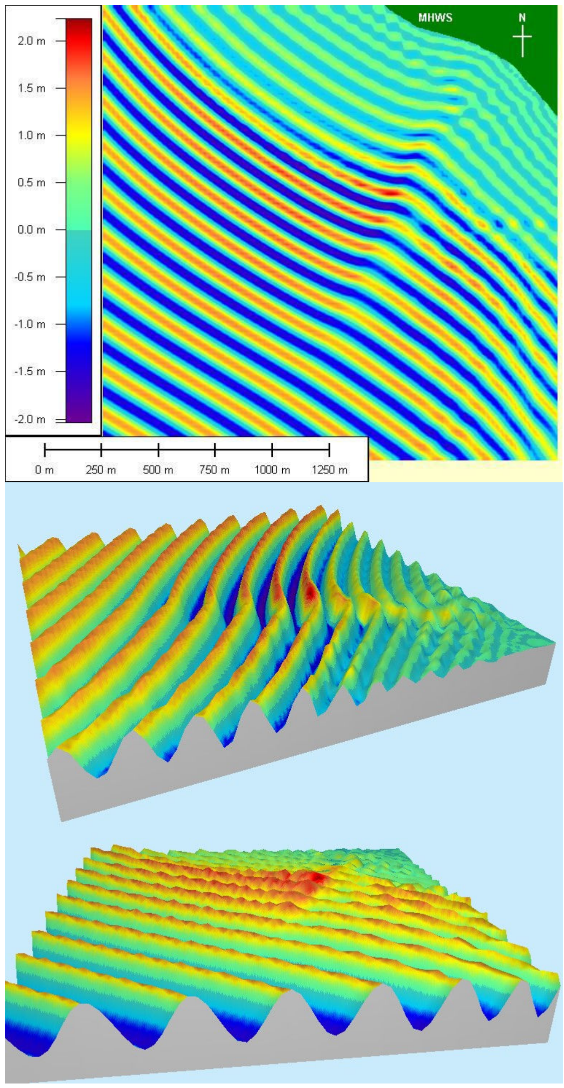

Figure 9 3m high waves of 14 sec period approach South Beach from the southwest. The waves can be seen deforming over the depression and focussing on the northwest side.

What processes caused, and maintain, the South Beach depression? Since no evidence of such a feature existed on pre-outfall maps and photographs, the pipeline is almost certainly responsible. This is supported by findings from Israel (Stadler, 1996), where 3 pipelines at Ashkelon, on the Mediterranean coast, have each resulted in the development of underwater depressions.

Research into scour around pipelines (Sumer, 1999) show that scour occurs by 'tunnel erosion' and/or 'lee-wake scour' when a pipe is subjected to a lateral current. In Wanganui, the strongest long-shore currents are wind-induced and reach speeds of 0.77 m/s (Bell, 1990). In addition, this wind-associated current may be supplemented by a tidal stream, which has an average velocity of 0.2 m/s.

Scour on both sides of the pipeline at Wanganui suggest that longshore current from both the northwest and southeast cause scour. However, more extensive erosion on the southeastern side indicates NW to SE currents are predominant on this coast. This agrees with Patterson's (1992) findings on littoral drift direction.

6. Conclusions

This study has quantitatively demonstrated wave deformation occurs in the vicinity of the long ocean outfall at Wanganui, by analysing aerial photographs and wave height measurements. The primary cause of wave deformation appears to be wave refraction caused by the irregular seafloor topography evident from a bathymetric survey.

This irregular topography is primarily due to a large underwater depression the axis of which lies on the southeastern side of the pipeline. Such features have also been documented in a similar situation in Israel. These depressions appear to result from long-shore currents perpendicular to the pipelines causing tunnel erosion and lee-wake scour. Whether an equilibrium-sized depression has been reached in Wanganui is unknown, further bathymetric surveys would be required to determine this.

Differences in water depth under the wave-crest causes wave refraction such that the section of wave above the depression moves faster and bends out towards the depression walls. Divergence of wave energy above the depression leads to reduced wave height, while wave energy convergence on either side of the depression increases wave height.

The amount of wave refraction appears to be related to the period of the incident waves. Comparisons between the control beach and South Beach show an exponential type relationship between period and difference in wave height. This is probably due to longer period waves starting to interact with the seafloor in deeper water, i.e. from further seaward, and hence undergo greater refraction and focusing than shorter period waves.

Observations at Wanganui on the effect wave period has on convergence and wave height increase, were consistent with the results of studies based around natural canyons at La Jolla, California.

Both numerical and empirical modelling show deformation occurring around the depression resulting in local wave height increases to the northwest and decreases to the southeast. Results of both are in very good agreement with site observation

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